Pelleting characteristics of selected biomass with and without steam explosion pretreatment

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Abstract: Processing and densification of agricultural biomass into high density and durable pellets are critical to facilitate handling, storage and transportation. Biomass pelleting experiments were designed to conduct single and pilot scale pelleting of non-treated and steam exploded barley, canola, oat and wheat straw grinds acquired from 6.4, 3.2, 1.6 and 0.8 mm hammer mill screen sizes at 10% moisture content (wb). Single-pelleting was performed by applying compression pressures of 31.6, 63.2, 94.7, and 138.9 MPa using a close-fit plunger die assembly (die length 135.3 mm and diameter of (6.30±0.5) mm). During pilot scale pelleting, customization of ground straw material was performed by adding steam exploded biomass in increments of 25% to non-treated ground straw for respective biomass at specific grind size. Ground straw samples were conditioned to 17.5% moisture content and 10% flaxseed oil was added to increase the bulk density and flowability of grinds, which resulted in the production of pellets. The quality of pellets from single pelleting experiments was ascertained by measuring their respective density and durability. In addition, the change in pellet density was measured after a storage period of one month to determine its dimensional stability. It was determined that applied pressure and pre-treatment were significant factors affecting the pellet density. Also, bigger grind sizes and lower applied pressures resulted in higher pellet relaxations (lower pellet densities) during storage of pellets. The pilot scale pellet mill produced pellets from ground non-treated straw at hammer mill screen sizes of 0.8 and 1.6 mm and customized samples having 25% steam exploded straw at 0.8 mm. It was observed that the pellet bulk density and particle density are positively correlated. The density and durability of agricultural straw pellets significantly increased with decrease in hammer mill screen size from 1.6 mm to 0.8 mm. Customization of agricultural straw by adding 25% of steam exploded straw by weight is possible, but it did not improve pellet quality. In addition, durability of pellets was negatively correlated to pellet mill throughput and was positively correlated to specific energy consumption.

Keywords: biofuels, biomass, density, durability, pelleting, specific energy, steam explosion, pretreatment

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1 Introduction

The two main sources of biomass for energy generation are purpose-grown energy crops and waste materials[1]. Energy crops, such as Miscanthus and short rotation woody crops (coppice), are cultivated mainly for energy purposes and are associated with the food vs. fuels debate, which is concerned with whether

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land should be used for fuel rather than food production. The use of residues from agriculture, such as barley, canola, oat and wheat straw, for energy generation circumvents the food vs. fuel dilemma and adds value to existing crops[2,3].

The main problem with straw is its relatively low density in its original or baled forms. The bulk density of loose and standard baled straw is approximately 40 kg/m^3 and 100 kg/m^3, respectively, compared with the bulk density of unprocessed wood residue, which is approximately 250 kg/m^3[4,5]. The relative low density of straw makes it more expensive to transport compared to wood and coal because a lower mass of straw can be transported per unit volume. Additionally, a larger storage area/volume is required for baled straw compared to wood chip. Densification into pellets increases the bulk density of biomass[6,7] and as a result, the net calorific content per unit volume is increased[8] and the storage, transport and handling of the material is easier and cheaper[8-10].

The quality of fuel pellet is usually assessed based on its density and durability. 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[11]. A bulk density of 650 kg/m^3 is stated as design value for wood pellet producers[7]. 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[12].

Raw materials causing uneven pellet production have low bulk density compared to other milled biofuel pellet raw materials. Low raw material bulk density will put higher demands on the die feeding system of the pelletizer with greater volume throughput for maintained production level. Larsson S H et al.[11] investigated the pre-compaction of straw as an alternative to avoid low and intermittent production of pellets. Pressurized steam conditioners are used in the feed pellet industry to decrease raw material porosity and to improve pellet hardness/durability[13].

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[14]. It is postulated that by disrupting the lignocellulosic biomass materials via steam explosion pretreatment, the compression and compaction characteristics can be improved[15]. Zandersons et al.[16] 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.[17] reported that the quality (durability) of pellets produced from steam exploded sawdust was 20% higher than non-treated sawdust.

In addition, the application of pretreatment operations such as size reduction/grinding is critical in order to increase the surface area of the material prior to densification[18]. Particle size reduction increases the total surface area, pore size of the material and the number of contact points for inter-particle bonding in the compaction process[19].

Traditionally, steam conditioning of biomass has been performed to increase flowability of grinds through pellet mill and enhance its natural binding capability[20]. The steam conditioning of straw grinds during pilot scale pelleting was not considered as an option in order to

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minimize energy input[21]. Previously, some work had been reported by Mani et al.[22,23] on mechanical properties of ground barley and wheat straw and by Shaw[15] on ground non-treated and steam exploded wheat straw as a feedstock for biofuel industry. However, there is a dearth of knowledge related to quality factors (density and durability) associated with densification of non-treated and steam exploded agricultural biomass and their relative comparison. In addition, literature on pilot scale pelleting of agricultural straw is scarce. Therefore, the objectives of this study are:

1) To determine the effect of pressure and biomass grind size on the density and durability of pellets from non-treated and steam exploded barley, canola, oat and wheat straw grinds using a single-pelleting apparatus having a close-fit plunger die assembly; the change in pellet density during storage was also studied;

2) To produce high density and high durability pellets from ground non-treated and steam exploded barley, canola, oat and wheat straw using a pilot scale pellet mill from the conclusions obtained in objective one as a guide.

2 Materials and methods

2.1 Agricultural biomass

Four types of agricultural biomass (barley, canola, oat and wheat straw) were used in the experiments. The straw samples were acquired in small square bale form (typically having dimensions of 0.45 m×0.35 m×1.00 m) during the summer of 2008 from a farmer in the Central Butte area of Saskatchewan, Canada.

The initial moisture contents of ground barley, canola, oat and wheat straw were 6.7%, 6.7%, 5.3%, and 4.0% (wb), respectively. The agricultural biomass was stored under a tarpaulin cover during the winter of 2008 (approximately for seven months). During this period, the moisture content of barley, canola, oat and wheat straw increased to 13.5%, 15.1%, 13.1%, and 15.6% (wb), respectively.

All of the baled straw samples were chopped using a chopper, which was fabricated in the Bioprocessing Lab, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Canada. The biomass chopper has six blades; each was fixed at a shearing angle of 14^o and rotated at 460 r/min. The chopped biomass was subsequently ground using a hammer mill (Serial No. 6M13688; 230 Brookdale, St. Maywood, NJ) having 22 swinging hammers, attached to a shaft powered by a 1.5 kW electric motor. The shaft was allowed to rotate at 3,800 r/min. Five screen sizes of 30, 6.4, 3.2, 1.6, and 0.8 mm were used to grind the non-treated biomass. A dust collector (House of Tools, Model No. DC-202B, Saskatoon, SK) having a 9 A suction fan rotating at 3,500 r/min 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. A portion (25 kg) of each of the biomass ground in the hammer mill using 30 mm screen was sent to FPInnovations in Quebec City, Quebec for steam explosion pretreatment.

