Factors affecting the quality of biomass pellet for biofuel and energy analysis of pelleting process

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Abstract: Agricultural biomass residue such as barley, canola, oat and wheat straw has the potential to be used for sustainable production of bio-fuels and offset greenhouse gas emissions. The biomass substrate must be processed and handled in an efficient manner in order to reduce industry's operational cost as well as meet the requirement of raw material for biofuel production. Biomass has low bulk density, making it difficult and costly to store and transport in its native loose form. Therefore, in this study, an integrated approach to densification of non-treated and steam exploded barley, canola, oat and wheat straw was developed. During this process, the significance of major contributing factors (independent variables such as biomass type, treatment, pressure and grind size) on pellet density, durability and specific energy were determined. It has been found that applied pressure (60.4%) was the most significant factor affecting pellet density followed by the application of steam explosion pre-treatment (39.4%) for lab-scale single pelleting experiments. Similarly, the type of biomass (47.1%) is the most significant factor affecting durability followed by the application of pre-treatment (38.2%) and grind size (14.6%) for pellets manufactured using the pilot-scale pellet mill. Also, applied pressure (58.3%) was the most significant factor affecting specific energy required to manufacture pellets followed by the biomass (15.3%), pre-treatment (13.3%) and grind size (13.2%), which had lower but similar effect on specific energy for lab-scale single pelleting experiments. Overall energy analysis of post-harvest processing and densification of agricultural straw was performed, which showed that a significant portion of original agricultural biomass energy (89%-94%) is available for the production of biofuels. Almost, similar amount of specific energy is required to produce pellets from barley, canola, oat and wheat straw grinds. Customized pellets having steam exploded straw required more energy to manufacture resulting in availability of only 89% of total energy for biofuel production.
Keywords: biofuel, biomass, steam explosion, pretreatment, pelleting, specific energy, barley straw, canola straw, oat straw, wheat straw
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1 Introduction

Agricultural biomass residues have the potential for the sustainable production of bio-fuels and to offset greenhouse gas emissions[1-3]. Compaction of low bulk density agricultural biomass is a critical and desirable

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operation for sustainable and economic availability of feedstock for biofuel industry. Due to its high moisture content, irregular shape and size, and low bulk density, biomass is very difficult to handle, transport, store, and utilize in its original form[4,5]. Densification of biomass into durable compacts is an effective solution to these problems and it can reduce material waste. Densification can increase the bulk density of biomass from an initial bulk density of 40-200 kg/m^3 to a final compact density of 600-1 200 kg/m^3[6-10]. Because of their uniform shape and size, densified products can easily be handled using existing handling and storage system used for cereal grains. They can be easily adopted in direct-combustion or co-firing with coal, gasification, pyrolysis, and utilized in other biomass-based conversions[11] such as biochemical processes.

The quality of fuel pellet is usually assessed based on its density and durability. High density of pellet represents higher energy per unit volume of material, while durability is the resistance of pellets to withstand shear and impact forces applied during handling and transportation. High bulk density increases storage and transport capacity of pellets. Since feeding of boilers and gasifiers generally is volume-dependent, variations in bulk density should be avoided[12]. A bulk density of 650 kg/m^3 is stated as design value for wood pellet producers[10]. Low durability of pellets results in problems like disturbance within pellet feeding systems, dust emissions, and an increased risk of fire and explosions during pellet handling and storage[13]. The quality of pellets can be affected by the amount of moisture in biomass[10,11,13-15,17-23], grind size[24,25] and pretreatment[5,15,26].

Upon densification, many agricultural biomass materials, especially those from agricultural straw and stover, result in a poorly formed pellets or compacts caused by lack of understanding on the natural binding characteristics and interaction of the components that make up biomass during compaction. These pellets are more often dusty, difficult to handle and costly to manufacture. The natural binding characteristics of lignocellulosic biomass can be enhanced by modifying the structure of cellulose-hemicellulose-lignin matrix by application of pre-processing and pre-treatment methods[5]. It is postulated that by disrupting the lignocellulosic matrix of biomass materials via application of various chemical, physico-chemical (steam explosion, microwave, and radio frequency heating), and biological pre-treatment, the compression and compaction characteristics can be improved[15,26].

Steam explosion is one of the most commonly applied pre-treatment processes owing to its low use of chemicals and limited energy consumption[27]. Steam explosion results in the hemicelluloses being hydrolyzed and become water soluble, the cellulose is slightly depolymerized, and the lignin melts and is depolymerized, which aid in binding particles together during densification. Zandersons et al.[28] stated that activation of lignin and changes in the cellulosic structure during the steam explosion process facilitate the formation of new chemical bonds. Lam et al.[29] reported that the quality (durability) of compacts produced from steam exploded sawdust was 20% higher than non-treated sawdust. During steam explosion pre-treatment process, the lignocellulosic biomass is heated with high pressure saturated steam having temperatures typically in the range of 180-230℃ for 2-10 minutes. Subsequently, the substrate is quickly flashed to atmospheric pressure resulting in the rapid vaporization and expansion of the water inside the biomass[30-32]. This causes great reduction in the particle size of the substrate. The heart of the explosion pulping process is the reactor, which allows the use of high pressure during heating and cooking. The reactor can be of either the batch[33] or continuous type[31].

