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Effects of Grinding Corn with Different Moisture Content on Subsequent Particle Size and Flowability

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Abstract: The objective of this study was to determine the effects of whole-corn moisture and hammermill screen size on subsequent ground corn moisture, particle size and flowability. Treatments were arranged as a 2 × 2 factorial design with two moisture concentrations (14.5 and 16.7%), each ground using 2 hammermill screen sizes (3 mm and 6 mm). Corn was ground using a lab-scale 1.5 HP Bliss Hammermill at three separate timepoints to create three replications per treatment. Ground corn flowability was calculated using angle of repose (AOR), percent compressibility, and critical orifice diameter (COD) measurements to determine the composite flow index (CFI). There was no evidence for a screen size × corn moisture interaction for ground corn moisture content (MC), particle size, standard deviation, or flowability metrics. Grinding corn using a 3 mm screen resulted in decreased ($p < 0.041$) moisture content compared to corn ground using the 6 mm screen. There was a decrease ($p < 0.031$) in particle size from the 6 mm screen to the 3 mm, but no evidence of difference was observed for the standard deviation. There was a decrease ($p < 0.030$) in percent compressibility as screen size increased from 3 mm to 6 mm. Angle of repose tended to decrease ($p < 0.056$) when corn was ground using a 6 mm screen compared to a 3 mm screen. For the main effects of MC, 16.7% moisture corn had increased ($p < 0.001$) ground corn MC compared to 14.5%. The 14.5% moisture corn resulted in decreased ($p < 0.050$) particle size and an increased standard deviation compared to the 16.7% moisture corn. The increased MC of corn increased ($p < 0.038$) CFI and tended to decrease ($p < 0.050$) AOR and COD. In conclusion, decreasing hammermill screen size increased moisture loss by 0.55%, decreased corn particle size by 126 µm and resulted in poorer flowability as measured by percent compressibility and AOR. The higher moisture corn increased subsequent particle size by 89 µm and had improved flowability as measured by CFI.

Keywords: corn; hammermill; moisture content; particle size

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1. Introduction

Reducing the particle size of cereal grains is often the first step in the feed manufacturing process. This process specifically ruptures the hard-outer shell, or hull, of the grain and exposes the interior nutrient-dense endosperm and germ. The grinding process alone typically consumes 70% of the total energy used during the feed production process [1]. Hammermills are the most commonly used size-reduction equipment because of their high throughput rates and versatility in the grinding of different materials [2].

Hammermills achieve particle size reduction by utilizing impact forces to shatter larger particles into smaller particles [3]. Overall mill performance is dependent on many different factors, such as initial particle size, material, feed rate, machine configuration, and moisture content (MC) [4]. Yellow dent #2 corn at approximately 15% moisture content is the most common grain used for feed in the US. However, the MC of corn can vary greatly based on the region of origin, weather patterns, harvest conditions, and corn genetics. Changes in the MC can affect the performance of the grinding equipment, energy usage, and the characteristics of the ground material [5]. Furthermore, MC influences the cohesion and adhesion of particles which, in turn, can alter the flowability of materials [6]. Therefore, the overall objective of this study was to determine the effects of whole-corn moisture prior to grinding and hammermill screen size on subsequent ground corn moisture, particle size and flowability.

2. Materials and Methods

Whole yellow dent #2 corn with an initial MC of 14.5% was used in this experiment. Treatments were arranged as a 2 × 2 factorial design with 2 moisture levels (14.5 and 16.7%) and ground using 2 hammermill screen sizes measuring 3 mm and 6 mm in diameter. Increasing initial whole corn moisture was accomplished by adding 5% water and heating at 55 °C for 3 h in sealed glass jars using a Fisherbrand Isotemp Oven (Model 15-103-051). Whole-corn moisture was analyzed using a Dickey-John GAC 2500-UGMA. Corn was then ground using a lab-scale 1.5 HP Bliss Hammermill (Model 6K630B, Bliss Industries, LLC, Ponca City, OK, USA) 3 separate times to create 3 replications per treatment. Samples of each treatment were collected and stored in vacuum-sealed bags to minimize moisture loss and later analyzed for moisture, particle size, and flowability characteristics. Ground corn samples were analyzed for moisture according to AOAC 930.15 [7].

Particle size analysis was conducted according to the ANSI/ASAE S319.2 standard particle size analysis method with dispersing agent [8]. A 100 ± 5 g sample was sieved with a 13-sieve stainless steel sieve stack containing sieve agitators with bristle sieve cleaners and rubber balls measuring 16 mm in diameter. Each sieve was individually weighed with the sieve agitators to obtain a tare weight. An additional 0.5 g of silicon dioxide dispersing agent was mixed into the sample and then placed on the top sieve. The sieve stack was placed in a Ro-Tap machine (Model RX-29, W. S. Tyler Industrial Group, Mentor, OH, USA) and shaken for 10 min. Once completed, each sieve was individually weighed with the sieve agitator(s) to obtain the weight of sample on each sieve. The amount of material on each sieve was used to calculate the geometric mean diameter (dgw) and geometric standard deviation (Sgw) according to the equations described in ANSI/ASAE standard S319.2 [9]. The weight of the dispersing agent was not subtracted from the weight of the pan, as specified in the ANSI/ASAE S319.2. Sieves were cleaned after each analysis with compressed air and a stiff bristle sieve cleaning brush.