2.2 Steam explosion of agricultural biomass

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 refiner having a plate gap of 0.5 mm, powered by a 160 kW (215 hp) motor with a variable speed drive was set to operate at 2,000 r/min. 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℃ (steam pressure of 900 kPa) for four minutes to perform steam explosion pretreatment of the agricultural biomass. A flash tube convective dryer having a 90 m long tube was used to dry the steam exploded barley, canola, oat and wheat straw having an initial average moisture content of 70.1%, 80.7%, 76.7%, and 81.0% (wb) to approximately an average moisture content of 12.2%, 13.6%, 12.0%, and 12.0% (wb), respectively. The direct heating of air was performed using 1,172 kW (4 million BTU/h) natural gas burner, which has variable control to operate at different temperatures.

During the transportation of steam exploded material from Quebec City, Quebec to Saskatoon, Saskatchewan, the average moisture content of steam exploded barley, canola, oat and wheat straw further decreased to 7.8%, 6.2%, 6.8%, and 7.0 % (wb), respectively. The steam exploded material was further ground in a hammer mill using four screen sizes of 6.4, 3.2, 1.6, and 0.8 mm following the procedure described in the previous section.

In addition, prior to pilot scale pelleting, customization of grounds straw material was performed by adding steam exploded biomass (e.g. barley 0.8 mm grind size) in increments of 25% (up to a maximum of 50%) to non-treated ground straw (e.g. barley 0.8 mm grind size) for respective biomass at specific grind size.

2.3 Moisture content

The moisture content of baled straw and steam exploded biomass was determined using ASABE S358[24], where 25 g of material was oven-dried at 103℃ for 24 h. The moisture content of ground straw at hammer mill screen sizes of 6.4, 3.2, 1.6 and 0.8 mm was determined using AACC Standard 44-15A[25], where 2-3 g of material was oven-dried at 130℃ for 90 min. All of the moisture content tests were performed in replicates of three.

2.4 Particle size analysis

The geometric mean particle diameter of ground non-treated and steam exploded agricultural straw samples was determined using ASABE Standard S319[26]. Due to the low bulk density of steam exploded straw, only 50 g of ground sample (instead of 100 g) was placed on a stack of sieves arranged from the largest to the smallest opening. A Ro-Tap sieve shaker (W. S. Tyler Inc., Mentor, OH) was used for particle size analysis. The sieve series selected were based on the range of particles in the samples. For grinds from 6.4 mm hammer mill screen opening, U.S. sieve numbers 10, 16, 20, 30, 50, and 70 (sieve opening sizes: 2.000, 1.190, 0.841, 0.595, 0.297, and 0.210 mm, respectively) were used. For grinds from 3.2, 1.6, and 0.8 mm hammer mill screen openings, U.S. sieve numbers 16, 20, 30, 50, 70, and 100 (sieve opening sizes: 1.190, 0.841, 0.595, 0.297, 0.210, and 0.149 mm, respectively) were used. A 10 min sieve shaking time was used as suggested in the ASABE Standard S319. The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated in replicates of three for each straw samples.

2.5 Bulk and particle density of biomass

Bulk density of hammer mill ground non-treated and steam exploded agricultural straw at four screen sizes of 6.4, 3.2, 1.6, and 0.8 mm was determined by carefully filling a standard 0.5 L cylindrical container (SWA951, Superior Scale Co. Ltd., Winnipeg, MB) with sample. After filling every third portion of the container with ground straw sample, it was tapped on a wooden table for approximately ten times to allow the material to settle down. After completely filling the container, excess material at the top was removed by moving a steel roller in a zig-zag pattern. The mass per unit volume gave the bulk density of the biomass in kg/m^3. A gas multi-pycnometer (Quanta Chrome, Boynton Beach, FL) was used to determine the particle density of the hammer mill ground straw by calculating the displaced volume of nitrogen gas by a known mass of material, following the method reported by Adapa et al.[27]. Three replicates for each sample were performed for both bulk and particle density measurements.

2.6 Chemical composition and higher heating values

The chemical composition analysis of non-treated and steam exploded barley, canola, oat and wheat straw was performed in duplicates by the SunWest Food Laboratory Ltd., Saskatoon, SK, Canada, and the Feed Innovation Centre, University of Saskatchewan. Crude protein, crude fat, starch, lignin, acid detergent fibre (ADF), neutral detergent fibre (NDF) and total ash contents were determined using standard methods. The crude protein content of the biomass was determined using the AOAC standard method 2,001.11[28], where the nitrogen content was multiplied by a factor of 6.25. The crude fat was determined using AOCS standard method Am2-93[29]. Total starch content was measured using AOAC standard method 996.11[30]. The lignin and ADF were determined using AOAC standard method 973.18[31], whereas NDF was determined using AOAC standard method 992.16[32]. The total ash content was determined using AOAC standard method 942.05[33]. The cellulose

percentage was calculated indirectly from percentage acid detergent fibre (ADF) and lignin (%ADF minus %lignin) and Hemicellulose percentage was calculated indirectly from the percentages of neutral detergent fibre (NDF) and ADF (%NDF minus %ADF)[22].

The calorific (heating) value of biomass feedstocks is indicative of the energy they possess as potential fuels. The gross calorific value (higher heating value, HHV) and the net calorific value (lower heating value, LHV) at constant pressure measures the enthalpy change of combustion with and without water condensed, respectively[34]. A Parr 1281 automatic isoperibol oxygen bomb calorimeter (Parr Instrument Company, Moline, IL) was used to determine the HHV of the non-treated and steam exploded straw in MJ/kg at the Feed Innovation Centre, University of Saskatchewan. ASTM Standard D5865-03[35] test method for gross calorific value of coal and coke, was used as a guideline for heating value testing.

2.7 Single-pelleting apparatus

A single-pelleting apparatus having a close fit plunger die assembly[36] was used to study the compression characteristics of selected agricultural straw[37]. The cylindrical die was 135.3 mm long and (6.30±0.5) mm in diameter. A thermal compound (Wakefield Engineering Inc., Wakefield, MA) was coated on the outer surface of the die prior to wrapping the outer surface with copper shim stock. A dual element heating tape (Cole-Parmer Instrument Company, Vernon Hills, IL) was then wound evenly around the shim stock to provide the necessary heat. One type-T thermocouple, connected to the outer surface of the cylinder, was linked to a temperature controller to regulate the power input to the heater, thus allowing temperature control of the cylinder. Another type-T thermocouple was also connected to the outer cylinder wall, allowed verification of the cylinder temperature via a digital thermocouple reader[15]. The die was fitted on a stainless steel base having a hole matching its outer diameter. This gave stability and allowed the plunger to move straight down with no lateral movement. The plunger was attached to the upper moving crosshead of the Instron Model 1011 testing machine (Instron Corp., Canton, MA).