An overall specific energy analysis is desired in order to understand the net amount of energy available for the production of biofuels after postharvest processing and densification of agricultural straw. Consequently, various energy intensive steps involved in pelleting of agricultural biomass are shown in the flow process diagram in Figure 1. Detailed information on the importance of each step in Figure 1 and respective method for determining specific energy values are provided by Adapa[34].

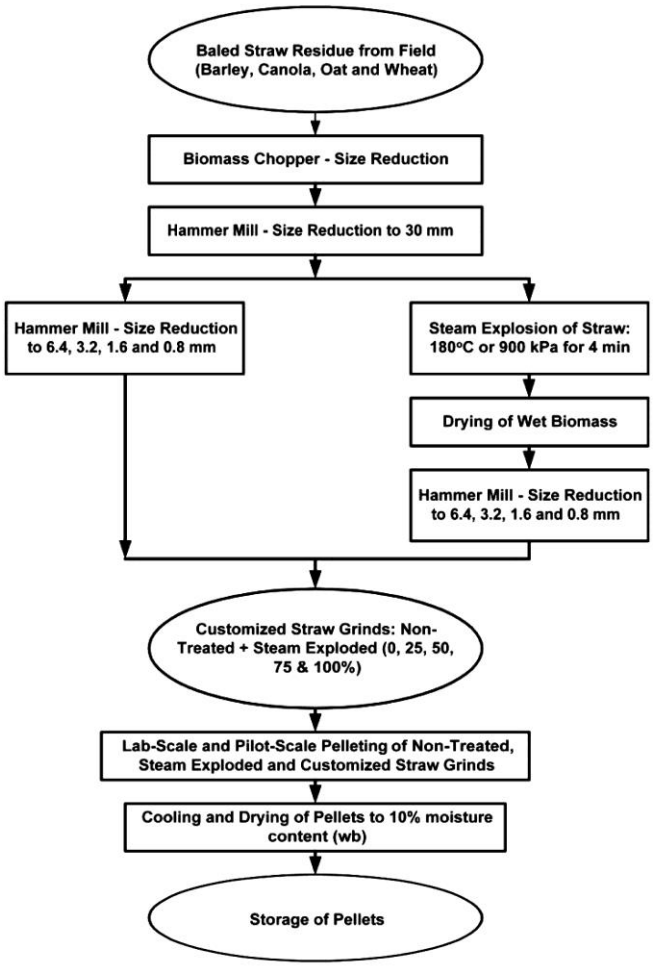

Figure 1 Flow chart showing the energy intensive steps involved in pelleting of agricultural biomass

Considering the above facts, there is a need to perform a study to analyze the experimental data and identify factors that significantly contribute towards pellet quality. The results of this analysis will guide a manufacturer to optimize the most significant factors affecting pellet density, durability and specific energy required during manufacturing. In addition, an overall energy analysis by identifying energy needs at various steps indicated in Figure 1 should be performed to make an assessment of energy that will be available for production of biofuel and optimize the post-harvest processing path in the flowchart. Therefore, the objectives of this study are 1) to determine the significance of major contributing factors (independent variables such as biomass type, pretreatment, pressure and grind size) on pellet density, durability and specific energy; 2) to perform an overall energy analysis of post-harvest processing and densification of agricultural straw.

2 Materials and methods

The materials and method for this study are similar to what has been reported by Adapa et al[40]. The method for measuring specific energy for chopping, grinding, steam explosion, pelletizing and pellet cooling is outlined.

2.1 Chopper and hammer mill

During the chopping and grinding experiments, 3 kg each of either non-treated or steam exploded straw was manually fed into the chopper[35] (no screen) and hammer mill[35] having four screen sizes of 30, 6.4, 3.2 and 1.6 mm. The chopper was fabricated in the Bioprocessing Lab, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, which is a modified and compact version of the currently available New Holland Forage Chopper series 770 having similar specifications of the chopper and cutter-bar, and motor size of 770 W. The biomass chopper was equipped with a feed hopper and a pair of rollers to feed the material to the chopping blades. The feed rate of biomass to the blades was dependent on the roller speed. After a few preliminary trials, the rollers were set to rotate at 0.83 Hz in order to avoid material clogging. Each of the six chopper blades were inclined at an angle of 14^{o} (with respect to horizontal axis of rotation) to deliver shearing effect on the biomass and were set to rotate at 7.7 Hz[35].

The chopped biomass was subsequently ground using a hammer mill (Serial No. 6M13688; Glen Mills Inc., Maywood, NJ) having 22 swinging hammers, attached to a shaft powered by a 1.5 kW electric motor. The shaft rotated at 63.3 Hz. A dust collector (House of Tools, Model no. DC-202B, Saskatoon, SK) having a 9 A suction fan rotating at 58.3 Hz was connected to the outlet of the hammer mill to control dust during operation, provide flowability of chopped biomass through the hammer mill, and collect the ground biomass[35].