The flowability characteristics of ground corn samples were evaluated using the results of percent compressibility, angle of repose, and critical orifice diameter, which were then compiled into a composite flow index (CFI) using equations [10].

$$\mathrm{CFI} = y_1 + y_2 + y_3$$

where:

Y_1 to y_3 are the transformed scores for test 1 to 3.

Critical orifice diameter value (COD; y_1) = $-1.111 \times$ COD + 37.778.

Compressibility (y_2) = $-0.667 \times$ Compresibility + 36.667/

Angle of repose (AoR; y_3) = $-0.667 \times$ AoR + 50.

Angle of repose was determined by allowing a sample to flow from a vibratory conveyor above a free-standing platform until it reached its maximum piling height. The angle between the free-standing platform of the sample pile and the height of the pile was calculated by taking the inverse tangent of the height of the pile divided by the platform radius [11].

The critical orifice diameter was determined using a powder flowability test instrument (Flodex Model WG-0110, Paul N. Gardner Company, Inc., Pompano Beach, FL, USA). Fifty grams of sample was allowed to flow through a stainless-steel funnel into a cylinder. The sample rested for 30 s in the cylinder, and then was evaluated based on the flow through an opening in a horizontal disc. The discs were 6 cm in diameter and the interior hole diameter ranged from 4 to 34 mm. A negative result was recorded when the sample did not flow through the opening in the disc or formed an off-center cylindrical tunnel or rathole. The disc hole size diameter was then sequentially increased by one-disc size until a positive result was observed. A positive result was recorded when the material flowed through the disc opening, forming an inverted cone shape. If a positive result was observed, the disc hole size diameter was decreased until a negative result was observed. Three positive results were used to determine the critical orifice diameter [8].

Compressibility was determined by measuring the initial and final tapped volume. A 100 g sample was poured into a 250 mL graduated cylinder and the initial volume was recorded. The cylinder was tapped until no further change in the volume was observed. The final volume was recorded and change in compressibility calculated. The change in compressibility, expressed as a percentage, was calculated by finding the difference between the initial and final volume, dividing by the initial volume, and multiplying by 100 [8].

Data were analyzed as 2 × 2 factorial using the PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Grinding run served as the experimental unit and each treatment was replicated three times. Results were considered significant if $p \leq 0.05$, and a trend if $0.05 < p \leq 0.10$. Tukey's test was used for comparisons between treatments.

3. Results

There was no evidence for a screen size × corn moisture interaction for MC, particle size, standard deviation, or flowability metrics (Table 1). Grinding corn using a 3 mm screen resulted in decreased ($p < 0.041$) MC compared to corn ground using the 6 mm screen. There was a decrease ($p < 0.031$) in particle size from the 6 mm screen to the 3 mm, but no evidence of difference was observed for the standard deviation of the mean particle sizes. There was a decrease ($p < 0.030$) in percent compressibility as screen size increased from 3 mm to 6 mm. Angle of repose tended to decrease ($p < 0.056$) when corn was ground using a 6 mm screen compared to a 3 mm screen. For the main effects of MC, 16.7% moisture corn had increased ($p < 0.001$) ground corn MC compared to 14.5% MC corn. The 14.5% moisture corn resulted in decreased ($p < 0.029$) particle size and an increase ($p < 0.038$) in standard deviation of the mean particle size compared to the 16.7%. The 16.7% moisture corn increased ($p < 0.038$) CFI and tended to decrease ($p < 0.100$) AOR and COD.

Table 1. Effect of initial corn moisture and screen size on physical characteristics of ground corn.

Item	3 mm		6 mm		SEM [1]	Probability, *p*<		
	14.5%	16.7%	14.5%	16.7%		Screen Size	Moisture	Interaction
Moisture, %	11.7	16.4	11.9	16.6	3.15	0.041	0.001	0.805
Particle size, d_{gw} µm [2]	348	401	438	563	44.58	0.031	0.029	0.240
Standard deviation, S_{gw}	2.49	2.39	2.75	2.41	0.03	0.240	0.038	0.189
Angle of repose, ° [3]	52.07	47.21	47.24	46.00	1.35	0.056	0.055	0.219
Critical orifice diameter, mm [4]	30.0	26.0	27.3	23.3	1.79	0.175	0.056	1.00
Compressibility, % [5]	26.8	26.1	25.4	23.0	0.85	0.030	0.112	0.344
Composite flow index [6]	38.5	46.6	45.6	52.4	3.02	0.063	0.038	0.839

[1] SEM = standard error of the mean. [2] Particle size and standard deviation (Sgw) are determined according to ASABE 319.2 methods. [3] Angle of repose was determined by measuring the height and radius of the cone formed by the material and using the following equation Tan θ = height of cone (mm)/radius of cone (mm). [4] Critical orifice diameter was determined using a Flodex device to determine product mass flow characteristics through varying discharge outlet sizes. [5] The change in compressibility, expressed as a percentage, was calculated by finding the difference between the initial and final volume, dividing by the initial volume, and multiplying by 100. [6] The composite flow index is calculated by the following equation CFI = (−0.667(AoR Result) + 50) + (−0.667(%C Result) + 36.667) + (−1.111(COD Result) + 37.778).

