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The angle of repose of bulk corn stover particles

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Abstract

Lignocellulosic biomass feedstock such as corn stover, the residues left on the field after corn grain harvest, has been studied as one of the renewable feedstocks to be used for fuel ethanol conversion in the near future. The primary objective of this work was to determine the angle of repose (AoR) of bulk corn stover particles prepared to four particle sizes (chopped and particles screened through 6.4, 3.2 and 1.6 mm) at two moisture contents (dry, <10% and wet, >20%). The results show that particles size and feedstock moisture content were important variables that affected the angle of repose for all three angle of repose methods (piling AoR loose-base, piling AoR fixed-base and sliding AoR) investigated. In general, increasing moisture content and particle size increased the piling AoR (loose-base), piling AoR (fixed-base) and sliding angle of repose. Characterization of the flow behavior of bulk corn stover particles using the piling AoR (loose-base) and comparison with three granular bulk solids of biological origin (corn, soybean and distillers dried grains with solubles, DDGS) indicated that dry and wet stover particles of the particle size ranges tested in this study have a poor flow behavior.

Keywords: Angle of repose; Biomass; Corn stover; Bulk particulates; Particle size; Particle size distribution

1. Introduction

The angle of repose (AoR) measures the angle of inclination of the free surface to the horizontal of a bulk solid pile. It is one of the primary properties of powders that indicates the interparticulate friction and has been used to characterize the flow behavior of powders and granular materials with respect to flowability [1,2], avalanching [3,4], stratification [5,6] and segregation [7,8]. While there are disagreements in the literature with respect to the usefulness of the angle of repose as a flow property, with some favoring its importance as a flow property [1,9] while others do not [10], it is generally agreed upon that the angle of repose is one of the easiest parameters to measure that gives a rough estimate of the cohesive behavior of powders and bulk solids. Carson and Marinelli [11] and Purutyan et al. [12] suggested that to design a vessel, one needs to "distinguish between tests that provide qualitative, relative data and tests that provide quantitative, absolute data". The angle of repose can only be considered as "qualitative and relative data" that "at best may help you find differences between samples but will not help you design the vessel". Nevertheless, the angle of repose has been used to evaluate flow properties in approximately 40% of the papers reviewed by Augsburger [13], and 80% among them considered it of some use in characterizing flow.

Train [14] conducted tests on simple free flowing materials (i.e. glass balls, lead shot and sand) to minimize the complications due to shape and surface characteristics. Four methods were used, including measuring the angle of repose of a pile formed on a fixed bed, free-standing pile formed by a fixed funnel, the angle for particulate materials to slide by tilting a rectangular box, and the angle formed by materials in a revolving cylinder. His results showed that the angle of repose tested using the first and second methods (static angle of repose) were lower than the third and fourth (dynamic angle of repose) methods. Chowdhury et al. [15] determined the angle of repose of a pile of grams formed by slowly moving the filling spout upward as the pile was formed. He found that the angle of repose increased nonlinearly with increase in moisture content (MC). Another angle of repose found in the literature is the

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"emptying angle of repose". The emptying angle of repose as defined by Stroshine [16] is the angle made by bulk materials after it empties from a flat bottom bucket with a circular orifice. The emptying angle of repose is different from the previous definitions of the angle of repose. The angles of repose using the various methods described previously provide the relative behavior of the bulk material under various test conditions and are applicable to various bulk handling scenarios. One of the practical applications for the use of the piling angle of repose is in the determination of the footprint and headroom of a flat storage structure for bulk solids, as well as the locations of overhead and floor conveying systems to transport the bulk solid into and out of flat storage structures. Flat storage structures are particularly used for storage of non-flowing bulk solids such as bulk biomass particulates (wood chips, chopped and ground plant biomass) and distillers dried grains with solubles (DDGS) because they enable the use of mobile loaders to sweep these solids into transport containers and unloading conveying trenches.

Hauhouot-O'Hara et al. [17] evaluated the effect of particle size and Tricalcium phosphate (TCP) concentration on the angle of repose of ground marigold petals. They found that larger particles had higher angles of repose than smaller ones. Kanawade et al. [18] evaluated the effects of moisture content on the angle of repose of pigeon pea, chick pea, cowpea, green gram, black gram, as well as soybean and moth bean seeds at five moisture levels. They concluded that the higher the moisture content, the larger the angle of repose. Additionally, Arora and Singh [19] tested the effect of moisture on the angle of repose of sunflower and groundnut and concluded that the angle of repose and moisture content were linearly related.

However, many reported values of the angle of repose for agricultural bulk materials did not provide the specifics of the test method used, although it is generally believed that the most common angle of repose reported is that for the piling angle of repose. No literature was found for the angle of repose of corn stover bulk particles or other similar types of biomass or particulate bulk materials except the initial work reported by Zhou and Ileleji [20] for corn stover and switchgrass grinds. The aforementioned study was primarily to establish protocols for determining bulk physical properties of biomass particulates in relation to their handling.