The power drawn by the chopper and hammer mill motors, and the time required for the grinding process were measured and recorded using a wattmeter (Ohio Semitronics International, Hilliard, OH). The meter was connected to a data logging system (LABMATE Data

Acquisition and Control System, Sciemetric Instruments, Ottawa, ON), which transmitted time-power data to a desktop computer for recording and further analysis[35]. The power required to run the empty chopper and hammer mill were recorded prior to the introduction of material in order to obtain base line data. This allowed determining the net power required to grind the material. The specific energy (kWh/t) required for chopping and grinding was determined by integrating the area under the power demand curve for the total time required to grind the sample for pre-determined quantity of material[24]. Each test was performed in replicates of three.

Total specific energy required to grind non-treated straw can be obtained by adding specific energy required for chopping of the baled straw plus the specific energy required for hammer mill grinding. Total specific energy required to grind steam exploded straw to 6.4, 3.2 and 1.6 mm hammer mill screen size can be obtained by adding specific energy required for chopping of the baled straw, specific energy for hammer mill grinding of straw at a screen size of 30 mm, and the respective specific energy required for hammer mill grinding of steam exploded material at 6.4, 3.2 and 1.6 mm.

2.2 Steam explosion

The steam explosion of ground straw obtained using 30 mm hammer mill screen size was performed at the pilot-scale continuous steam explosion plant of FPInnovations, Quebec City, Quebec. The Andritz (ANDRITZ AG, Graz, Austria) pressurized disc refiner having a plate gap of 0.5 mm, powered by a 160 kW (215 hp) motor with a variable speed drive set to operate at 33.3 Hz. The biomass flow through the refiner is wet (in suspension). The throughput of the equipment can vary between 50 kg and 200 kg of dried material per hour, depending on the bulk density of the raw material and the desired final particle size of the steam exploded material. The feed rate of agricultural straw into the digester was controlled using a plug screw feeder. The digester was operated at 180^{o}C (steam pressure of 900 kPa) for four minutes to perform steam explosion of the agricultural biomass. A flash tube convective dryer having 90 m long tube was used to dry the steam exploded barley, canola, oat and wheat straw at an average moisture content of 70.1%, 80.7%, 76.7%, and 81.0% (w.b.) to approximately an average moisture content of 12.2%, 13.6%, 12.0% and 12.0% (w.b.), respectively. The direct heating of air was performed using 1 172 kW natural gas burner, which has variable control to operate at different temperatures. Detailed information on this process is reported by Adapa et al[36].

2.2.1 Steam explosion pre-treatment

Energy required during steam explosion process can be calculated by following the procedure described by Abolins and Gravitis[37]. A model provided in Figure 2 is used to calculate the cost of steam explosion treatment in terms of energy. The effect can be assessed by some critical limit of moisture content M_c at which the energy spent on heating the waterless part of the biomass to the required temperature is equal to the energy spent on raising the temperature of the moisture (Equation (1)).

$$M_c = \frac{c_b(\Delta T)}{c_b(\Delta T) + (\Delta h)m_w} \quad (1)$$

where c_b is specific heat of dry biomass, kJ/kg·℃; ΔT is difference between the operation temperature and the initial temperature, ℃; Δh is enthalpy difference of water content of the biomass, kJ/kg; and m_w is mass of moisture in biomass, kg.

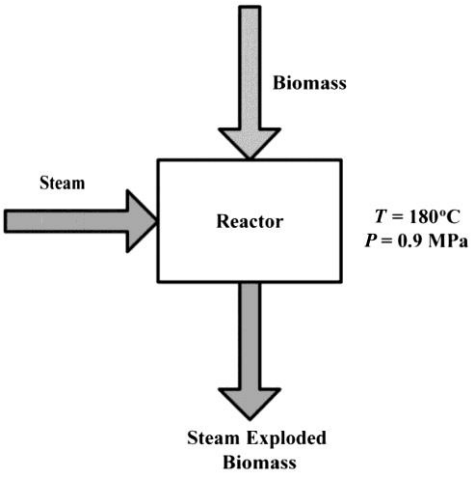

Figure 2 Block diagram of steam explosion model used for energy calculations

Energy E_b consumed to heat the biomass up to the required operation temperature can be calculated as follows[37].

$$E_b = C_b(\Delta T) + m_w(\Delta h) \quad (2)$$

Similarly, the energy for biomass treatment by steam

explosion being supplied by saturated steam at the operation temperature can be expressed in terms of the amount of steam consumed per unit mass of the processed dry organic substance. Assuming that biomass is heated at the expense of energy released at the condensation of saturated steam at the operation temperature, the mass of condensed saturated steam m_{cs} is found from the following Equation (3)[37]:

$$m_{cs}E_{evap} = E_b \quad (3)$$

where, E_{evap} is the heat of evaporation at the operating temperature, kJ/kg and E_b is given by Equation (2).