2.8 Single-pelleting test

Prior to the single-pelleting experiments, the biomass was re-moistened to 10% moisture content (wb) by adding/sprinkling a calculated amount of water to non-treated and steam exploded straw grinds at 6.4, 3.2, and 1.6 mm hammer mill screen sizes. The samples were subsequently stored in plastic bags and kept in a cold room at 4℃ for a minimum of 72 h. Only one moisture level of 10% (wb) was used based upon literature review to produce high density and durability pellets/briquettes from various straw and biomass[7,22,38–41].

The single-pelleting apparatus was used to make a single pellet in one stroke of the plunger from ground straw samples. In order to simulate frictional heating during commercial pelleting operation, the pelleting die was maintained at a temperature of (95±1)℃[23,36]. The mass of samples used for making pellets varied between 0.5 and 0.7 g. Compressive force was applied using the Instron Model 1011 testing machine fitted with a 5,000 N load cell and a 6.25 mm diameter plunger. Four preset loads 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 used to compress samples in the die. The crosshead speed of the Instron testing machine was set at 50 mm/min. After compression, the plunger was retained in place for 30 s once the preset load was attained in order to avoid spring-back effect of biomass grinds[23,36]. Later, the base plate was removed and the pellet was ejected out of the die by using the plunger.

2.9 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 and 44.6 mm, respectively. The ring hole diameter and l/d ratio were 6.10 and 7.31 mm, respectively. The rotational speed of the pellet mill was 250 r/min. All of the above specifications were adopted from previous studies performed by Tabil and Sokhansanj[20], Adapa et al.[42], and Hill and Pulkinen[43]

to produce high quality pellets from biomass.

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 (wb) by adding/sprinkling a calculated amount of water and mixed a rotating concrete mixer. Only one moisture level of 10% (wb) was used based upon literature review to produce high density and quality pellets/briquettes from various straw and biomass[7,22,38–41]. 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. As pre-compaction[11] and steam addition[13] 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, resulted 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.

2.10 Pellet density, bulk density and durability

2.10.1 Single-pelleting test

The mass, length and diameter of pellets were measured to determine the density in kg/m^3, following the extrusion of the pellets. Ten replicates (pellets) were made using each ground straw samples. Similar process was followed to determine the change in pellet density (% expansion) after a storage period of one month. The durability of pellets is usually measured following the ASABE Standard S269[44], which requires about 50-100 g of pellets/ compacts. However, due to limited number of pellets, it was not feasible to use this test. Instead, the durability of pellets was measured by following the drop test method[45–48], where a single pellet was dropped from a 1.85 m height on a metal plate. The larger intact portion of the mass retained is expressed as the percentage of the initial weight. Each drop test was replicated ten times.

2.10.2 Pilot scale pelleting

The mass, length and diameter of individual pellets were measured to determine pellet density in kg/m^3. Ten pellets were selected from respective biomass samples. The bulk density of manufactured pellets was calculated by measuring the mass of pellets filled in a 0.5-L cylindrical container (SWA951, Superior Scale Co. Ltd., Winnipeg, MB). Three replicates of bulk density measurements were performed for each biomass sample. The durability of pellets was measured following the ASABE Standard S269[44]. A 100 g of pellet sample was weighed and placed in a dust-tight enclosure/ chamber, and tumbled for 10 min at 50 r/min. A 5.70 mm sieve was used to determine the fines produced by the pellets during the tumbling process. The mass of pellets left on the sieve, as percentage of the total mass of pellet sample used during the test, was considered as the durability of the pellets. Three replicates of the durability test were performed for each sample.

2.11 Statistical analysis

The experiments were set up as completely randomized experimental design with density and durability as the dependent variables, and straw type, pre-treatment, hammer mill screen size and pressure as the independent variables. Statistical analyses were conducted using SAS for Windows (version 8.2)[49]. In order to further understand and explain the experimental variables and their interactions, the SAS General Linear Model (GLM) for Completely Randomized Design (CRD) procedure was used and the Student-Neuman-Keuls test

(SNK) was performed. SNK determines the difference between any two treatment means at 5% level of significance[49].

3 Results and discussion

3.1 Geometric mean particle size

Table 1 shows the mean geometric particle diameters for non-treated and steam exploded barley, canola, oat and wheat straw. The mean geometric particle diameter for any particular biomass decreased with a decrease in hammer mill screen size from 6.4 mm to 0.8 mm. The non-treated wheat straw at 6.4 mm and canola straw at 0.8 mm resulted in largest (0.997±0.038) mm and smallest (0.340±0.003) mm mean particle diameters, respectively, while for steam exploded straw, the largest and smallest geometric mean diameter of (0.698± 0.127) mm and (0.296±0.013) mm were obtained for canola at 6.4 mm and barley at 0.8 mm hammer mill screen sizes, respectively.

Table 1 Moisture content, geometric mean particle size, bulk and particles densities for non-treated and steam exploded barley, canola, oat and wheat straw samples

Agricultural biomass	Hammer mill screen size/mm	Moisture CONTENT POST-GRINDing/% wb	Geometric mean particle diameter/mm	Bulk density /kg · m^{-3}	Particle density /kg · m^{-3}
Non-treated straw					
Barley straw	6.4	8.9±0.4‡†	0.883±0.025 aDX£	96±02 aDX	1016±137 aDEX
	3.2	5.3±0.3	0.463±0.016 bDX	149±03 bDEX	1089±32 aDX
	1.6	7.8±0.2	0.456±0.004 bDX	155±01 cDX	1149±02 aDX
	0.8	9.7±0.2	0.371±0.001 cDX	180±05 dDX	1288±11 bDX
Canola straw	6.4	12.6±0.2	0.885±0.020 aDX	144±02 aEX	1019±19 aDEX
	3.2	9.2±0.1	0.521±0.061 bDEX	190±09 bFX	1192±11 bEX
	1.6	8.3±0.2	0.367±0.001 cEX	203±11 bEX	1309±02 cEX
	0.8	9.9±0.1	0.340±0.003 cEX	247±05 cEX	1345±06 dEX
Oat straw	6.4	10.9±0.1	0.935±0.013 aDX	111±08 aFX	873±18 aEX
	3.2	9.4±0.3	0.566±0.015 bEX	156±04 bDX	1093±38 bDX
	1.6	7.7±0.1	0.404±0.014 cFX	196±04 cEX	1240±18 cFX
	0.8	10.2±0.2	0.383±0.008 cFX	185±02 dDX	1280±06 cDX
Wheat straw	6.4	9.5±0.4	0.997±0.038 aEX	107±02 aFX	1078±14 aDX
	3.2	9.5±0.3	0.719±0.015 bFX	141±02 bEX	1225±11 bEX
	1.6	8.6±0.3	0.452±0.016 cDX	154±02 cDX	1269±23 cDX
	0.8	10.2±0.2	0.361±0.003 dGX	203±03 dFX	1370±07 dFX
Steam exploded straw					
Barley straw	6.4	5.8±0.3	0.607±0.028 aDY	38±03 aDY	1033±19 aDX
	3.2	4.8±0.2	0.368±0.002 bDY	73±02 bDY	1342±60 bDY
	1.6	4.6±1.2	0.296±0.013 cDY	93±06 cDY	1415±79 bDY
	0.8	7.9±0.3	0.295±0.000 cDY	143±01 dDY	1449±82 bD
Canola straw	6.4	4.3±0.0	0.698±0.127 aDY	33±02 aEY	968±38 aDX
	3.2	4.2±0.1	0.447±0.010 bEY	44±00 bEY	1138±17 bEY
	1.6	4.6±0.1	0.364±0.007 bEY	67±02 cEY	1294±17 cDX
	0.8	9.9±0.2	0.329±0.001 bEY	111±10 dEY	1312±106 cDY
Oat straw	6.4	4.6±0.2	0.602±0.012 aDY	43±01 aFY	1143±23 aEY
	3.2	4.5±0.1	0.367±0.010 bDY	77±04 bDY	1272±13 bDY
	1.6	4.1±0.2	0.327±0.022 cDY	91±03 cDY	1368±18 cDY
	0.8	8.0±0.2	0.308±0.001 cFY	149±05 dDY	1392±68 cDY
Wheat straw	6.4	4.5±0.2	0.568±0.10 aDY	41±01 aDFY	1119±52 aEX
	3.2	4.7±0.4	0.387±0.005 bFY	73±05 bDY	1314±32 bDY
	1.6	4.3±0.3	0.309±0.012 cDY	100±05 cDY	1380±80 bDXY
	0.8	6.3±0.1	0.299±0.006 cDY	138±03 dDY	1418±70 bDY