1.1. Study objectives

With the increasing growth in fuel ethanol production from corn, currently at over 6 billion gallons per year [21], there is increasing interest by the industry to explore the use of lignocellulosic biomass such as corn stover, switchgrass and woodchips, etc. as feedstock for fuel ethanol production. In fact the United States Energy Policy Act of 2005 (H.R. 6) signed into law a Renewable Fuels Standard (RFS) that beginning in 2013, a minimum of 946.4 million liters (250 million gallons) a year of cellulose derived ethanol be included in the RFS [22]. Corn stover, the plant residue left on the field after corn grain harvest, has since been the primary favorite for the first implementation of cellulose to ethanol production on a commercial scale in the United States and most of the conversion studies have focused on corn stover feedstock [23–29]. Therefore it is important that research on the handling properties of corn stover be investigated as well, the results which will benefit the design of bulk handling and storage systems in biorefineries processing this feedstock. Currently, very little work has been conducted on biomass feedstock handling and this will be one of the major technological barriers to overcome in the production of fuel ethanol from lignocellulosic biomass. In the light of the need for this study, the primary objectives of this work were to:

1. Determine the angle of repose based on three methodologies for the angle of repose (piling loose-base, piling fixed-base and sliding) for bulk corn stover particles conditioned to two moisture content (MC) levels (dry stover, <10% and wet stover, >20%) and prepared to four particle sizes (chopped and ground through 6.4, 3.2 and 1.6 mm hammermill screens),
2. Determine the effect of moisture content, particle size and their interaction on the angle of repose of bulk corn stover particles, and
3. Qualitatively characterize the flow behavior of bulk corn stover particles in comparison with other granular bulk feedstocks of biological origin using the angle of repose.

2. Materials and methods

2.1. Bulk corn stover sample preparation

Corn stover, that is the whole plant tissue except the ear from two hybrids with the same parent genetic but different dry down characteristics were hand harvested in the fall of 2005 from two replicate plots per hybrid at Purdue's Agronomy Center for Research and Education (ACRE) in West Lafayette, Indiana. The hybrids were from Beck's Hybrid Company (Atlanta, Indiana) and labeled conventional corn (Beck's No. 5538) and staygreen corn (Beck's No. 5727). After hand-harvesting from the field by manually cutting with shears about 51 mm above the ground level, ears were separated from the stalks before the stalks and leaves were chopped with a modified John Deere model 72 stationary forage chopper powered by the tractor's power take-off drive. Thus, corn stover or "stover" referred to in this work only contained stalks and leaves without the ear. The chopped material designated as "chopped" in this paper was put in air-tight zip-loc bags and transferred to a walk-in cooler set at about 10 °C for storage until further tests.

Stover samples from both conventional and staygreen hybrids were prepared for bulk physical property determination at two moisture content levels (dry, <10% MC and wet, >20% MC) and for four particle sizes, chopped stover and ground stover screened through 6.4 mm (1/4 in.), 3.2 mm (1/8 in.), and 1.6 mm (1/16 in.). To prepare dry stover samples, part of the stover was taken out of the zip-loc bags, thoroughly hand-mixed and spread in a thin layer to air-dry at room temperature to the target moisture (<10% MC) before size reduction. For wet stover samples, stover stored at harvest moisture in a cooler at 10 °C was placed on the lab bench while still sealed in the zip-loc bags for 2 h to equilibrate to the ambient lab temperature before size reduction. A hammermill (Type 1200, Glen Mills Inc., Clifton, NJ) with a variable speed controller to regulate the motor speed was used to grind stover samples. A 6.5 hp Craftsman shopvac (Emerson Electric, Macalon, TX) connected to the hammermill bottom hopper outlet was used to pull the ground material through three hammermill screen sizes (6.4, 3.2, and 1.6 mm) to achieve three different ground stover particle sizes. During grinding, ground materials were screened in succession through the largest screen size (6.4 mm) to the smallest (1.6 mm) screen size. Chopped stover particles were manually fed into the hopper of the hammermill and ground to achieve a sufficient quantity of material for the screen size in-place before the next smaller screen was used. Thus, ground materials sized with the 6.4 mm screen passed through the hammermill about 1 to 3 times, 2 to 6 times for materials sized with the 3.2 mm screen and 3 to 9 times for materials sized with the 1.6 mm screen. In industrial practice, large particle that are unable to pass through the screen during milling are automatically aspirated from above the screen and recycled through the mill until they pass through the screen. In summary, the sample treatments in this study were: hybrid (two levels: conventional and staygreen) × %MC (two levels: dry and wet stover) × particle size (four levels: chopped, 6.4, 3.2 and 1.6 mm screened).

Moisture contents of stover particles for both hybrids were determined immediately after sample collection, after grinding, and after all the physical property measurements using a Halogen Moisture Analyzer (Model HB 43, Mettler-Toledo, Inc., Columbus, Ohio) set at 105 °C. Moisture loss on drying a 1 g sample replicate was determined when the weight of the test material being heated stopped changing within a 30 s period. All moisture contents for replicate samples of the various stover particle sizes measured for moisture were reported on a percent wet basis.