The total amount of saturated steam necessary for the process is found as the sum of the amount of steam being condensed to heat the biomass and the amount of steam m_o necessary to maintain the pressure in the reactor (Equation (4))[37]:

$$m_o = \frac{V}{v} \quad (4)$$

where V is volume of the reactor occupied by the biomass containing one mass unit of the dry substance to be treated, m^3; v is the specific volume of saturated steam under operation pressure and temperature, m^3/kg.

Therefore, the energy to generate the total amount of steam $m_s = m_{cs}+m_o$ is provided in Equation (5)[37]:

$$E_s = m_s(\Delta h) \quad (5)$$

where E_s is total energy required to generate steam, kJ/kg.

Total amount of energy required during steam explosion process is given by the following Equation (6):

$$E_t = E_b + E_s \quad (6)$$

2.2.2 Drying of wet biomass after steam explosion

During the steam explosion process, the moisture content of biomass significantly increases and reaches approximately 80% (w.b.). Consequently, the wet biomass must be dried to approximately 12% (w.b.) prior to storing and densification into pellets. Therefore, the energy supplied to evaporate water depends upon the drying temperature. The quantity of energy required per kg of water is called the latent heat of vaporization. The heat energy required to vaporize water under any given set of conditions can be calculated from the latent heats given in the steam table[38] and provided by the following Equation (7):

Heat energy (kJ) required for 1.0 kg biomass = heat energy to raise temperature of biomass to drying temperature + latent heat to remove water (7)

where Heat energy = $C_b(\Delta T)$; Latent heat = $m_w L$, in which L is latent heat of vaporization of water, kJ/kg.

2.3 Lab-scale single pelleting

The compaction apparatus and the process used for manufacturing single pellet at a time is similar to what has been reported by Adapa et al[36,39]. Four levels of compressive forces of 1 000, 2 000, 3 000 and 4 400 N corresponding to pressures of 31.6, 63.2, 94.7 and 138.9 MPa were applied using the Instron Model 1011 (Instron, Norwood, MA) testing machine fitted with a 5 000 N load cell and a 6.25 mm diameter plunger. The mass, length and diameter of compacts were measured to determine the density in kg/m^3, following the extrusion of the compact. Ten replicates (pellets) were made using each ground straw samples.

During compression and extrusion process of individual compacts, the force-displacement data were recorded. Specific compression and extrusion energies were calculated following the methodology of Mani et al[40]. The area under the force-displacement curve was integrated using the trapezoid rule[41]; when combined with the pellet mass, it yielded the specific energy values in MJ/t. The specific energy calculations did not include the energy required to operate the Instron testing machine.

2.4 Pilot-scale pelleting

A laboratory scale CPM CL−5 pellet mill (California Pellet Mill Co., Crawfordsville, IN) was used for processing of non-treated and steam exploded agricultural straw grinds into pellets. The pellet mill consisted of a corrugated roller (diameter 85.0 mm) and ring die assembly. The ring die size (radius) and length (thickness) were 125.3 mm and 44.6 mm, respectively. The ring hole diameter and l/d ratio were 6.10 mm and 7.31 mm, respectively. The rotational speed of the pellet mill was 250 r/min[14,36,43].

At the onset of pelleting experiments, 2 kg each of ground non-treated barley, canola, oat and wheat straw grinds from 6.4, 3.2, and 1.6 mm hammer mill screen size

were re-moistened to 10% moisture content (w.b.) by adding/sprinkling a calculated amount of water and mixed a rotating concrete mixer. Due to low bulk density and poor flowability of ground straw, the pellet mill continuously clogged without producing any pellets. The non-treated and steam exploded straw was ground using 0.8 mm hammer mill screen size to improve the flowability of straw grinds. The specific energy required to grind straw samples to 0.8 mm screen size was added to determine the total specific energy as per procedure indicated in section 2.1. As pre-compaction[12] and steam addition[46] are energy intensive operations, it was decided to add both moisture and flax seed oil in incremental steps of 0.5% to further increase the bulk density and flowability of ground straw through pellet mill. Addition of moisture and oil to a level of 17.5% and 10%, respectively, would result in production of pellets. Similar process was repeated for customized ground straw obtained from 6.4, 3.2, 1.6, and 0.8 mm hammer mill screen sizes.

The feed rate of material to the pellet mill was controlled using a vibratory feeder. Each successful pilot-scale pelleting test was performed for an average period of 10 min. During this period, manufactured pellets were collected and weighed to determine the pellet mill throughput (kg/h). In addition, the pellet mill energy consumption (kWh) was recorded in real time using a data logger connected to a computer and was used to calculate the specific energy (MJ/t) required to manufacture pellets from respective agricultural biomass. The manufactured pellets were allowed to dry in ambient condition for 24 h and subsequently stored in black plastic bags for at least two weeks prior to pellet density and durability tests.

