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Grinding energy and physical properties of chopped and hammer-milled barley, wheat, oat, and canola straws

J.S. Tumuluru [a,*], L.G. Tabil [b], Y. Song [c], K.L. Iroba [b], V. Meda [b]

[a] Biofuels & Renewable Energy Technologies Department, Energy Systems & Technologies Division, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-2025, USA
[b] Department of Chemical and Biological Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9
[c] College of Engineering, Shenyang Agricultural University, Shenyang, China

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ABSTRACT

In the present study, specific energy for grinding and physical properties of wheat, canola, oat and barley straw grinds were investigated. The initial moisture content of the straw was about 0.13–0.15 (fraction total mass basis). Particle size reduction experiments were conducted in two stages: (1) a chopper without a screen, and (2) a hammer mill using three screen sizes (19.05, 25.4, and 31.75 mm). The lowest grinding energy (1.96 and 2.91 kWh t^{-1}) was recorded for canola straw using a chopper and hammer mill with 19.05-mm screen size, whereas the highest (3.15 and 8.05 kWh t^{-1}) was recorded for barley and oat straws. The physical properties (geometric mean particle diameter, bulk, tapped and particle density, and porosity) of the chopped and hammer-milled wheat, barley, canola, and oat straw grinds measured were in the range of 0.98–4.22 mm, 36–80 kg m^{-3}, 49–119 kg m^{-3}, 600–1220 kg m^{-3}, and 0.9–0.96, respectively. The average mean particle diameter was highest for the chopped wheat straw (4.22-mm) and lowest for the canola grind (0.98-mm). The canola grinds produced using the hammer mill (19.05-mm screen size) had the highest bulk and tapped density of about 80 and 119 kg m^{-3}; whereas, the wheat and oat grinds had the lowest of about 58 and 88–90 kg m^{-3}. The results indicate that the bulk and tapped densities are inversely proportional to the particle size of the grinds. The flow properties of the grinds calculated are better for chopped straws compared to hammer milled using smaller screen size (19.05 mm).

1. Introduction

Interest in biomass production is growing because it is considered both carbon neutral and a sustainable resource for industrial-scale energy production [1]. Some engineering challenges—like harvesting, handling, transportation, storage, and processing of biomass feedstock in large scale for biofuels applications—are major concerns [2–4]. Many industrial and academic organizations are working to overcome these limitations. Agricultural and oilseed straws are a major part of crop residues and considered as important feedstocks for bioenergy applications as they have low nutritional value when used as feed for animals [5].

* *Corresponding author*. Biofuels and Renewable Energy Division, Idaho National Laboratory, P.O. Box 1625, MS 2025, Idaho Falls, ID 83415-2025, USA. Tel.: +1 208 526 0529; fax: +1 208 526 2639.
E-mail addresses: JayaShankar.Tumuluru@inl.gov, tjayashankar@yahoo.com (J.S. Tumuluru).

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The commonly available cereal straws are wheat, barley, and rice, and oat [6]. There are some competing uses for these materials; for example, straw is sometimes used as feed or bedding for animals, or used as a soil amendment and incorporated into the plowed layer or used as mulch. But both cereal and oilseed straws are finding use as feedstock for bioenergy, for both thermochemical and bioconversion applications. For all these applications, the size of these straws has to be reduced. Particle size reduction is considered an important step in the conversion process.

1.1. *Particle size reduction*

Particle size reduction of biomass is necessary, as the current biorefinery technologies cannot efficiently digest whole stems of grass and woody feedstocks. Paulrud [7] indicated that corn stover particle sizes ranging from 0.5 to 3 mm are necessary in corn stover ethanol production. In addition, size-reduced biomass for direct combustion produces a more stable flame, high burnout, and low CO_2 and ash emissions when compared to pellets and bales. Hess et al. [8], Wu et al. [9], Cundiff and Grisso [10], Hess et al. [11] and Wendt et al. [12] indicated that the smaller biomass particles produced after size reduction have better digestibility in the conversion reactor than the same material in baled format. Oasmaa et al. [13], Wei et al. [14], and Kumar et al. [15] concluded that feedstock should be in particulate form for biorefinery pathways like hydrolysis, fermentation, gasification, pyrolysis, and chemical synthesis. Thus, many studies have been conducted in the last few years to understand the effect of varying particle sizes on conversion efficiency.