2.2. Bulk corn stover particle size distribution analysis

Particle size distribution (PSD) analysis was conducted for all the particles sizes based on the ANSI/ASAE standard S319.3 [30] for determining and expressing fineness of feed materials. Because of the very low density of bulk stover particles compared to granular grain and feed, only one half of the recommended 100 g charge was used for this analysis in order for the material to be contained in the limited sieve volume. Thus, 50 g of corn stover bulk particles was weighed and put in the topmost sieve of a nest of sieves with US sieve Nos. 3, 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 270, and a bottom pan. The nest of sieves was vibrated in a Ro-tap shaker (Model RX-29, W.S. Tyler, Inc., Mentor, OH, USA) for 10 min and an additional 1-min to check for any material changes by 0.1% or less of the charge mass during sieving after which each sieve was weighed. The weights were recorded and the amount of material retained on each sieve was determined by subtraction. The geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) were determined using the procedures specified in the standard and plots of the cumulative percentage weight of particles smaller than a given size were prepared. The particle sieve analysis was conducted with three sample replications per corn stover treatment. Because of the large particle sizes for the chopped stover samples, additional measurements for the particle sizes of the chopped material were determined by randomly pulling a handful of chopped materials (sub-samples) from the conventional and staygreen bulk sample, and measuring the length of ten randomly selected particles using a caliper. Measurement of particle size with the caliper was used only to obtain an estimate of the size of chopped corn stover by length, but not for any comprehensive particle analysis. The particle size distribution of all corn stover treatments by sieve analysis gave a good estimate of the particle size distribution of particles in a bulk sample.

2.3. Measurement methods for the angle of repose

Three different angles of repose were determined: loose-base piling angle of repose, fixed-base piling angle of repose, and the sliding angle of repose were conducted for all the sample treatments.

2.3.1. Piling angle of repose (loose-base) and (fixed-base)

For the loose-base angle of repose, a brass filling hopper (Seedburo Equipment Company, Chicago, IL) with a funnel slope of 31.8° to the vertical axis and 3.2 cm funnel orifice opening was used. The bottom of the funnel was positioned on a

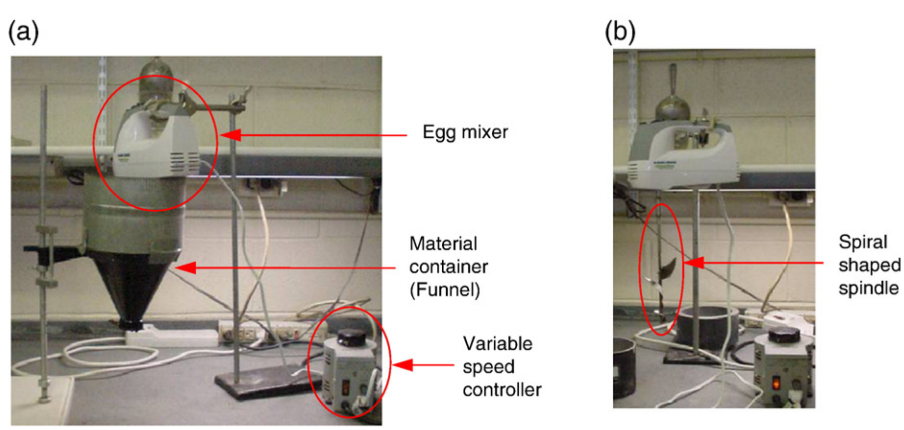

Fig. 1. Apparatus used for measuring the piling angle of repose (loose-base and fixed-base). (a) full assembling of the apparatus, (b) assembly of mechanical stirrer to automatically facilitate material flow.

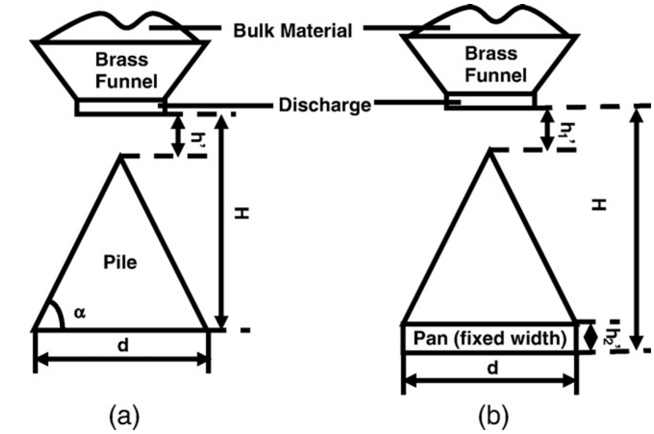

Fig. 2. Schematic diagram for estimation of the angle of repose of a pile. (a) angle of repose (loose-base), (b) angle of repose (fixed-base).

stand above the center of the base. Because bulk biomass particles will not flow freely by gravity through a hopper or funnel with a small orifice due to bridging caused by interlocking particles, mechanical agitation was required to enable a uniform flow through the funnel's orifice. This also ensured that the same material discharge rate was used for all the replications conducted, thereby providing good repeatability. A mechanical stirrer with two spiral spindles powered by an egg mixer (Applica Consumer Products, Inc., MX78WS Type 2, Miramar, FL) connected to a variable speed regulator was used (Fig. 1a and b). Measurements were randomized for conventional and staygreen corn stover particles at the same moisture content and particle size.