2.5 Cooling of pellets

Biomass pellets are cooled to reduce the moisture and temperature in the pellets to levels that are safe for storage and provide ease in handling. The relatively high levels of moisture (soft pellets) and temperature (about 100℃) in the pellets arise from the frictional heating of the die during pelleting. Inadequate cooling and drying of pellets contributes to poor pellet quality, spoilage, heating and spontaneous combustion, caking in storage bags and holding bins[47,48]. Thus, it is a common practice to let them get air cooled through a conveyor belt. Under these conditions, the lignin polymer inside biomass fibres gets stabilized, producing pellets of increased hardness properties[47].

Typically, pellets experience a temperature change greater than 70^{o}C during the cooling process. The energy required to cool the pellets (sensible energy) is three times greater than the energy required to dry the pellets (latent heat)[48]. Fasina and Sokhansanj[49] reported that the sensible heat for cooling alfalfa pellets was 2 600 MJ/h assuming an average specific heat of 1 800 J/(kg·K) and the pelleting plant operates at capacity of 16 t/h. The latent heat was 800 MJ/h when the latent heat of vaporization of alfalfa pellets was taken to be 2,500 kJ/kg[49].

2.6 Statistical analysis

The experiments were set up as completely randomized experimental design with 10 replications of compacts and four-variable (straw, pre-treatment (steam explosion), hammer mill screen size and pressure) factorial design. Density, durability and specific energy were the dependent variables, while straw, pre-treatment, hammer mill screen size and pressure were the independent variables. Statistical analyses were conducted using SAS for Windows (version 8.2)[50]. In order to further understand and explain the experimental variables and their interactions, the SAS general linear model (GLM) was used. Values of sum of squares (SS) for each factor (independent variable) were obtained from the GLM factorial model. Subsequently, the SS were re-calculated to percentage base and presented in graphical form[51].

3 Results and discussion

3.1 Contribution of factors affecting pellet quality

The experimental data, regression analysis and discussion on properties of ground biomass (geometric mean particle diameter, bulk density, and particle density), lignocellulosic composition, pellet density, pellet durability and specific energy are provided by Adapa et al[35,52]. The present section will focus on contribution of independent variables such as biomass, pre-treatment,

applied pressure and grind size on pellet density, durability and specific energy.

After performing the statistical analysis on density data for pellets manufactured from lab-scale single pelleting experiments[52], it was determined that the applied pressure (60.4%) was the most significant factor affecting pellet density followed by the application of steam explosion pre-treatment (39.4%) (Figure 3). Type of biomass and grind size did not have significant effect on the pellet density (Figure 3).

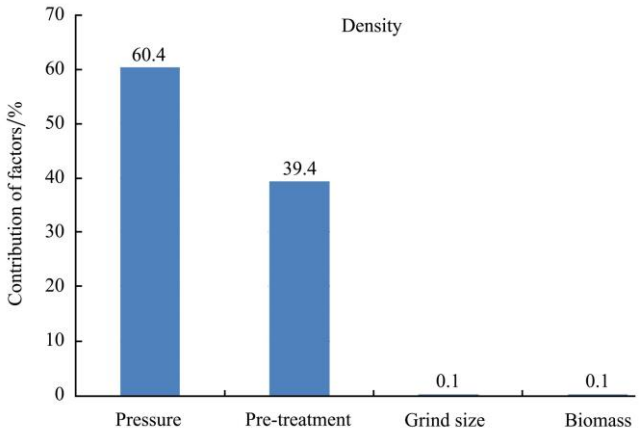

Figure 3 Contribution of independent variables to durability of pellets manufactured from lab-scale single pelleting experiments[52]

Similarly, the statistical analysis of durability data for pellets manufactured from pilot-scale pelleting experiments[36] indicated that the type of biomass (47.1%) is the most significant factor affecting durability followed by the application of pre-treatment (38.2%) and grind size (14.6%) (Figure 4).

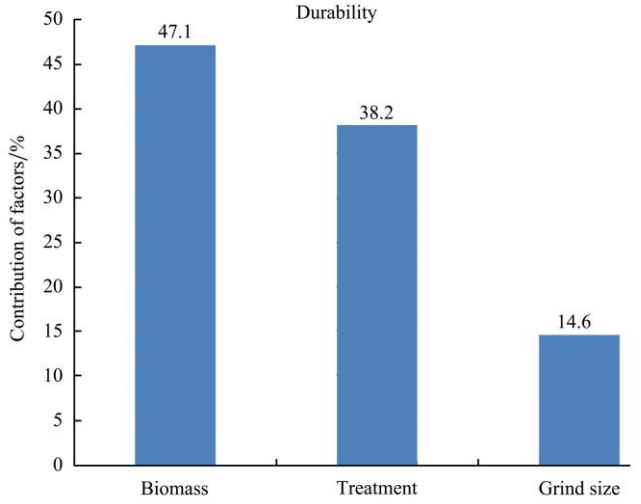

Figure 4 Contribution of independent variables to durability of pellets manufactured from pilot-scale pelleting experiments[36]

The statistical analysis of specific energy data for pellets manufactured from lab-scale single pelleting experiments[52] showed that the applied pressure (58.3%) was the most significant factor affecting specific energy required to manufacture pellets followed by the biomass (15.3%), pre-treatment (13.3%) and grind size (13.2%), which had lower but similar effect on specific energy (Figure 5).