Note: ‡3 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass at various hammer mill screen sizes (a, b, c and d); at same hammer mill screen size for different sample biomass (D, E, F and G); for any particular biomass at same hammer mill screen size for non-treated and steam exploded biomass (X and Y).

The geometric mean particle diameter of steam exploded straw grinds at any specific hammer mill screen size was significantly smaller than non-treated straw grinds. This could be due to the fact that steam explosion pre-treatment disintegrated the lignocellulosic structure of the biomass leading to lower shear strength (easier to grind the straw).

3.2 Bulk density

The bulk density values for barley, canola, oat and wheat straw grinds are also given in Table 1. The bulk density of non-treated and steam exploded straw significantly increased with a decrease in hammer mill screen size from 6.4 mm to 0.8 mm. For non-treated straw, the highest bulk density of (247±05) kg/m^3 was obtained for canola straw grinds at 0.8 mm hammer mill screen size, while lowest bulk density of (96±02) kg/m^3 was obtained for barley straw grinds at 6.4 mm hammer mill screen size. For steam exploded straw, the highest and lowest bulk densities were obtained for wheat straw (138±03) kg/m^3 at 0.8 mm screen size and canola straw (33±02) kg/m^3 at 6.4 mm screen size, respectively.

The bulk density of non-treated barley, canola, oat and wheat straw at any specific hammer mill screen size was significantly higher than steam exploded straw (Table 1). This could again be attributed to the fact that steam explosion pre-treatment disintegrates the organized and compact lignocellulosic structure of biomass leading to lower bulk densities. This low bulk density of steam exploded straw grinds could be problematic in pelletizing the biomass as discussed later.

3.3 Particle density

In general, the particle density of non-treated and steam exploded canola and oat straw significantly increased with a decrease in hammer mill screen size from 6.4 mm to 0.8 mm (Table 1). For non-treated straw, the highest particle density of (1370±07) kg/m^3 was obtained for wheat straw at 0.8 mm and lowest particle density of (873±18) kg/m^3 was obtained for oat straw at 6.4 mm screen size. For steam exploded straw, the highest and lowest particle densities were obtained for barley (1449±82) kg/m^3 straw at 0.8 mm and canola (968±38) kg/m^3 straw at 6.4 mm screen sizes, respectively. The grinds obtained from smaller screen size will have less pore volume than larger particles, resulting in higher particle densities[18].

The particle density of steam exploded barley, canola, oat and wheat straw at any specific hammer mill screen size was significantly higher than non-treated straw, except for barley straw at 6.4 mm screen size, canola and wheat straw at 6.4 and 0.8 mm. This could be due to application of steam explosion pretreatment, which disintegrated the long chain lignocellulosic structure into short chains leading to lower geometric particle sizes and consequently resulting in higher particle densities[18].

3.4 Chemical composition and Higher Heating Values (HHV)

Table 2 enumerates the average chemical composition of non-treated and steam exploded barley, canola, oat and wheat straw samples for tests performed in duplicates. The non-treated canola straw had the highest protein content (6.53%); barley straw had the highest level of fat (1.91%) and lignin (17.13%), while wheat straw showed the highest levels of starch (2.58%) and ash (2.36%) contents. The steam exploded canola straw had the highest protein content (2.21%), canola straw has the highest level of lignin content (12.04%), barley straw had the highest level of starch content (0.38%) and ash content (3.62%). Non-treated canola and wheat straw showed the highest level of cellulose (42.39%) and hemicelluloses content (23.68%), respectively, while steam exploded oat and barley straw showed highest level of cellulose (47.52%) and hemicelluloses (26.49%), respectively.

Traditionally, steam explosion is accepted as one of the most attractive and cost-effective methods for hardwoods and straws to enhance the cellulose susceptibility to enzymatic attack during fermentation process[50] by destruction of hemicelluloses and incomplete disruption of lignin–carbohydrate matrix. During the steam explosion process, pressurized steam disintegrates the lignocellulosic structure of the straw, and hydrolyses the lignin and hemicellulose content; a portion which is washed and drained with waste water. Therefore, the percentage of lignin and hemicellulose in dry steam exploded straw was lower than non-treated straw, thus increasing the relative percentage of cellulose

content (Table 2).

Cellulose, hemicelluloses and lignin are major components of plant biomass. Therefore, a change in their composition could potentially lead to a change in the HHV of the biomass. The cellulose content of steam exploded barley, canola, oat and wheat straw was 37%, 7%, 26% and 36% higher than non-treated straw, respectively. The hemicelluloses content of steam exploded barley, canola and oat straw was 30%, 6% and 9% higher, respectively; however wheat straw was 14% lower than non-treated straw. The lignin content of steam exploded barley, canola, oat and wheat straw was 50%, 15%, 25% and 14% lower than non-treated straw, respectively. These observations were contrary to Shaw[15] where a decrease in cellulose and hemicelluloses content and an increase in lignin content of steam exploded poplar wood and wheat straw were reported. This could be due to the fact that they have performed the steam explosion at 200-205℃ for four to five and a half minutes as opposed to the present study in which steam explosion was performed at 180℃ for four minutes.