Prior to measuring the piling angle of repose, the material discharge (drop height) was determined such as to form a conical pile with minimum pile disturbance. For dry and wet corn stover, a drop height of 23 cm was found to be suitable for both loose-base and fixed-base piling angle of repose. Before the outlet of the funnel was opened, a thin layer of biomass grind was spread across the flat surface onto which, the biomass was dropped. This eliminated the effect of the base surface characteristics on the test result. For the fixed-base angle of repose, an aluminum pan 20 cm in diameter and 1.6 cm in depth was used as the fixed-base. The bottom of the funnel was positioned right above the center of the base with the same drop height as used for loose-base angle of repose.

The angle of repose, α° for both loose-base and fixed-base measurements was calculated using Eq. (1), and is based on Fig. 2 a and b.

$$\alpha^{\circ} = \frac{180}{\pi} \times \mathrm{ATAN}[(H-h')/r] = \frac{180}{\pi} \times \mathrm{ATAN}[2 \times (H-h')/d] \quad (1)$$

2.3.2. Sliding angle of repose

The sliding angle of repose was determined using a movable inclined metal plane onto which was attached a hollow square container (126 mm×126 mm×37.8 mm) at one end (Fig. 3a and b). Bulk stover was filled into the container to the brim and was gently leveled with a brush. The sliding angle of repose was determined by gradually lifting the inclined plane until the surface of the bulk stover began to slide. The angle made by the inclined plane to the horizontal at which the material began to slide was estimated as the sliding angle of repose (Eq. (2)).

$$\alpha^{\circ} = \frac{180}{\pi} \times \mathrm{ASIN}[(h-0.5)/12.5] \quad (2)$$

A comprehensive description of this work can be found in Zhou [31].

2.4. Data analysis

To evaluate the effect of moisture content, particle sizes and their interactions on the angles of repose, the angle of repose data were subjected to two-way analysis of variance (ANOVA) using the PROC GLM procedure in the statistical analysis software, SAS [32]. Tukey's Honestly Significant Difference (HSD) was used to determine differences in the particle size and angles of repose among sample treatments and measurement methods at $\alpha = 0.05$ level using SAS. Additionally, one-way analysis of variance (ANOVA) using the PROC GLM procedure and their means separated with Tukey's HSD (at

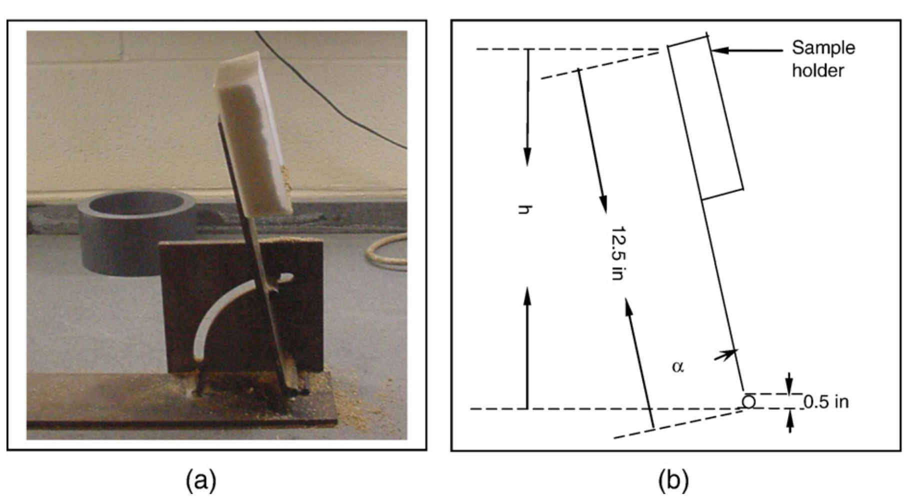

Fig. 3. Apparatus used for measuring the sliding angle of repose. (a) assembly of apparatus, (b) schematic of apparatus with dimensions.

Table 1
Moisture content (% wet basis) of bulk corn stover particles at which the angles of repose were measured

Stover sample/treatment type	Particle size classifications (Mean, %MC, w.b.)			
	Chopped	6.4 mm	3.2 mm	1.6 mm
Conventional corn stover (dry) [a]	7.2	6.0	6.1	5.3
Conventional corn stover (wet) [b]	63.2	57.0	27.4	19.8
Staygreen corn stover (dry) [a]	6.2	6.6	6.5	6.0
Staygreen corn stover (wet) [b]	61.6	38.9	26.3	18.5

[a] Mean moisture content for dry stover particles was measured after samples were prepared to their particle sizes and before the angle of repose measurements were conducted.

[b] Mean moisture content for wet stover particles was measured after samples were prepared to their particle sizes and before and after the angle of repose measurements were conducted.