For proper design and optimization of biomass size-reduction equipment, it is necessary to know its mechanical properties. Power or energy requirements for size reduction of straw is one of these properties, and is influenced by initial particle size, moisture content, material properties, feed rate of the material, and machine variables [16]. Size reduction of biomass feedstocks helps to increase the surface area, pore size, and number of points of contacts for inter-particle bonding in compaction operations like densification [17]. Tub grinders and hammer mills are the most commonly used pieces of equipment as they are relatively inexpensive, easy to operate, and produce a wide range of particle sizes. Bitra et al. [18] and Soucek et al. [19] indicated that size reduction is an important unit operation for densification and to reduce transportation costs.

1.2. *Specific energy*

Balk [20] studied the specific energy requirement of a hammer mill for grinding of coastal Bermuda grass. This author related the specific energy requirement with moisture content, as well as the feed rate of the material. Von Bargen et al. [21] reported that corn residues used more energy among three crop residues tested viz. wheat straw, corn, and grain sorghum at a hammer mill peripheral speed of 15.8 ms^{-1}. They also reported that grain sorghum residues required the least specific energy. Datta [22] reported that coarse size reduction (0.2–0.6 mm) of hardwood chips required 20–40 kWh t^{-1}, whereas size reduction to 0.15–0.3 mm required 100–200 kWh t^{-1} of grinding energy. In their studies on power consumption of fine grinding of corn and grain sorghum, Martin and Behnke [23] reported that high energy was consumed for fine grinding of material. Himmel et al. [24], Pfost and Headley [25], Fang et al. [26], Samson et al. [27], and Mani et al. [16] studied the effect of particle size on energy consumption and concluded that grinding to smaller particle sizes requires higher energy. Total specific energy for particle size reduction of wheat straw using a 1.6-mm hammer mill screen size was twice that for a 3.2-mm screen size. In the case of switchgrass, a specific energy of 44.9 kWh t^{-1} was required for a screen size of 5.6 mm using a hammer mill.

1.3. *Physical properties of biomass*

Physical properties like bulk, tapped, and particle density are important to understand the quality of feedstock delivered to the biorefinery or for co-firing plants [28]. Lam et al. [29] indicated that bulk density is a major physical property in designing the logistic systems for biomass handling. They concluded that biomass material is dependent on size, shape, moisture content, individual particle density, and surface characteristics. Physical properties like bulk density also have an impact on storage requirements, sizing of the material handling systems, and on the final conversion process [30]. The study of Ryu et al. [31] on the effect of bulk density on combustion characteristics of biomass indicated that ignition front speed is inversely proportional to bulk density. Peleg [32], Lang et al. [33], and Sokhansanj and Lang [34] indicated that bulk density of biomass is dependent on material composition, particle shape and size, specific density, and moisture content. Mani et al. [16] demonstrated a polynomial relationship between bulk density and particle size of ground switchgrass, corn stover, and wheat straws. Bulk density of biomass increases during transportation, handling, and storage, which can be caused by compaction due to vibration, tapping, or normal load [35]. According to Fasina [36], the compaction behavior of biomass is very important for capacity sizing and supply logistics. Chevanan et al. [37] reported that the bulk density of comminuted biomass significantly increased by vibration during handling and transportation, and by normal pressure during storage. Their studies on compaction characteristics by tapping and by application of normal pressure affected the bulk density of switchgrass, wheat straw, and corn stover chopped in a knife mill.

1.4. *Flow properties of biomass*

Flowability is one of the major factors for efficient supply of biomass to refineries. Flow properties data on biomass is necessary to design silos and other bulk solid handling equipment to make the material flow without obstructions, segregation, irregular flow, flooding, etc. Quantitative information regarding flowability of bulk products is required to understand the behavior of the material in the storage bins. Flowability depends on several parameters—like particle-size distribution, particle shape, biomass chemical composition, moisture, and temperature [38]. Fine particles of sizes <100 μm may be cohesive in nature and will have less free-flowing properties, whereas larger and denser particles tend

