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

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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].

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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