$\alpha=0.05$) were used to evaluate the effect of test methodology (loose-base, fixed-base, and sliding) and hybrid (conventional and staygreen corn) individually. The particle size distribution of bulk stover particles for the sample treatments were expressed in terms of the cumulative frequency of particles retained on a given sieve size using MS Excel [33].

3. Results and discussion

3.1. Moisture content of bulk corn stover particles

The moisture content at which stover particles were measured for their angle of repose is shown in Table 1. Moisture loss occurred during grinding and was greater for wet stover particles than for dry stover particles. Moisture loss for wet stover particles increased with decrease in particle size due to increase in particle surface area as well as the number of ground material passes through the hammermill. Whenever plant material is ground, more surface area is created promoting rapid drying. Multiple passes of the ground material through the hammermill for adequate sizing also promoted moisture loss. This was also observed in an earlier work on corn stover and switchgrass particles by Zhou and Ileleji [20].

3.2. Particle size and particle size distribution of corn stover bulk particles

Table 2 shows the geometric mean diameter for stover particles of all treatments. The two-way analysis of variance (ANOVA) indicated that the geometric mean diameter for stover particles from conventional corn varied significantly among particle sizes ($P<0.0001$), but did not vary significantly among dry and wet moisture samples ($P=0.22$). However, for the staygreen corn hybrid, the geometric mean diameters of stover particles varied significantly among both moisture content ($P<0.0001$) and particle sizes ($P<0.0001$). The geometric mean diameters for particle sizes from dry staygreen corn hybrid were significantly larger than the wet stover particles. This might be due to more passes of the wet material through the hammermill relatively to the dry material for the staygreen hybrid, however this fact needs to be further investigated for certainty. Furthermore, there was a significant interaction between moisture content and particle size for both conventional ($P=0.0009$) and staygreen ($P=0.0004$) corn hybrids.

Particle size distributions of wet and dry stover particles were different among chopped and ground stover particles screened through 6.4, 3.2 and 1.6 mm screens for both hybrids (Figs. 4, 5, 6 and 7). However, the differences in the particle size distribution between stover particles sized through 3.2 and 1.6 mm screens were smaller for the wet stover particles. For all samples for the chopped particle size, 80% of the particles were larger than 2.28 mm, the nominal sieve opening for U.S. sieve no. 8. The caliper measurements of some individual particles showed particles sizes of the chopped stover to range between 4.0 and 64.3 mm in length for both corn hybrids.

3.3. Effect of corn hybrid, moisture content, particle size, and their interaction on the angle of repose of bulk corn stover particles

In general, the one-way analysis of variance (ANOVA) indicated that the angle of repose ($\alpha°$) was not significantly different ($P>0.05$) among stover particles of conventional corn and staygreen corn hybrids for all the test methods. However, the

Table 2
Means of geometric mean diameter (μm) for dry (low MC) and wet (high MC) corn stover particles

Sample type		Stover particle size, geometric mean diameter, d_{wg} (μm) (S_{wg} [a])				Mean [b]
		Chopped	6.4 mm	3.2 mm	1.6 mm	
Conventional	Dry (low MC)	4317.4 (2004.3 [a])	886.5 (788.4)	459.7 (430.3)	276.7 (243.8)	1485.1a
	Wet (high MC)	4520.1 (1721.7)	784.2 (577.7)	263.0 (269.7)	228.0 (191.4)	1448.8a
	Mean [c]	4418.8a	835.3b	361.4c	252.3c	
Staygreen	Dry (low MC)	3928.9 (2315.1)	1073.1 (961.5)	570.6 (470.7)	273.5 (223.6)	1461.5a
	Wet (high MC)	3688.7 (2615.6)	364.4 (322.6)	231.1 (207.5)	206.9 (165.5)	1122.8b
	Mean [c]	3808.8a	718.8b	400.9c	240.3c	

[a] Geometric standard deviation (S_{wg}).

[b] Means of the geometric mean diameter (d_{wg}) for a hybrid type followed by the same lower case letter are comparison between moisture contents for particle sizes that are not significantly different ($P\geq0.05$) according to Tukey's honestly significant difference test.

[c] Means of the geometric mean diameter (d_{wg}) for a hybrid type followed by the same lower case letters are comparison between particle sizes for dry and wet corn stover that are not significantly different ($P\geq0.05$) according to Tukey's honestly significant difference test.

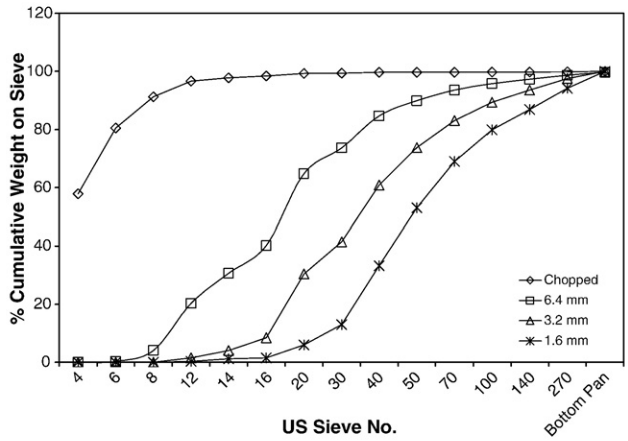

Fig. 4. Particle size distribution for dry stover particles from conventional corn hybrid.