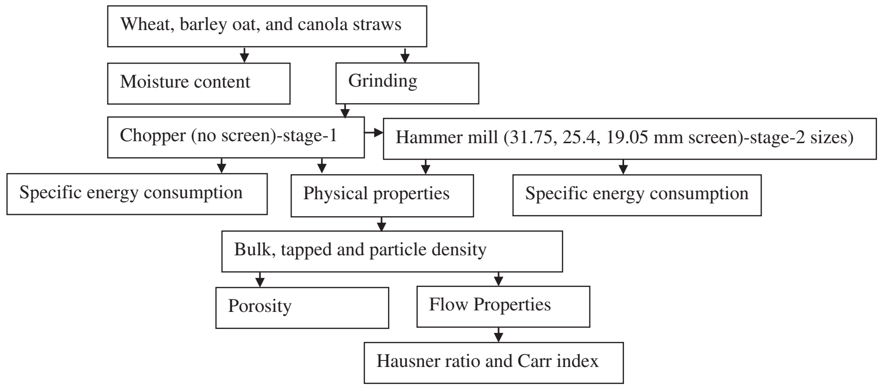

Fig. 1 – Flow diagram of the experimental studies on grinding and physical properties measurement of agricultural straws.

to be more free-flowing. The Hausner ratio and Carr's index are two widely used measurements to indicate flowability of bulk solids, and are commonly referred to as the compressibility index. They are calculated using the following equations [38]:

$$\text{Hausner ratio} = \frac{V_o}{V_f} \tag{1}$$

$$\text{Carr Index} = \frac{100\,(V_o - V_f)}{V_o} \tag{2}$$

where V_o is tapped density and V_f is pour (bulk) density.

The trend to use particle-size reduction techniques before transportation and to supply flowable and uniform particles to biomass end-users is becoming common [8,11,12,39]. Most of the research published on size reduction of biomass is for smaller particles. Mani et al. [16,17] has used smaller screen sizes in the range of 0.8–3.2 mm in their size-reduction studies, which recorded the energy consumed when using a hammer mill for comminution of wheat and barley straw, corn stover, and switchgrass.

The parameters used for evaluating the performance of size-reduction equipment include the energy efficiency of the equipment, and the resulting particle bulk density and physical properties (such as particle size, shape, distribution, density, and particle surface area) [12,16,18,40–44]. The advantages of efficient size reduction of biomass include (a) retention of biomass quality, (b) reduction of biomass losses, and (c) minimization of the economic and environmental costs of bioenergy production. Commonly used biomass particle-size reduction equipment includes choppers, hammer mills, knife mills, balls mills, needle mills, shredders, linear knife grids, and disk attrition mills [42,43]. These same researchers have commented that there is a definite lack of information on specific energy consumption and corresponding physical properties for promising cereal and oilseed straws for bioenergy applications. Another relevant study is Adapa et al. [17], who conducted grinding and pelleting studies on raw and steam-exploded wheat, barley, oat, and canola straws using smaller screen sizes of 30, 6.4, 3.2, and 1.6 mm, and measured the pelletization energy consumption characteristics.

The present study focuses on understanding the grinding energies and physical properties of chopped straw (without screen, resulting in bigger particle sizes), and further grinding to smaller particle sizes using a hammer mill. Four agricultural straws (wheat, oat, canola, and barley) are considered. The specific objectives of the present research are to study: (a) grinding energy requirements for wheat, barley, oat, and canola straws using a chopper with no screen (Stage 1 grinding) and a hammer mill (Stage 2 grinding) with screen sizes of 19.05, 25.4, and 31.75 mm; (b) the physical properties (namely moisture content, bulk, tapped and particle density, porosity, and average mean particle diameter); and (c) Hausner ratio and Carr index of chopped and ground straws.

2. Material and methods

The current study builds upon the work conducted by Adapa et al. [17], using the same feedstock (agricultural straw samples: barley, canola, oat, and wheat) to explore the grinding energy and physical properties using a chopper and hammer mill using larger screen sizes. These samples were acquired from a farmer in the Central Butte area of Saskatchewan, Canada, from crops combined in August 2008, and then left on the field to dry [17]. These samples were later baled in September 2008 (typically having dimensions of 0.45 × 0.35 × 1.00 m) [17].

Fig. 1 indicates the flow diagram of the material prepared for the grinding energy and physical properties studies [17]. The initial moisture content of ground barley, canola, oat, and wheat straw were 0.67, 0.67, 0.53, 0.40 (fraction total mass basis), respectively [17]. The agricultural residues were placed over a thick plastic sheet and then left under a tarpaulin cover during the winter of 2008 (approximately 7 months) [17]. During this period, the moisture content of the barley, canola, oat, and wheat straw decreased to 0.135, 0.151, 0.131, and 0.156 (fraction total mass basis), respectively [17].