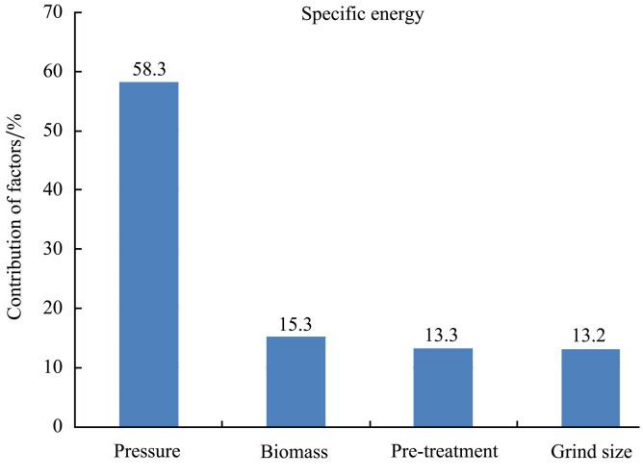

Figure 5 Contribution of independent variables to specific energy of pellets manufactured from lab-scale single pelleting experiments[52]

3.2 Overall energy analysis

An overall specific energy analysis is desired in order to understand the net amount of energy available for the production of biofuels after postharvest processing and densification of agricultural straw (Figure 1). Barley, canola, oat and wheat straw at moisture content of 13.5%, 15.1%, 13.1% and 15.6% (w.b.), respectively was subjected to steam explosion pre-treatment at 180℃ (steam pressure of 900 kPa) for four minutes. Table 1 shows the thermodynamic characteristics of saturated steam and biomass along with specific energy calculations. Subsequently, the steam exploded barley, canola, oat and wheat straw at an average moisture content of 70.1%, 80.7%, 76.7% and 81.0% (w.b.) to approximately an average moisture content of 12.2%, 13.6%, 12.0% and 12.0% (w.b.), respectively. The specific energy calculations for drying wet steam exploded biomass are provided in Table 2.

The overall specific energy analysis was performed for pilot-scale pelleting of non-treated and customized

(75% non-treated + 25% steam exploded) barley, canola, oat and wheat straw using 1.6 and 0.8 mm hammer mill screen sizes (Table 3). The specific energy for grinding of straw at 0.8 mm was calculated using regression equations reported in Adapa et al[35]. The specific energy for chopping and grinding of biomass, production of pellets using pellet mill and higher heating values for straw were obtained from experimental data in the studies by Adapa et al.[35,36] and Table 3. In addition, the power required for operating the chopper, hammer mill and pellet mill were 337, 759 and 429 W, respectively.

Table 1 Thermodynamic properties of saturated steam, biomass, and energy analysis

Thermodynamic properties	Steam	Barley	Canola	Oat	Wheat
Enthalpy difference Δh at 180℃/kJ kg^{-1}	2777				
Evaporation energy E_{evap} at 180℃/kJ kg^{-1}	2014				
Specific volume v at 180℃/m^3 kg^{-1}	0.194				
Mass of moisture content m_w/kg		0.677	0.594	0.701	0.572
Straw specific heat C_b[53]/kJ kg^{-1} ·℃$^{-1}$		1.63[a]	1.57[a]	1.57	1.63
Energy to heat the biomass E_b/kJ kg^{-1}		312.2	298.5	301.3	309.3
Mass of condensed steam m_{cs}/kg		0.155	0.148	0.150	0.154
Volume of reactor V/m^3 (five liters)[b]	0.005				
Amount of steam m_o/kg		0.026	0.026	0.026	0.026
Total steam $m_s = m_{cs}+m_o$/kg		0.181	0.174	0.175	0.179
Energy to generate total steam E_s/kJ kg^{-1}		502.1	483.2	487.1	498.1
Total energy for steam explosion E_t/kJ kg^{-1}		814.3	781.7	788.4	807.4

Note: [a] The bulk density reported by Anh et al.[53] for wheat straw was comparable to barley straw and for oat straw was comparable to canola straw hence similar straw specific heat values;

[b] Assuming that 1 kg of biomass would fit loosely with an volume of five liters[37].

Table 2 Specific energy required to dry wet steam exploded biomass

Properties and Calculations	Barley	Canola	Oat	Wheat
Biomass initial moisture Content/% (w.b.)	70.1	80.7	76.7	81.0
Biomass final moisture Content/% (w.b.)	12.2	13.6	12.0	12.0
Dryer inlet temperature 120℃				
Latent heat of vaporization of water at 120℃ is 2202/kJ kg^{-1}[a]				
Initial mass of water in 1 kg of biomass	0.701	0.807	0.767	0.810
Mass of dry biomass/kg	0.299	0.193	0.233	0.190
Final mass of water/kg	0.042	0.030	0.032	0.026
Mass of water evaporated/kg	0.659	0.777	0.735	0.784
Specific heat of biomass /kJ kg^{-1} ·℃$^{-1}$	1.63	1.57	1.57	1.63
Temperature of biomass at reactor outlet is 100℃ (assumption)				
Energy required to raise biomass temperature to 120℃/kJ	32.6	31.4	31.4	32.6
Latent energy required to remove water/kJ	1 452.1	1 710.1	1 619.0	1 726.6
Total energy required for drying/kJ	1 484.7	1 741.5	1 650.4	1 759.2
Specific energy required for drying/kJ kg^{-1}	2 251.4	2 242.4	2 244.7	2 243.6

Note: [a] Latent heat is obtained from steam table provided by Earle[38].