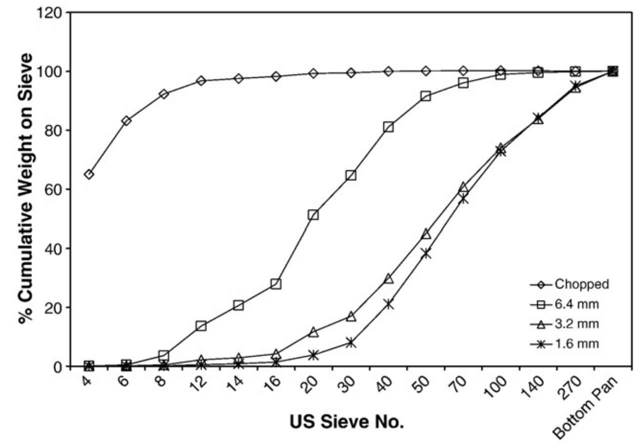

Fig. 6. Particle size distribution for wet stover particles from conventional corn hybrid.

two-way analysis of variance (ANOVA) indicated that the angle of repose (α°) for all the three test methods (loose-base, fixed-base, and sliding) varied among dry and wet stover particles ($P<0.05$), as well as among particle sizes ($P<0.05$) for stover from conventional corn and staygreen corn hybrids, respectively. As expected, the angle of repose of the dry stover particles was significantly lower than the angle of repose for the wet stover particles for both corn hybrids, irrespective of the method used.

Table 3a shows the data for stover particles from the dry and wet conventional corn hybrid. For conventional corn stover particles, the angle of repose (loose-base, α°) of dry and wet stover (conventional) particles sized to 6.4 mm and 1.6 mm were not significantly different. They were both significantly lower than the angle of repose for the chopped stover particles, but higher than stover particles sized to 3.2 mm. The angle of repose (fixed-base, α°) for bulk stover sized through 6.4 mm, 3.2 mm and 1.6 mm screens were not significantly different but were all significantly lower than the chopped stover particles. The sliding angles of repose for stover particles of all sizes were not significantly different among particles sizes but significantly different among dry and wet stover.

Table 3b shows the data for stover particles from the dry and wet staygreen corn hybrid. For staygreen bulk corn stover particles, the angle of repose (loose-base, α°) were not significantly different among particle sizes screened through 6.4, 3.2 and 1.6 mm, whose angles of repose were significantly lower than the chopped stover particles. For the angle of repose (fixed-base, α°) particles sizes screened through 3.2 and 1.6 mm were similar and significantly lower than the angles of repose for particles screened through 6.4 mm and the chopped particle size. The sliding angle of repose for particles screened through 6.4, 3.2 and 1.6 mm screens were not significantly different, but were significantly lower that the chopped particle size. As was observed for the conventional corn stover hybrid, the sliding angle of repose for the staygreen dry stover bulk particles were significantly lower than for the wet stover particles for all the angle of repose measurement methods in this study.

There was a significant interaction between the moisture content and grind size ($P<0.005$) for both conventional and staygreen corn hybrids for all angles of repose indicating that the trend in particle size differences was not the same for dry

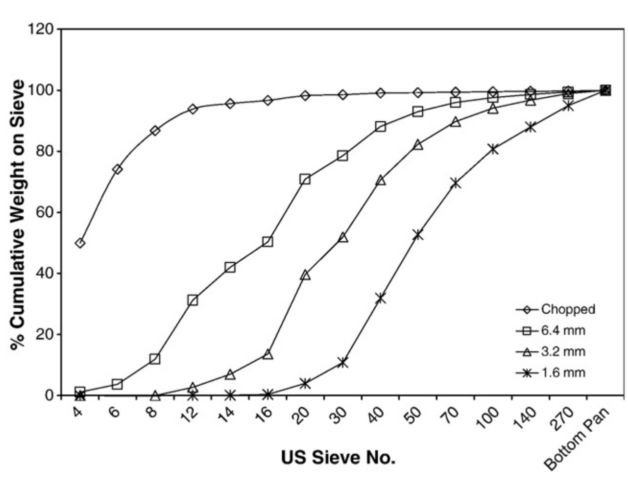

Fig. 5. Particle size distribution for dry stover particles from staygreen corn hybrid.

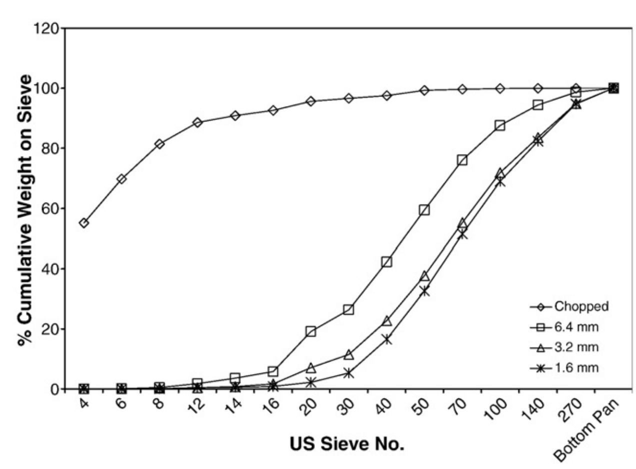

Fig. 7. Particle size distribution for wet stover particles from staygreen corn hybrid.