The baled straw sample was chopped using a chopper fabricated by Bioprocessing Lab, Department of Agricultural and Bioresource Engineering, University of Saskatchewan [17]. The chopper was equipped with a feed hopper and a pair of rollers to feed the material to the chopping blades. It was operated with no screens. After a few preliminary trials, the rollers were set to rotate at 0.83 Hz to avoid clogging of material. Complete details of the chopper and its configuration used in the present study were discussed by Adapa et al. [17].

The chopped biomass was further 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 [17]. The shaft rotates at 63.3 Hz with three screen sizes (19.05, 25.4, and 31.75 mm) to grind the chopped materials. The outlet of the hammer mill was connected to a dust collector (House of Tools, Model no. DC-202B, Saskatoon, SK) having a 9 A suction fan rotating at 58.3 Hz to control dust during the milling operation, to allow for the flow of chopped biomass through the hammer mill, and for the collection of the ground biomass [17]. Power consumption of the chopper and hammer mill motors was measured using a wattmeter (Ohio Semitronics International, Hilliard, OH). The meter was connected to a datalogging 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.

2.1. *Specific energy*

During the chopping and grinding experiments, 3 kg of each straw type was manually fed into the chopper (no screen) and hammer mill (three screen sizes of 19.05, 25.4, and 31.75 mm). The power used by the chopper and hammer-mill motors and the time required for the grinding process were measured and recorded. The power required to run the empty chopper and hammer mill was recorded prior to the introduction of material in order to obtain baseline data. This allowed determination of the net power required to grind the material. The specific energy (kWh t^{-1}) 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 the pre-determined quantity of material [16,17]. Each test was performed in replicates of three.

2.2. *Physical properties measurement*

Moisture content of chopped and hammer-milled biomass was measured using ASAE Standard S358 [45]. Then, 25 g of the material was oven-dried at 103 °C for 24 h, and the moisture content was expressed in a mass fraction (of total mass). All of the moisture content tests were performed in replicates of three.

2.3. *Loose bulk and tapped density*

The loose bulk density of chopped and hammer mill ground agricultural straw at three screen sizes (19.05, 25.4, and 31.75 mm) was determined by carefully filling a standard 0.5-L cylindrical container (SWA951, Superior Scale Co. Ltd., Winnipeg, MB) with a sample. Initially, the material was filled up to the top of the container and the excess material was removed using a steel ruler. At this point, the material was weighed. The container was tapped on a flat surface about 10 times to allow the material to settle. The container was further filled with material, and the excess material was removed using the same steel ruler. The material was again weighed, and the bulk and tapped density were calculated based on the volume of the container and weight of material. The bulk and tapped densities were then used to calculate the Hausner ratio (Eq. (1)) and Carr's index (Eq. (2)).

2.4. *Particle density*

A gas multi-pycnometer (QuantaChrome, 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 sample material [29,46]. The pressure was set at around 40 kPa (near maximum as specified by the instrument specifications). The sample volume (V_p) is calculated from Equation (3):

$$V_P = V_C - V_R\left(\frac{P_1}{P_2} - 1\right) \tag{3}$$

where P_1 is the pressure reading after pressurizing the reference cell (kPa), and P_2 is the pressure after connecting the reference cell to the sample cell. The particle density (ρ_s) of the sample is its mass m_p divided by the pycnometer particle volume (V_{pvc}), as shown in Equation (4). The instrument readings on each sample were also repeated three times.

$$\rho_s = \frac{m_p}{V_{pvc}} \tag{4}$$

2.5. *Geometric mean particle length*

The geometric mean particle length of chopped and hammer-milled agricultural straw samples was determined using ASAE Standard S424 [47]. A set of 5 square-hole screens and pans having widths of 406 mm and lengths of 565 mm were used for the tests. The screens had nominal opening sizes of 19.0, 12.7, 6.3, 3.96, and 1.17 mm. The screens were stacked over each other with the screen having the largest opening size on top followed by other screens in decreasing opening size. Due to the low bulk density of the chopped material, only 750 g of material was placed at the top screen. The screen shaker was set to shake the screens for 5 min as suggested by the standard. The mass of the agricultural straw left over in each screen was determined, and further calculations were performed to calculate the geometric mean particle length (X_{gm}) of the chopped and hammer-milled agricultural straw. The tests were performed in replicates of three.