The net combined percentage change of cellulose, hemicelluloses and lignin in steam exploded barley, canola, oat and wheat straw is 17%, -2%, 10% and 8% higher than non-treated straw, respectively. As a result, the average HHV of steam exploded barley, canola, oat and wheat straw was 6%, 10%, 9%, and 5% higher than non-treated straw, respectively (Table 2). An increase in HHV for steam exploded canola straw could be due to a 4% decrease in ash content. Similar observations of increased HHV with a decrease in ash content was reported by Shaw[15] and Sheng and Azevedo[51].

Table 2 Chemical composition and Higher Heating Values (HHV) of non-treated and steam exploded barley, canola, oat and wheat straw

Composition/% DM[a]	Barley straw		Canola straw		Oat straw		Wheat straw	
	NT	SE	NT	SE	NT	SE	NT	SE
Protein	3.62	1.49	6.53	2.21	5.34	1.19	2.33	1.08
Fat	1.91	ND	0.69	ND	1.65	ND	1.59	ND
Starch	0.11	0.38	0.34	0.18	0.12	0.22	2.58	0.30
Lignin	17.13	8.64	14.15	12.04	12.85	9.64	13.88	11.89
Cellulose[b]	33.25	45.48	42.39	45.29	37.60	47.52	34.20	46.64
Hemicellulose[c]	20.36	26.49	16.41	17.36	23.34	25.33	23.68	20.39
Ash	2.18	3.62	2.10	2.02	2.19	3.47	2.36	3.30
HHV/MJ · kg^{-1}	16.4±0.3‡†	17.4±0.1	16.7±0.3	18.3±0.0	16.4±0.1	17.8±0.0	17.0±0.2	17.8±0.0

Note: NT – Non-treated; SE – Steam Exploded agricultural biomass.

[a]DM – Dry Matter.

[b]Cellulose percentage is calculated indirectly from percentage acid detergent fiber (ADF) and lignin (%ADF-%lignin) [22].

[c]Hemicellulose percentage is calculated indirectly from percentage neutral detergent fiber (NDF) and ADF (%NDF-%ADF) [22]

HHV – Higher Heating Values (Parr 1281 Bomb Calorimeter)

‡3 replicates; † 95% confidence interval

3.5 Single-pellet density

In general, the density of pellets (subsequent to single-pelleting experiments) from non-treated and steam exploded agricultural straw significantly increased with an increase in applied pressure at any specific hammer mill screen size (Tables 3, 4, 5 and 6). An increase in pressure results in plastic deformation of ground particles and consequently leads to pellets that have densities closer to their respective particle densities (Table 1). There was no significant difference in pellet density obtained from different hammer mill screen sizes for non-treated and steam exploded straw at higher pressures of 94.7 and 138.9 MPa. This could be due to the fact that the pellet density at 94.7 MPa approached near to their respective particle densities (Table 1) and any higher pressure (138.9 MPa) did not account for significant increase in pellet density (Tables 3, 4, 5 and 6). The pellet density of steam exploded straw at any specific hammer mill screen size and pressure was significantly higher than non-treated straw. This observation can be directly related to significantly lower geometric mean particle diameters and significantly higher particle

densities of steam exploded grinds compared to non-treated grinds. Further details on compression characteristics of Non-Treated and Steam Exploded Barley, Canola, Oat and Wheat Straw Grinds are provided in Adapa et al.[52].

Tables 3, 4, 5 and 6 also give the densities of pellets measured after one month of storage period to ascertain its dimensional stability, and associated handling and storage costs. A reduction in pellet density is usually expected due to relaxation of grinds in the pellet after release of pressure. For both non-treated and steam exploded straw, it has been observed that the relaxation was higher for larger hammer mill screen sizes and lower applied pressures, with a very few exceptions usually having higher standard deviations in the measured densities. In some cases the average reduction in density was negative giving the impression that the pellet density actually increased during storage period. However, these negative values are primarily due to higher standard deviations in pellet density measurements. Therefore, from a practical manufacturing point of view, these values should be considered as a zero percent change in pellet density.

Due to limited number of pellets, it was not feasible to measure the bulk density of pellets; therefore, this was not undertaken.

Table 3 Measured pellet density and durability data for non-treated and steam exploded barley straw at 10% moisture content (wb)

Barley straw	Hammer mill screen size/mm	Applied load/N/ Pressure/MPa	Pellet density/kg·m^{-3}		Durability/%
			After pelleting	After one month	
Non-treated	6.4	1,000 / 31.6	798±19 aDX£	791±38	93±03 aDX
		2,000 / 63.2	934±40 bDX	933±48	98±03 bDX
		3,000 / 94.7	991±24 cDX	999±58	97±02 bDX
		4,400 / 138.9	1003±32 cDX	947±52	97±02 bDX
	3.2	1,000 / 31.6	788±27 aDX	726±46	61±08 aEX
		2,000 / 63.2	915±28 bDX	876±48	73±10 bEX
		3,000 / 94.7	976±18 cDX	973±39	83±06 cEX
		4,400 / 138.9	1,024±25 dDX	1,033±29	63±06 aEX
	1.6	1,000 / 31.6	781±38 aDX	750±73	49±10 aFX
		2,000 / 63.2	914±19 bDX	897±42	50±09 aFX
		3,000 / 94.7	972±12 cDX	967±22	50±07 aFX
		4,400 / 138.9	994±28 cDX	1,001±31	51±04 aFX
Steam exploded	6.4	1,000 / 31.6	903±43 aDY	875±32	90±07 aDX
		2,000 / 63.2	1,081±24 bDY	1,045±29	96±03 aDX
		3,000 / 94.7	1,131±25 cDY	1,150±28	97±03 aDX
		4,400 / 138.9	1,116±62 bcDY	1,017±132	98±02 bDX
	3.2	1,000 / 31.6	882±32 aEY	875±49	81±13 aDY
		2,000 / 63.2	1,022±28 bEY	1,031±43	89±05 abEY
		3,000 / 94.7	1,130±22 cDY	1,150±17	93±03 bEY
		4,400 / 138.9	1,159±35 dEY	1,172±29	89±06 abEY
	1.6	1,000 / 31.6	931±21 aDEY	935±23	86±05 abDY
		2,000 / 63.2	1,053±18 bFY	1,057±18	81±05 bcFY
		3,000 / 94.7	1,112±23 cDY	1,139±28	79±06 cFY
		4,400 / 138.9	1,169±12 dEY	1,194±24	89±06 aEY

Note: ‡10 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass and hammer mill screen size at various loads (a, b and c); same sample biomass and loads at various hammer mill screen sizes (D, E and F); for non-treated and steam exploded biomass at same hammer mill screen size (X and Y).