Table 3a
Mean angle of repose (α°) for four particle sizes [a] of conventional corn stover at low (dry) and high (wet) moisture contents [b] using three different measurement methods

Factors	Method for angle of repose	Moisture	Factor A = Particle size (mean ± SE): Chopped	6.4 mm	3.2 mm	1.6 mm	Mean [b]
Factor B = moisture content	Loose-base, α°	Dry (low MC)	51.9 ± 0.7	36.6 ± 1.2	36.2 ± 2.1	39.8 ± 1.7	41.1 ± 7.4a
		Wet (high MC)	49.3 ± 0.5	49.2 ± 0.5	45.0 ± 1.4	45.9 ± 0.4	47.3 ± 2.3b
		Mean [a]	50.6 ± 1.8a	42.9 ± 8.9b	40.6 ± 6.2c	42.9 ± 4.1b	
	Fixed-base, α°	Dry (low MC)	55.2 ± 0.7	40.0 ± 1.6	39.3 ± 1.1	43.4 ± 1.0	44.5 ± 7.4a
		Wet (high MC)	52.5 ± 0.4	49.4 ± 0.0	49.1 ± 0.9	46.7 ± 1.0	49.4 ± 2.4b
		Mean [a]	53.9 ± 1.9a	44.7 ± 6.6b	44.2 ± 6.9b	45.1 ± 2.3b	
	Sliding, α°	Dry (low MC)	64.8 ± 3.4	49.8 ± 2.3	49.2 ± 0.5	52.2 ± 1.6	54.0 ± 7.3a
		Wet (high MC)	62.1 ± 1.9	77.7 ± 1.5	72.5 ± 2.1	69.6 ± 2.5	70.5 ± 6.5b
		Mean [a]	63.5 ± 1.9a	63.8 ± 19.7a	60.9 ± 16.5a	60.9 ± 12.3a	

[a] Means of angle of repose for a method followed by the same lowercase letters are comparison for particle sizes for dry and wet bulk stover that are not significantly different ($P \geq 0.05$) according to Tukey's honestly significant difference test.
[b] Means of angle of repose for a method followed by the same lowercase letter are comparison for moisture content for all particle sizes that are not significantly different ($P \geq 0.05$) according to Tukey's honestly significant difference test.

and wet stover particles. In general, the angle of repose for the wet stover particles was higher than for the dry stover particles for the smaller sized material, i.e. particles screened through 6.4, 3.2 and 1.6 mm screens, irrespective of the measurement method. However, this was the opposite case for the chopped stover particles were the angle of repose for the dry stover particles was larger than the wet stover particles. Additionally, the angles of repose decreased with the decrease in particle size, although this was not always the case for all the sample treatments in this study.

3.4. Effect of measurement methodology on the angle of repose of corn stover particles

In general, the one-way analysis of variance (ANOVA) indicated that the angle of repose (α°) varied among test methods ($P < 0.05$) for stover particles from both corn hybrids (Table 3a and b). The loose-base and fixed-base angles of repose were not significantly different (at $\alpha = 0.05$), but both were significantly lower than the sliding angle of repose. The fixed- and loose-base piling angles of repose was different from the sliding angle of repose by a magnitude of about 15° on average for dry stover particles and this difference increased to 23° for wet stover particles. This shows how important it is to define the angle of repose referred to when reporting data because they could be quite different by significantly large magnitudes for different angle of repose measurement methods.

3.5. Characterization of the flow behavior of bulk corn stover particles using the angle of repose

The piling angle of repose (loose-base) for dry bulk stover particles was in the range of 36.0°–52.0° for chopped stover and ground stover screened through 6.4, 3.2 and 1.6 mm screens. In comparison to the angle of repose for a grain, oilseed and grain co-product, it was much higher than low moisture (<14% MC) corn (AoR = 27.7°) [16,34], soybean (AoR = 29°) [34,35] and distillers dried grains with solubles, DDGS (AoR = 29.3°) [36]. High moisture content comparison could not be made between the fixed and loose-base piling angle of repose of bulk stover particles determined in this study and other similar high moisture bulk solids of biological origin because of lack of data in the literature. In addition, the methodology used for the angle of repose determination was not reported in almost all the

Table 3b
Mean angle of repose (α°) for four grind sizes [a] of staygreen corn stover at low (dry) and high (wet) moisture contents [b] using three different measurement methods