2.6. *Statistical analysis*

Standard deviation was calculated to measure the variability in the measured data. Holm–Sidak Test was used for pairwise comparisons of column means of experimental data. This test is more useful than the Tukey and Bonferroni tests as it can detect differences and is recommended as the first-line procedure for pairwise comparison testing. The Sidak–Holm procedures are similar to Bonferroni–Holms method except the differences are not compared to the alpha, but instead are compared to the Sidak-adjusted alpha. In this test, the P values of all comparisons are computed and ordered from smallest to largest. Each P value is then compared to a critical level that depends upon the significance level of the test (set in the test options), the rank of the P value, and the total number of comparisons made. A P value less than the critical level indicates there is a significant difference between the corresponding two groups [48].

3. Results and discussions

Table 1 shows the average moisture content of the agricultural straws prior to grinding studies. Statistical analysis of the data indicated that there is a significant difference ($P < 0.05$) between the moisture content of the different agricultural straws measured (wheat, oat, barley, and canola).

3.1. *Specific energy consumption*

Table 2 lists the specific energy consumption of the chopper and the hammer mill for the different particle sizes of barley, wheat, canola, and oat straws at average moisture contents of 0.135, 0.156, 0.151, and 0.131 (fraction total mass basis), respectively. It is very clear that the hammer mill fitted with the smallest screen size (19.05 mm) consumed the most energy. Grinding oat feedstock in a hammer mill with a 19.05-mm screen required the highest amount of energy at 8.05 kWh t^{-1}, with canola straw requiring the least (2.91 kWh t^{-1}) among the biomass samples. During chopping, barley consumed the highest energy at 3.15 kWh t^{-1}, and canola consumed the least energy at 1.96 kWh t^{-1}.

Statistical analysis using the Holms–Sidak multiple comparison test at $P < 0.05$ indicated that in a comparison of chopped barley and oat to wheat and canola, wheat and oat are not statistically significant. In case of hammer milling using screen sizes of 31.75 and 19.05 mm, the combinations of barley, wheat, and canola were found to be statistically not significant, whereas for screen size of 25.40 mm, barley and wheat were found to be statistically not significant.

3.2. *Loose bulk density, tapped density, and particle density*

The loose bulk and tapped bulk density values of barley, wheat, oat and canola straw grind are given in Table 3. It is obvious that grinding to smaller particle size resulted in higher loose bulk density and tapped bulk density. Among all the different feedstock studied canola has the highest density and wheat and oat, the lowest. The highest loose bulk density of 80.4 kg m^{-3} was observed for grinds from 19.05 mm screen size for canola and a minimum for wheat and oat straws of about 58 kg m^{-3}.

The observations are similar for tapped bulk density where highest value of 119 kg m^{-3} was recorded for canola straw grinds from 19.05 mm screen and lowest value of 88–90 kg m^{-3} was recorded for wheat and oat straw grinds. The particle density of agricultural straw grinds significantly increased with decrease in hammer mill screen size (see Table 3). The highest value (1219 kg m^{-3}) was recorded for canola and lowest (about 781 kg m^{-3}) was for wheat. For the chopped material, oat straw recorded the lowest value of about 600 kg m^{-3}. These results have corroborated the observations of Adapa et al. [17], where smaller screen sizes resulted in higher particle densities. Statistical analysis of the experimental data on bulk density indicated that barley, wheat, and oat were not statistically significant for chopped and hammer-milled straws using a screen size of 31.75 mm. In case of 25.40-mm grinds, barley and wheat and wheat and oat were not statistically significant. The observations were similar for tapped density except for the sample using the screen size of 31.75 mm. For particle density, the hammer-milled grinds using a screen size of 19.05 mm were found to be statistically significant.

The porosity values calculated based on bulk and particle density (see Equation (5)) are listed in Table 4. Canola straw grind has the lowest porosity values for both chopped and hammer-milled samples. Among the chopped agricultural straws, the barley straw grind had the highest porosity values of 0.96.

$$\text{porosity} = \frac{\rho_b}{\rho_s} \quad (5)$$

where ρ_b = bulk density and ρ_s = particle density.