The total specific energy required to form pellets increased with a decrease in hammer mill screen size from 1.6 to 0.8 mm and also the total specific energy significantly increased with customization of straw at 0.8 mm screen size (Table 3). Figures 7-9 showed the contribution of factors toward total specific energy required to manufacture barley, canola, oat and wheat straw pellets. In all of the plots, the pellet mill consumed the highest proportion of total specific energy followed by hammer mill and chopper for non-treated barley straw at 1.6 mm grind size. A decrease in grind size to 0.8 mm for non-treated straw significantly increased the proportion of hammer mill contribution. The most significant factor for customized straw is the specific energy required for steam explosion pre-treatment (including drying) of biomass followed by pellet mill (Figures 6-9). It has been

observed that the net specific energy available for production of biofuel is a significant portion of original agricultural biomass energy (89%-94%) for all agricultural biomass (Table 3). Almost, similar amount of specific energy is required to produce pellets from barley, canola, oat and wheat straw grinds. Customized pellets having 25% of steam exploded straw (25% by mass) required more energy to manufacture resulting in availability of only 89% of total energy for biofuel production. It should be noted that the base specific energy required for operating the steam explosion, drying and cooling equipment are not included in the total numbers. In future studies, an increase in the higher heating values due to addition of flax seed oil to agricultural straw should also be included.

Table 3 Overall specific energy showing the net energy available for production of biofuels after postharvest processing and densification of agricultural straw

Treatment	Hammer mill screen size /mm	Specific Energy /MJ t^{-1}							HHV /MJ t^{-1}	Net energy$^{\gamma}$ /MJ t^{-1}
		Chopping biomass	Grinding biomass	Steam explosion	Drying of steam exploded biomass	Pilot-scale pelleting	Total operating energy$^{¥}$	Total$^{§£}$		
Barley										
NT*	1.6	11.3	90.4			293	528.8	924	16 400	15 476
NT	0.8	11.3	206.6			353	528.8	1 100	16 400	15 300
75% NT + 25% SE*	0.8	11.3	189.3	203.6	562.9	301	528.8	1 797	16 650	14 853
Canola										
NT	1.6	7.1	128.5			385	466.8	987	16 700	15 713
NT	0.8	7.1	363.3			440	466.8	1 277	16 700	15 423
75% NT + 25% SE	0.8	7.1	341.6	195.4	560.6	265	466.8	1 837	17 100	15 263
Oat										
NT	1.6	9.9	149.5			340	529.6	1 029	16 400	15 371
NT	0.8	9.9	253.6			344	529.6	1 137	16 400	15 263
75% NT + 25% SE	0.8	9.9	245.2	197.1	561.2	335	529.6	1 878	16 750	14 872
Wheat										
NT	1.6	8.2	153.3			381	505.6	1 048	17 000	15 952
NT	0.8	8.2	382.7			297	505.6	1 194	17 000	15 806
75% NT + 25% SE	0.8	8.2	332.1	201.9	560.9	342	505.6	1 951	17 200	15 249

Note: *NT means Non-Treated; SE means Steam Exploded;

¥ Total Operating Energy is the no load energy required for operating the chopper, hammer mill, and pellet mill; energy required for operating the chopper, hammer mill and pellet mill were 337, 759 and 429 W, respectively;

§ Energy is based on moisture contents of the biomass at operating conditions and not based on dry matter;

£ Total Specific Energy = Specific Energy (Chopping Biomass + Grinding Biomass + Steam Explosion + Pilot-Scale Pelleting + Operating Energy);

γ Net Energy = HHV – Total.

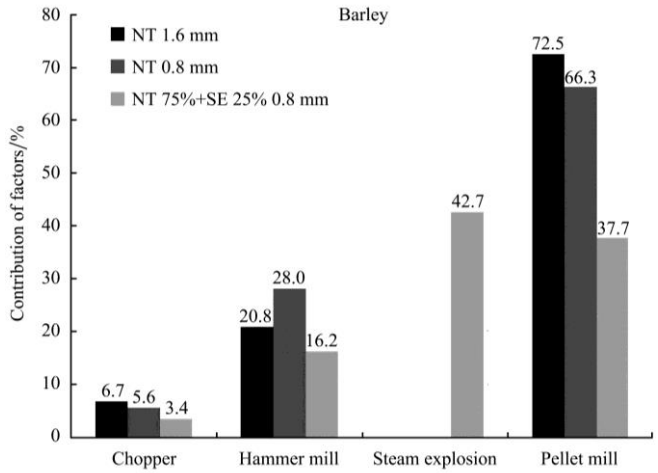

Figure 6 Contribution of factors toward total specific energy required to manufacture barley straw pellets