Factors	Method for angle of repose	Moisture	Factor A = Particle size (mean ± SE): Chopped	6.4 mm	3.2 mm	1.6 mm	Mean [b]
Factor B = moisture content	Loose-base, α°	Dry (low MC)	45.5 ± 0.8	36.7 ± 0.7	37.1 ± 1.4	40.3 ± 2.4	39.9 ± 4.1a
		Wet (high MC)	48.0 ± 1.0	49.1 ± 0.3	45.6 ± 0.5	44.9 ± 1.2	46.9 ± 2.0b
		Mean [a]	46.8 ± 1.8a	42.9 ± 8.8b	41.4 ± 6.0b	42.6 ± 3.3b	
	Fixed-base, α°	Dry (low MC)	55.6 ± 0.9	40.4 ± 1.1	38.2 ± 0.0	41.1 ± 1.2	43.8 ± 7.9a
		Wet (high MC)	49.9 ± 0.9	49.6 ± 1.2	46.1 ± 0.0	46.6 ± 0.5	48.1 ± 2.0b
		Mean [a]	52.8 ± 4.0a	45.0 ± 6.5b	42.2 ± 5.6c	43.9 ± 3.9c	
	Sliding, α°	Dry (low MC)	73.1 ± 1.1	51.0 ± 1.9	51.3 ± 0.0	55.1 ± 2.0	57.6 ± 10.5a
		Wet (high MC)	66.0 ± 1.6	75.2 ± 5.8	75.2 ± 3.8	69.0 ± 0.9	71.4 ± 4.6b
		Mean [a]	69.6 ± 5.0a	63.1 ± 17.1b	63.3 ± 16.9b	62.1 ± 9.8b	

[a] Means of angle of repose for a method followed by the same lowercase letters are comparison for particle sizes for dry and wet bulk stover that are not significantly different ($P \geq 0.05$) according to Tukey's honestly significant difference test.
[b] Means of angle of repose for a method followed by the same lowercase letter are comparison for moisture content for all particle sizes that are not significantly different ($P \geq 0.05$) according to Tukey's honestly significant difference test.

literature found. Thus, the values for angle of repose for corn and soybean (except DDGS) found in the literature were assumed to be the piling angle of repose (loose-base).

Other granular bulk materials of biological origin such as low moisture grain and oilseeds (corn and soybean) that are free flowing and DDGS that is fair to poor flowing were used to qualitatively characterize bulk stover particles flow behavior. This comparison was relative and meant to give only an indication of the relative flow behavior between bulk materials of plant origin comprising of starchy grains and oilseeds and bulk material comprising of lignocellulosic plant biomass. The criteria for characterization were as follows: AoR lower that 30° was considered free flowing, AoR between 30° and 35° was good, AoR above 35° was fair flowing, AoR greater than 40° was poor flowing and AoR greater than 50° was very poor flowing. As the angle of repose increases so does the granular bulk become less flowable. According to this angle of repose criteria described and using only the piling angle of repose (loose-base), dry and wet bulk stover particles sized as chopped, and ground stover screened through 6.4, 3.2 and 1.6 mm screens all had poor flow behavior. Additionally, in comparison to the piling angle of repose values for corn, soybean and DDGS found in the literature, the flow behavior of the bulk stover particles of the sample treatments in this study were poor and can been classified as “non-free flowing.”

4. Conclusions

In general, the angles of repose for stover particles from both conventional and staygreen corn hybrids were not significantly different for all the angle of repose measurement methods (piling loose-base and fixed-base, and sliding angles of repose) investigated. For dry and wet stover particles, the loose-base and fixed-base piling angle of repose were similar but lower than the sliding angle of repose. Additionally, the angles of repose for the wet stover particles were higher than for the dry stover particles. Likewise, larger particles had a higher angle of repose than smaller particles, although the interaction of moisture content and particle size did not always show this trend. Because the angle of repose for the three measurement methods were significantly different, it is advisable to report and describe the angle of repose method used as well as the moisture and bulk particle size when reporting angle of repose data for bulk granular solids or particulates. Characterization of the flow behavior of bulk stover particles in comparison with three granular bulk solids of biological origin (corn, soybean and DDGS) indicated that dry and wet bulk stover particles of size ranges from chopped to ground particles screened through 6.4, 3.2 and 1.6 mm screens have a poor flow behavior and can be classified as “non-free flowing.” The data of the angle of repose generated from this study could serve as base-line data for designing flat storage structures for bulk stover feedstock.

List of symbols

d	cone base diameter (for fixed-base, $d=21.0$ cm)
H	drop height of funnel orifice (23 cm for dry stover and wet stover)
h	plane height at which material begins to slide as indicated in Fig. 3b (plane length=316.7 mm and height for the plane's axis above its base=12.6 mm)
h'	distance from funnel orifice to cone apex as indicated in Fig. 2(a) for loose-base piling angle of repose
$H-h'$	pile height for loose-base angle of repose as indicated in the Fig. 2(a)
h_1'	distance from funnel orifice to cone apex as indicated in Fig. 2(b) for fixed-base piling angle of repose
h_2'	depth of pan used for fixed-base as indicated in Fig. 2 (b), $h_2'=1.6$ cm
$H-(h_1'+h_2')$	pile height for fixed-base piling angle of repose as indicated in the Fig. 2(b)
r	cone base radius, cm
$\alpha°$	angle of repose, degrees °

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