3.3. *Geometric mean particle size*

Table 5 shows the geometric mean particle size of chopped and ground straws. The results clearly indicate that chops have the highest average geometric mean particle size, and material ground using a hammer mill with a 19.05-mm screen have the lowest values. Among the chopped materials, wheat straw has the highest geometric mean particle size (4.22 mm), and canola has the lowest value (2.42 mm). These values significantly decreased with further grinding to different screen sizes. Among the ground biomass, canola has the lowest values. The mean particle size for straw ground with 19.05 mm screen size was 0.98 mm for canola and 1.5 mm for oat. Statistical analysis indicated that for chopped straws, all of the geometric mean particle diameter values were found to be statistically different. In the case of hammer-milled straws, only the wheat and barley combination was found to be statistically not significant.

3.4. *Hausner ratio and Carr index*

Table 6 lists the Hausner ratio and Carr index calculated based on the bulk density and particle density of chopped and ground wheat, barley, oat, and canola straws. Among the agricultural straws studied, canola had better Hausner ratio

Table 1 – Moisture content of the barley wheat, canola and oat straws ($n = 3$).

Straw	Moisture content (fraction total mass basis)	SD
Barley	0.135[a]	0.07
Wheat	0.156[b]	0.14
Canola	0.151[c]	0.06
Oat	0.131[d]	0.06

Different superscripts indicate the means are statistically significant based on the Holms–Sidak method at a significance level of 0.05.
'n' indicates the number of samples.

Table 2 – Specific energy consumption for chopping and grinding of agricultural straws ($n = 3$).

Grinding energy (kWh t^{-1})								
Agricultural straw	Chopper		Hammer mill/31.75 mm screen		Hammer mill/25.40 mm screen		Hammer mill/19.05 mm screen	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Barley	3.15^{b}	0.12	1.70^{a}	0.23	2.99^{a}	0.56	3.23^{a}	0.42
Wheat	$2.27^{a,c}$	0.39	2.05^{a}	0.25	3.10^{a}	0.34	3.52^{a}	0.13
Canola	1.96^{c}	0.22	1.46^{a}	0.56	1.47^{b}	0.39	2.91^{a}	0.44
Oat	$2.74^{a,b}$	0.09	5.68^{b}	0.19	7.51^{c}	0.33	8.05^{b}	0.37

Different superscripts indicate the means are statistically significant based on the Holms–Sidak method at a significance level of 0.05. 'n' indicates the number of samples.

and Carr index as compared with wheat, oat, and barley straws. Chopped straws had a Hausner ratio of 1.23–1.31 and a Carr index of 18–25. Further grinding the chopped material using hammer mill with the smallest screen size (19.05 mm) increased the Hausner ratio to 1.48–1.55 and Carr index to 33–36. Grinding the materials using smaller screens (25.4 and 19.05 mm) increased the Hausner ratio and Carr index values significantly.

3.5. *Discussion*

From the present investigation, it is very clear that the specific energy requirement for grinding biomass increases with a decrease in the screen size or degree of fineness of the grind, as similarly reported by Tavakoli et al. [5]. Holtzapple et al. [49] reported that there is an inverse relationship between grinding energy and length of wood chips. They also concluded that grinding energy increases greatly as the particle size is reduced. Mani et al. [16] reported that specific energy consumption for grinding wheat straw and corn stover decreased with an increase in the screen size fitted on the hammer mill. These authors reported that the grinding energy of wheat straw with the hammer mill having screen sizes of 0.8, 1.6, and 3.2 mm were 51.6, 37.0 and 11.4 kWh t^{-1}, respectively, at 0.083 moisture content (fraction total mass basis). They also reported that the energy required for grinding the corn stover using hammer-mill screen sizes of 3.2, 1.6, and 0.8 mm were 7.0, 14.8, and 22.0 kWh t^{-1}, respectively. From the studies by Akunov [50], Cadoche and López [51], Jannasch et al. [52], Morrell [53], Bitra et al. [18], Igathinathane et al. [42,54], and Kaliyan and Morey [55], specific energy required for biomass size reduction is a function of the degree of size reduction required. The results observed in the present study in terms of energy consumption have corroborated the results of these researchers.