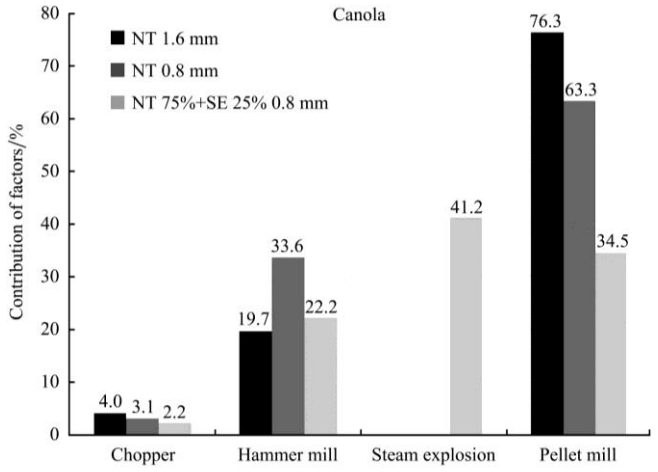

Figure 7 Contribution of factors toward total specific energy required to manufacture canola straw pellets

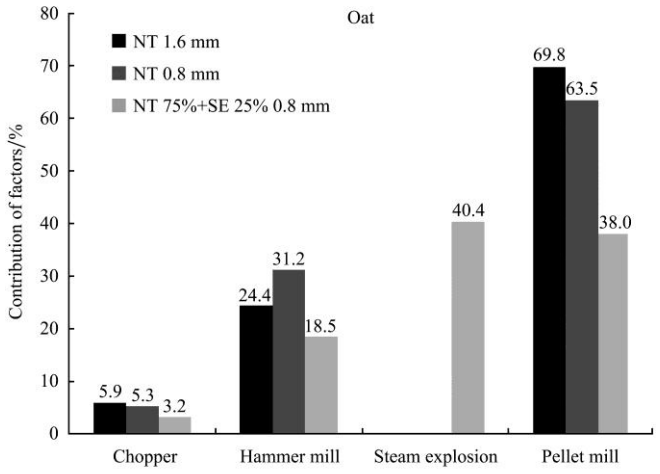

Figure 8 Contribution of factors toward total specific energy required to manufacture oat straw pellets

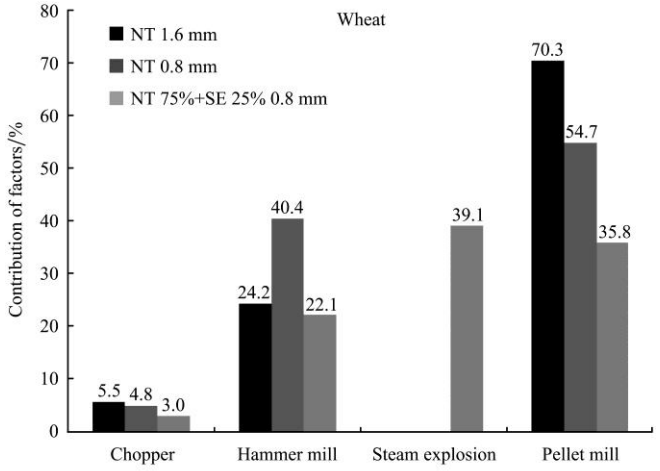

Figure 9 Contribution of factors toward total specific energy required to manufacture wheat straw pellets

4 Conclusions

From this analysis, it is concluded that the applied pressure (60.4%) was the most significant factor affecting pellet density followed by the application of steam explosion pre-treatment (39.4%) for lab-scale single pellet experiments. Similarly, the type of biomass type (47.1%) is the most significant factor affecting durability followed by the application of pre-treatment (38.2%) and grind size (14.6%) for pellets manufacture from pilot-scale pellet mill. The applied pressure (58.3%) was the most significant factor affecting specific energy required to manufacture pellets, followed by the biomass type (15.3%), pre-treatment (13.3%) and grind size (13.2%), for lab-scale single pellet experiments.

The pellet mill consumed the highest proportion of total specific energy followed by hammer mill, cooler and chopper for non-treated barley straw at 1.6 mm grind size. A decrease in grind size to 0.8 mm for non-treated straw significantly increased the proportion of energy contributed by the hammer mill. The most significant factor for customized straw is the specific energy required for steam explosion pre-treatment followed by pellet mill. An overall energy balance showed that a significant portion of original agricultural biomass energy (89%-94%) is available for the production of biofuels. Almost, similar amount of specific energy is required to produce pellets from barley, canola, oat and wheat straw grinds. Therefore, biofuel pellet manufacturers should focus on increasing the pellet bulk density and durability since comparable amount of specific energy is required at any specific grind size and pretreatment. Also, it is recommended to develop or use pellet mills that could pellet agricultural straw grinds obtained from higher hammer mill screen sizes (>1.6 mm) to increase the net available specific energy for production of biofuels.

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