Table 4 Measured pellet density and durability data for non-treated and steam exploded canola straw at 10% moisture content (wb)

Barley straw	Hammer mill screen size/mm	Applied load/N/Pressure/MPa	Pellet density/kg·m^{-3}		Durability/%
			After pelleting	After one month	
Non-treated	6.4	1,000 / 31.6	795±38 aDX£	742±55	91±17 aDX
		2,000 / 63.2	974±29 bDX	920±40	97±02 aDX
		3,000 / 94.7	1,009±35 bDX	971±66	98±01 aDX
		4,400 / 138.9	990±38 bDX	1000±38	98±01 aDX
	3.2	1,000 / 31.6	779±22 aDX	757±24	39±12 aEX
		2,000 / 63.2	933±42 bEX	898±25	48±08 abEX
		3,000 / 94.7	994±21 cDEX	982±42	54±05 bEX
		4,400 / 138.9	1,035±18 dEX	1,015±24	54±16 bEX
	1.6	1,000 / 31.6	791±30 aDX	753±31	22±07 aFX
		2,000 / 63.2	912±19 bEX	873±15	24±07 aFX
		3,000 / 94.7	976±16 cEX	937±12	28±06 abFX
		4,400 / 138.9	1,027±22 dEX	1,010±35	33±03 bFX
Steam exploded	6.4	1,000 / 31.6	849±47 aDY	847±75	82±18 aDX
		2,000 / 63.2	1,016±35 bDY	1,023±53	97±01 bDX
		3,000 / 94.7	1,105±27 cDY	1,121±41	98±02 bDX
		4,400 / 138.9	1,154±27 dDY	1,179±29	100±00 bDY
	3.2	1,000 / 31.6	846±41aDY	789±107	92±06 aDY
		2,000 / 63.2	1,059±25 bEY	1,076±37	99±01 bDY
		3,000 / 94.7	1,126±33 cDY	1,149±58	99±01 bDY
		4,400 / 138.9	1,165±26 dDY	1,234±26	100±00 bDY
	1.6	1,000 / 31.6	923±31 aEY	939±27	90±07 aDY
		2,000 / 63.2	1,070±20 bEY	1,091±25	95±05 abDY
		3,000 / 94.7	1,123±16 cDY	1,161±26	99±01 bDY
		4,400 / 138.9	1,163±24 dDY	1,185±64	100±00 bDY

Note: ‡10 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass and hammer mill screen size at various loads (a, b and c); same sample biomass and loads at various hammer mill screen sizes (D, E and F); for non-treated and steam exploded biomass at same hammer mill screen size (X and Y).

Table 5 Measured pellet density and durability data for non-treated and steam exploded oat straw at 10% moisture content (wb)

Barley straw	Hammer mill screen size/mm	Applied load/N/Pressure/MPa	Pellet density/kg·m^{-3}		Durability/%
			After pelleting	After one month	
Non-treated	6.4	1,000 / 31.6	817±26 aDX£	771±46	89±08 aDX
		2,000 / 63.2	945±24 bDX	918±54	99±01 bDX
		3,000 / 94.7	982±29 cDX	968±41	99±01 bDX
		4,400 / 138.9	985±43 cDX	966±19	99±01 bDX
	3.2	1,000 / 31.6	811±26 aDX	791±34	52±05 aEX
		2,000 / 63.2	907±24 bEX	915±45	64±08 bEX
		3,000 / 94.7	948±24 cEX	982±47	75±13 cEX
		4,400 / 138.9	988±35 dDX	986±29	82±11 cEX
	1.6	1,000 / 31.6	795±23 aDX	800±34	44±08 aFX
		2,000 / 63.2	912±17 bEX	865±29	45±09 aFX
		3,000 / 94.7	992±26 cDX	1,002±42	54±12 abFX
		4,400 / 138.9	1,024±26 dDX	995±48	57±10 bFX
Steam exploded	6.4	1,000 / 31.6	889±30 aDY	895±50	93±03 aDX
		2,000 / 63.2	1,034±55 bDY	1,051±61	95±03 aDY
		3,000 / 94.7	1,130±32 cDY	1,138±64	95±03 aDX
		4,400 / 138.9	1,151±21 cDY	1,201±47	100±00 bDX
	3.2	1,000 / 31.6	923±40 aEY	936±40	94±03 aDY
		2,000 / 63.2	1,068±17 bEY	1,105±30	91±05 aDY
		3,000 / 94.7	1,129±30 cDY	1,159±24	100±00 bEY
		4,400 / 138.9	1,144±14 cDY	1,194±26	99±01 bDY
	1.6	1,000 / 31.6	954±20 aFY	964±24	93±04 aDY
		2,000 / 63.2	1,090±16 bEY	1,127±27	94±03 aDY
		3,000 / 94.7	1,143±16 cDY	1,173±19	99±01 bEY
		4,400 / 138.9	1,165±27 dDY	1,227±27	99±01 bDY

Note: ‡10 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass and hammer mill screen size at various loads (a, b and c); same sample biomass and loads at various hammer mill screen sizes (D, E and F); for non-treated and steam exploded biomass at same hammer mill screen size (X and Y).

Table 6 Measured pellet density and durability data for non-treated and steam exploded wheat straw at 10% moisture content (wb)

Barley straw	Hammer mill screen size/mm	Applied load/N/ Pressure/MPa	Pellet density/kg·m^{-3}		Durability/%
			After pelleting	After one month	
Non-treated	6.4	1,000 / 31.6	782±22 aDX£	760±50	97±04 aDX
		2,000 / 63.2	923±32 bDX	983±24	95±05 aDX
		3,000 / 94.7	965±52 cDX	1,073±22	96±02 aDX
		4,400 / 138.9	1,001±21 dDX	1,038±24	98±02 aDX
	3.2	1,000 / 31.6	778±22 aDX	805±48	58±09 aEX
		2,000 / 63.2	917±17 bDX	959±27	63±07 aEX
		3,000 / 94.7	967±27 cDX	1,047±31	64±08 aEX
		4,400 / 138.9	1,007±26 dDX	1,042±48	64±08 aEX
	1.6	1,000 / 31.6	819±23 aEX	815±30	63±07 aEX
		2,000 / 63.2	948±18 bEX	941±37	52±09 bFX
		3,000 / 94.7	997±19 cDX	999±27	56±06 abFX
		4,400 / 138.9	1,009±21 cDX	1,022±18	57±07 abFX
Steam exploded	6.4	1,000 / 31.6	893±39 aDY	845±54	98±02 aDX
		2,000 / 63.2	1,064±26 bDEY	1,033±38	98±02 aDX
		3,000 / 94.7	1,118±23 cDY	1,153±34	99±01 aDX
		4,400 / 138.9	1,176±29 dDY	1,159±26	100±00 aDX
	3.2	1,000 / 31.6	909±37 aDY	895±49	97±02 aDY
		2,000 / 63.2	1,086±16 bDY	1,093±18	98±02 abDY
		3,000 / 94.7	1,140±19 cDY	1,144±31	98±02 abDY
		4,400 / 138.9	1,180±23 dDY	1,132±47	100±00 bDY
	1.6	1,000 / 31.6	926±47 aDY	896±49	96±02 aDY
		2,000 / 63.2	1,057±32 bEY	1,057±41	95±05 aDY
		3,000 / 94.7	1,128±24 cDY	1,100±30	96±04 aDY
		4,400 / 138.9	1,171±27 dDY	1,118±51	94±04 aEY

Note: ‡10 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass and hammer mill screen size at various loads (a, b and c); same sample biomass and loads at various hammer mill screen sizes (D, E and F); for non-treated and steam exploded biomass at same hammer mill screen size (X and Y).