Mechanical size reduction (comminution) of biomass helps to increase the bulk density. To further increase the densities of ground biomass, they were made into pellets and briquettes by mechanical compaction. The ground agricultural biomass, which had about 80 kg m^{-3} of bulk density, can be increased to 600–700 kg m^{-3} when briquetted or pelleted. According to Lam et al. [29], loose bulk density and tapped bulk density are functions of particle size, shape, porosity, and moisture content. The present results indicate that using smaller screen in

Table 3 – Loose bulk density, tapped density and particle density of chopped and ground agricultural straws ($n = 3$).

Agricultural straw	Chopper		Hammer mill/31.75 mm screen		Hammer mill/25.40 mm screen		Hammer mill/19.05 mm screen	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Loose bulk density (kg/m^3)								
Barley	36.25^{a}	2.36	48.54^{a}	3.45	64.9^{a}	3.56	67.2^{b}	2.34
Wheat	37.98^{a}	1.76	49.68^{a}	2.11	$58.8^{a,b}$	2.90	58.2^{a}	3.12
Canola	48.58^{b}	1.12	67.15^{b}	1.88	73.6^{c}	2.29	80.4^{c}	3.09
Oat	40.15^{a}	1.54	54.35^{a}	2.01	53.5^{b}	2.39	58.3^{a}	2.87
Tapped density (kg/m^3)								
Barley	48.78^{a}	2.11	65.05^{a}	3.23	99.4^{b}	3.89	101^{b}	3.45
Wheat	49.87^{a}	1.89	59.39^{b}	2.01	80.7^{a}	2.87	88.2^{a}	3.05
Canola	59.87^{b}	1.01	79.66^{c}	1.97	113^{c}	2.39	119^{c}	3.89
Oat	52.23^{a}	1.33	68.94^{a}	2.36	85.1^{a}	2.77	90.6^{a}	3.07
Particle density (kg/m^3)								
Barley	809^{a}	10.9	817.5^{a}	16.4	869.5^{b}	19.2	873.6^{a}	20.1
Wheat	649.2^{b}	9.78	663.2^{b}	10.2	709.0^{a}	12.78	781.4^{b}	15.6
Canola	800.2^{a}	7.6	818.2^{a}	9.9	969.4^{c}	12.2	1219.7^{c}	17.3
Oat	600.2^{c}	5.7	620.9^{c}	8.9	714.2^{a}	12.1	839.3^{d}	18.9

Different superscripts indicate the means are statistically significant based on the Holms–Sidak method at a significance level of 0.05. 'n' indicates the number of samples.

Table 4 – Porosity values of chopped and ground agricultural straws.

Porosity				
Biomass	Chopper	Hammer mill/31.75 mm screen	Hammer mill/25.4 mm screen	Hammer mill/19.05 mm screen
Oat	0.93	0.91	0.92	0.93
Barley	0.96	0.94	0.92	0.92
Canola	0.93	0.90	0.90	0.90
Wheat	0.95	0.94	0.94	0.95

the hammer mill resulted in smaller particle size of the grind with corresponding increase in the bulk and tapped densities. Miao et al. [56] reported that bulk density values of ground miscanthus, switchgrass, and willow decreased with increase in the aperture size of the milling screens. The increase in tapped bulk density values of the biomass for all the grind sizes in the present study corroborated the observations of Lam et al. [29]. Based on grinding and physical properties studies on the four agricultural straws, canola can make better densified products in terms of density and durability as it has higher initial bulk and particle densities and smaller geometric mean particle size (mm) (which can help to increase the contact area during densification and results in more durable products).

The flow properties calculated based on bulk and tapped densities indicated that there is a distinction between the Hausner ratio and Carr's index values of chopped and hammer-milled biomass. A Hausner ratio of <1.25 indicates a solid that is free-flowing, whereas >1.25 indicates poor flowability. The chopped biomass was mostly of poor flowability, except that of chopped canola (1.23). The hammer-mill-ground biomass with screen sizes of 25.4 and 19.05 mm also generally had poor flowability. The smaller the Carr's index, the better the flow properties, where 5–15 indicates excellent, 12–16 good, 18–21 fair, and >23 poor flow [57]. The results obtained from this study indicated that screen size of the hammer mill contributed to the flow properties during processing. Singh and Kumar [38] reported that increase in cohesion plays a dominant role in flow dynamics as it directly affects the bulk flowability of solid material. Their study reported that biomass ground in smaller screen sizes (25.4 and 19.05 mm) tended to behave like cohesive solids, sticking together; this may be due to static electrical attraction that developed between the particles. Singh and Kumar [38] also reported that increased cohesiveness can cause jamming of the flow of granular material, causing lower rates of material flow. The structure and shape of chopped biomass prevents easy orientation that enhances easy and free flow.