4. Discussion

Corn particle size is a key quality measure when manufacturing feed. The experiment reported herein shows that corn of different initial MCs ground using two different screen sizes will result in different physical characteristics post grinding. Previous research [12] details the basic characteristics of grinding corn with a hammermill and the use of screens to control subsequent particle size. The decrease in particle size observed from the 6 mm screen to the 3 mm was expected. To achieve the increased particle size reduction, material may spend more time in the grinding chamber to reach the desired particle size [13]. The observed loss in MC with a larger reduction in particle size can be attributed to this increase in grind time, as more frictional heat is generated, causing more moisture and energy efficiency to be lost [14].

It has previously been described that increased MC influences the breaking behavior of material during the grinding process [15,16]. The results of the experiment reported herein suggest that as MC decreased, the Sgw of the ground material increased. The increase in MC and subsequent reduction in Sgw can be explained as a lower MC corresponds with a harder product to be ground. The hardness of the kernels impacts the shatter patterns of grain and, therefore, increases the production of fine particles as well as the overall variation in the ground material. Previous research evaluated corn as well as corn cobs at three different moisture contents, looking at grinding performance and the characteristics of the ground material [5]. An increase in post-grinding moisture loss as well as an increase in Sgw was observed as initial MC increased. A similar loss of moisture post grinding was seen in the experiment reported herein; however, corn with a 16.7% initial MC resulted in a smaller Sgw or a more uniform grind.

The particle size of the material as well as its distribution can cause segregation during handling and affects the flowability of materials [17]. Kalivoda et al. [8] reported that a reduction in particle size corresponded with poorer flowability characteristics, caused predominantly by fine particles or particles measuring less than 150 microns. The shape of these fine particles may be the main cause of their negative impacts on flowability [18]. Previous research details the characteristics of particles that may cause poor flowability, such as particle size, shape, density, and surface, among other factors [10]. Small or fine particles are a significant flowability concern due to the attractive forces between particles. Smaller particles result in a smaller distance between individual particles. Therefore, the cohesion forces between particles, primarily due to the Van der Waals attraction, is stronger and results in poorer flowability [19]. In the experiment reported herein, flowability was measured using angle of repose, percent compressibility, and critical orifice diameter. These analyses evaluate different characteristics of ground materials. Angle of repose corresponds to the inner-particulate friction or the resistance to movement between particles [20]. The percent compressibility is defined as an indication of the incremental, volumetric, structural and/or increase in external forces [21]. Critical orifice diameter is a method that employs a cylinder with a series of interchangeable base plate discs with different diameter orifices. The critical orifice diameter is the size of the smallest orifice in a base plate disc through which the powder in a cylinder will discharge, and is a direct measure of powder cohesiveness and arch strength [22]. These measurements were then compiled into a composite flow index using the equations [10]. A single value of flowability that considers all evaluations can be beneficial when evaluating flowability results, as it can demonstrate the overall rating as well as individual characteristics of ground material and where problems may arise. A previously reported scale [10] helps to further understand the results of the composite flow index. A score of less than 15 corresponds to very, very poor flowability, while a score over 85 results in an excellent rating. A powder with a composite flow index of 45 or greater is considered passable. In the experiment reported herein, all treatments met this standard, with the exception of 14.5% moisture corn that was ground using the 3 mm screen, which had a poor rating.

While energy consumption and animal performance were not evaluated in the experiment reported here in, there is evidence that MC can have an impact on mill efficiency and animal performance [23]. Tran et al. [24] found a linear relationship between MC and grinding energy that decreased with increased moisture content. This decrease in energy consumption is due to lower MCs, resulting in a harder product to be ground. However, Armstrong et al. [25] reported that changes in grinding energy consumption are more predictable in the region of from 10 to 13% moisture content. Commercial swine diets are fed on an as-is basis and corn makes up a large percentage of the complete diet. Therefore, increasing the moisture content of the corn dilutes the concentrations of nutrients provided by the corn. Further research is needed on the impact of moisture content in field conditions as well as changes in the grinding system on the particle size of corn, as well as the energy consumption and possible impacts on animal performance.

5. Conclusions

This experiment shows the different initial moisture content when corn samples are ground using two different screen sizes on a hammermill will lead to different physical characteristics post-grinding. Decreasing screen size decreased particle size and resulted in poorer flowability. A CFI of greater than 45 is considered passable and all treatments met this standard, except 14.5% moisture corn that was ground using the 3 mm screen. When corn was ground using the 3 mm screen, a 0.55% moisture loss was observed compared to the 6 mm screen, regardless of the initial corn moisture. Increasing the initial corn moisture resulted in increased particle size and an improved standard deviation, which created improved flow characteristics.

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