3.6 Single-pellet durability

At any specific hammer mill screen size, the durability of non-treated straw did not show any significant change with increase in applied pressures (Tables 3, 4, 5 and 6). However, durability of non-treated straw significantly decreased with a decrease in hammer mill screen size from 6.4 mm to 1.6 mm at any specific applied pressure. High durability values (>80%) were observed for non-treated straw grinds at 6.4 mm hammer mill screen size. This could be primarily due to mechanical interlocking of relatively long fibers at higher grind sizes (Table 1).

High durability values (>80%) were obtained for steam exploded straw at any hammer mill screen size and applied pressure levels. Though lignin content of steam exploded straw was lower than non-treated straw, it is believed that the higher durability values are primarily due to higher cellulose content (Table 2). In addition, during the steam explosion process, the lignin and hemicelluloses are free from the lignocellulosic matrix, thus, are more available for binding the particles during compression (Figure 1).

The durability of non-treated and steam exploded straw at hammer mill screen size of 6.4 mm at any applied pressure was not significantly different. However, the durability of steam exploded straw pellets was significantly higher than non-treated straw at 3.2 and 1.6 mm hammer mill screen sizes at respective applied pressures. Statistically, no significant correlation (R^2 values) was obtained for change in density with applied pressure for any specific biomass and hammer mill screen sizes.

Figure 1 Non-treated (30 mm hammer mill screen size) and steam exploded barley, canola, oat and wheat straw grinds

3.7 Pilot scale pelleting

The pellet mill produced pellets from ground non-treated barley, canola, oat and wheat straw at hammer mill screen sizes of 0.8 and 1.6 mm having moisture content of 17.5% (wb) and flax seed oil of 10% by weight. The non-treated ground straw at 3.2 and 6.4 mm screen size did not produce pellets. Similar pelleting process was followed for ground steam exploded straw. Due to very low bulk density and poor flowability, the steam exploded grinds did not produce pellets at any of the hammer mill screen sizes used in the investigation. However, the customized barley, canola, oat and wheat straw having 25% steam exploded material by weight at 0.8 mm screen size successfully produced pellets. Addition of higher percentage of steam exploded straw and customization at screen sizes of 1.6, 3.2, and 6.4 mm did not produce pellets, which could be due to the fact that adding steam exploded (having very low bulk density) to non-treated straw (having relatively higher bulk density) decreased the overall bulk density and flowability of the grinds, thus hindering the production of pellets in the pilot scale mill. The pilot scale pellet mill is constrained with a small motor (3.7 kW (5 hp)) running it, whereas in a commercial pellet mill, the motors are much bigger and more tolerant to changes in feed bulk density. Shaw et al.[21] reported similar trends where the quality of wheat straw pellets increased with an increase in moisture content to 15.9% (wb).

Figure 2 The photograph of pellets manufactured from barley, canola, oat and wheat straw from non-treated grinds at 0.8 and 1.6 mm screen sizes, and customized straw grinds at 0.8 mm having 25% steam exploded straw by weight.

Table 7 shows the pellet density obtained from non-treated straw samples at 1.6 and 0.8 mm, and customized samples having 25% steam exploded straw at 0.8 mm screen size. In general, pellet density increased with a decrease in screen size from 1.6 mm to 0.8 mm. However, no significant differences in density values were observed for non-treated samples at 0.8 mm and customized samples, except for canola and oat straw. This could be due to large fluctuation in individual pellet density values. All of the pellet density values reached near individual biomass particle densities at respective grind sizes (Table 1), except for barley straw pellets at

1.6 mm (1158±109) kg/m^3 and wheat straw pellets at 0.8 mm (1278±136) kg/m^3, which were higher. This could again be attributed to large fluctuations in individual pellet density values.

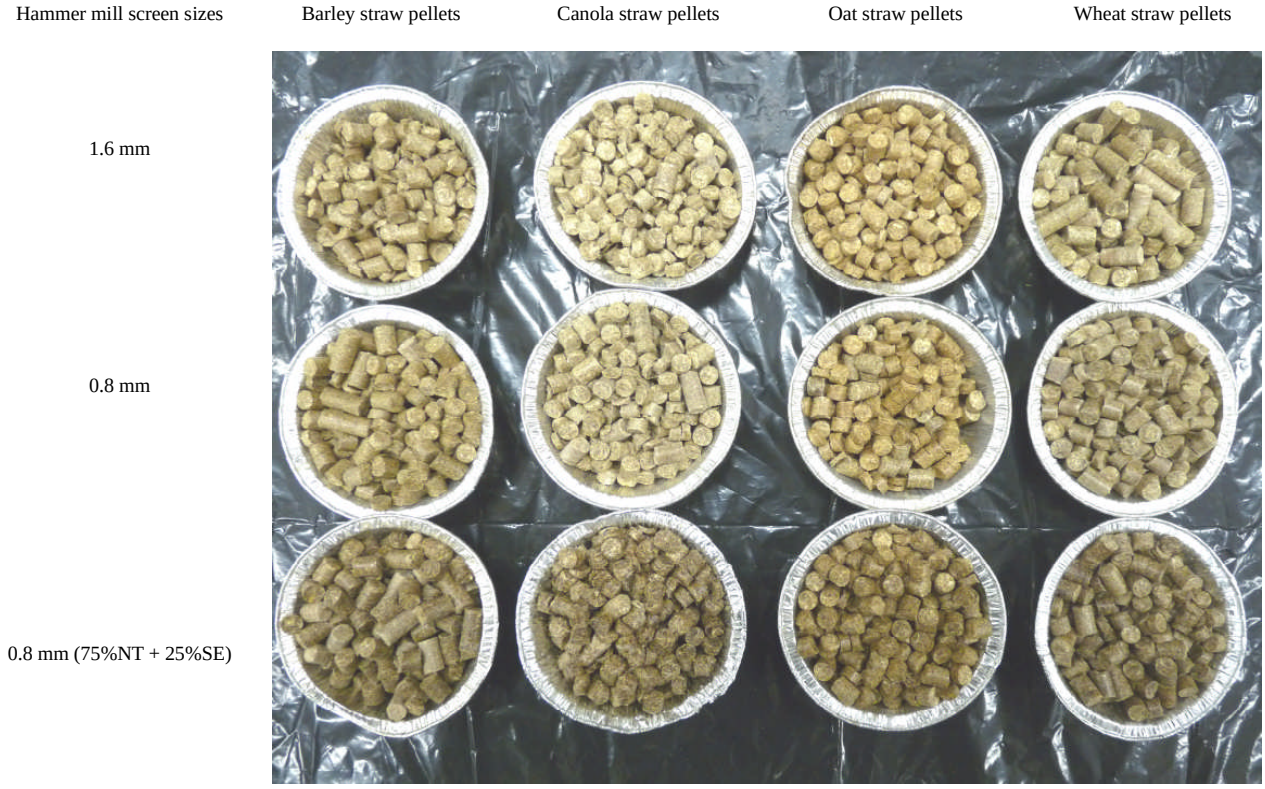

Figure 2 Photograph of pellets manufactured using a pilot scale pellet mill for non-treated (NT) straw at 1.6 and 0.8 mm hammer mill screen size, and customized grinds at 0.8 mm screen size having 25% steam exploded (SE) straw