Canola and wheat straws ground with hammer mill (screen size of 31.75 mm) have an intrinsic property that enhances or allows easy orientation and better flow properties. Oat and barley straws ground with hammer mill with 31.75-mm screen size had poor flowability. Further reduction of the hammer mill screen size increased the degree of packing (bulk density) of ground straw. However, high pressure does not always increase the tendency of solid material to flow, as it does in liquid. Instead, increased pressure tend to pack the particles of solid material more tightly together and makes flow more difficult [58].

Finely ground biomass tends to behave like dry powder that seems like a mass of tightly packed particles (due to particle interlocking), and adheres strongly to vertical surfaces of bins or silos and causes difficulty of flow. McCabe et al. [58], also reported that when the particle size of solid materials becomes very small, then such material is no longer free-flowing. This implies that there must be a limit to which the biomass screen size can be reduced for efficient and economical processing. Therefore, having poor flowability of ground biomass would limit the options of how to handle and transport these materials in a processing plant.

4. Conclusions

The present investigation studied the effect of two-stage grinding of four types of agricultural straws —barley, wheat, oat, and oat—using a chopper and hammer mill on their grinding energy and physical properties. The following conclusions can be drawn from this study:

Table 5 – Geometric mean particle diameter (mm) of chopped and ground agricultural straws ($n = 3$).

Geometric mean particle diameter (mm)								
Agricultural straw	Chopper	SD	Hammer mill/31.75 mm screen	SD	Hammer mill/25.40 mm screen	SD	Hammer mill/19.05 mm screen	SD
Oat	4.15^{a}	0.012	2.18^{b}	0.014	1.63^{b}	0.022	1.50^{b}	0.019
Canola	2.42^{b}	0.023	1.21^{c}	0.027	1.04^{c}	0.090	0.98^{c}	0.023
Wheat	4.22^{c}	0.045	1.68^{a}	0.043	1.26^{a}	0.032	1.17^{a}	0.056
Barley	3.37^{d}	0.043	1.63^{a}	0.051	1.28^{a}	0.031	1.13^{a}	0.074

Different superscripts indicate the means are statistically significant based on the Holms–Sidak method at a significance level of 0.05.
'n' indicates the number of samples.

Table 6 – Hausner ratio and Carr index of chopped and ground agricultural straws.

Straw	Chopper	Hammer mill/31.75 mm screen	Hammer mill/25.4 mm screen	Hammer mill/19.05 mm screen
Hausner index				
Oat	1.30	1.27	1.59	1.55
Barley	1.34	1.34	1.53	1.50
Canola	1.23	1.19	1.53	1.48
Wheat	1.31	1.19	1.37	1.52
Carr Index				
Oat	23.13	21.16	37.13	35.65
Barley	25.69	25.38	34.71	33.46
Canola	18.86	15.70	34.87	32.44
Wheat	23.84	16.35	27.14	34.01

a) Canola consumed the least grinding energy of 1.96 kWh t^{-1} for chopping and 2.91 kWh t^{-1} for hammer milling using 19.05 mm screen size, whereas oat and barley straws consumed the highest. Grinding energy increased with decrease in screen size of the hammer mill.
b) The physical properties (geometric mean particle diameter, loose bulk density, tapped bulk density, particle density, and porosity) of the chopped and hammer milled wheat, barley, canola and oat straws were in the range of 0.98–4.22 mm, 36–80 kg m^{-3}, 49–119 kg m^{-3}, 600–1220 kg m^{-3}, 0.9–0.96, respectively.
c) Ground canola straw had the highest loose bulk and tapped bulk density values of about 80 kg m^{-3} and 119 kg m^{-3}, respectively, whereas wheat had the lowest for chopped and hammer milled straw using a 19.05 mm screen size.
d) Loose bulk and tapped bulk density values are inversely proportional to the particle size of the grinds.
e) Canola recorded the highest particle density of 1219.7 kg m^{-3} and wheat the lowest of 781.4 kg m^{-3}after hammer milling using a 19.05 screen size.
f) The Hausner ratio and Carr index calculated were better for chopped biomass compared to hammer milled at 19.05 mm screen size.

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