Table 7 Pellet density, durability, throughput and specific energy data for non-treated and steam exploded barley canola, oat and wheat straw at 17.5% moisture content (wb) and 10% flaxseed oil content

Agricultural biomass	Hammer mill screen size /mm	Pellet density /kg/m^{-3}	Pellet bulk density /kg/m^{-3}	Durability/%	Throughput /kg/h^{-1}	Specific energy /MJ/t^{-1}
Barley straw	1.6 (100% NT)	1158±109$^{*\dagger £}$ aD	665±01‡ aD	91±00‡ aD	4.88	293
	0.8 (100% NT)	1174±46 aD	700±07 bD	93±01 bD	4.21	353
	0.8 (75% NT + 25% SE)	1184±63 aD	714±02 cD	87±01 cD	3.46	301
Canola straw	1.6 (100% NT)	1023±85 aE	629±01 aE	90±01 aD	3.86	385
	0.8 (100% NT)	1204±43 bDE	720±04 bE	95±00 bE	3.63	440
	0.8 (75% NT + 25% SE)	1144±50 cD	641±01 cE	82±00 cE	5.51	265
Oat straw	1.6 (100% NT)	1140±63 abD	631±03 aE	89±01 aE	4.48	340
	0.8 (100% NT)	1188±78 aDE	649±02 bF	93±00 bD	3.81	344
	0.8 (75% NT + 25% SE)	1071±101 bE	676±06 cF	89±01 aF	4.03	335
Wheat straw	1.6 (100% NT)	1163±57 aD	673±02 aF	94±01 aF	5.44	381
	0.8 (100% NT)	1278±136 bE	721±04 bE	95±01 bE	3.81	297
	0.8 (75% NT + 25% SE)	1213±88 abD	722±04 bG	95±00 cG	4.08	342

Note: NT – Non-treated Straw Samples; SE – Steam Exploded Straw Samples; *10 replicates; ‡3 replicates; † 95% confidence interval; £ Student-Neuman-Keuls test at 5% level of significance for same sample biomass at various hammer mill screen sizes (a, b and c); at same hammer mill screen size for different sample biomass (D, E, F and G).

Bulk density of pellets from barley, canola, oat and wheat straw showed significant difference with grind size and customization, except for wheat straw pellets at 0.8 mm for non-treated and customized samples (Table 7). In general, average pellet bulk densities obtained for customized straw samples were higher (except for barley straw), which is consistent with increase in particle densities (Table 1). The bulk densities of pellets

manufactured were higher than the minimum design value of 650 kg/m^3 suggested by Obernberger and Thek [7] for wood pellet producers, except for canola straw pellets from non-treated 1.6 mm (629±01) kg/m^3 and 0.8 mm customized (641±01) kg/m^3 samples, and non-treated oat straw at 1.6 mm (631±03) kg/m^3 screen size.

Table 7 also lists the durability values of pelletted samples. The durability of pellets obtained from non-treated straw samples at 1.6 and 0.8 mm, and customized samples having 25% steam exploded straw at 0.8 mm screen size were significantly different, except for oat straw at 1.6 mm and 0.8 mm customized samples. In general, higher durability values were observed for non-treated straw samples at 0.8 mm hammer mill screen size. The durability of pellets significantly increased with a decrease in grind size for non-treated samples from 1.6 mm to 0.8 mm. However, addition of steam exploded straw to non-treated straw at 0.8 mm screen size significantly decreased the durability, except for wheat straw. This could be due to the fact that steam exploded material has lower lignin content compared to non-treated straw (Table 2), which acts as the natural binding agent. This observation is in contrast to Lam et al.[17], who reported that the quality (durability) of pellets produced from steam exploded sawdust was 20% higher than non-treated sawdust. Though, it is important to note that high durability values (>80%) were obtained for all pilot scale pelleting tests.

Durability of pellets was negatively correlated to pellet mill throughput and was positively correlated to specific energy consumption (Table 7). The specific energy values obtained from pilot scale pellet mill are 10-25 times higher than reported by Mani et al.[23] and Adapa et al.[53] for agricultural straw, using a single pellet Instron testing machine. The higher pellet mill specific energy numbers could be due to higher friction values and practical pelleting conditions, which are closer to industrial operations.

Lower bulk densities, and concerns with uneven and low flowability of straw grinds (especially, steam exploded straw grinds) are critical issues to be addressed in future to achieve a sustainable and broader pelleting process involving higher grind sizes. Therefore, pre-compression of straw grinds needs to be investigated as an alternative to increase their bulk density and flowability through the pellet mill[11]. In addition, steam conditioning of higher grind sizes should be explored that could result in production of pellets. However, an energy balance study is required to determine a trade-off between using steam conditioning or pre-compression vs. energy saved during hammer mill grinding of straw to large grind sizes.

4 Conclusions

It is envisioned that results and conclusions from this study will assist researchers, equipment manufacturers and biomass pellet operators to determine optimal conditions suitable for their respective purpose. In addition, redundant factors could be eliminated from future studies and possibly aiding in development of novel studies. The following conclusions are derived from this study:

Single-Pelleting Test

1) Applied pressure and pre-treatment were significant factors affecting the pellet density;

2) Higher grind sizes and lower applied pressures resulted in higher relaxations (lower pellet densities) during storage of pellets;

3) Higher durability values (>80%) for non-treated straw at 6.4 mm hammer mill screen size and steam exploded straw at 6.4 to 1.6 mm hammer mill screen sizes were primarily due to mechanical interlocking of relatively long and free/ disintegrated fibers.

Pilot Scale Pelleting

1) Pellet bulk density and particle density are positively correlated;

2) Density and durability of agricultural straw pellets significantly increased with a decrease in hammer mill screen size from 1.6 mm to 0.8 mm;

3) Customization of agricultural straw by adding 25% of steam exploded straw by weight is possible, but in the pilot scale pellet mill, it did not improve pellet quality;

4) Durability of pellets was negatively correlated to pellet mill throughput and was positively correlated to specific energy consumption.

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