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Evaluation of Hammermill Tip Speed, Air Assist, and Screen Hole Diameter on Ground Corn Characteristics

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Abstract: This study was performed to evaluate hammermill tip speed, assistive airflow, and screen hole diameter on hammermill throughput and characteristics of ground corn. Corn was ground using two Andritz hammermills measuring 1 m in diameter each equipped with 72 hammers and 300 HP motors. Treatments were arranged in a 3 × 3 × 3 factorial design with three tip speeds (3774, 4975, and 6176 m/min), three screen hole diameters (2.3, 3.9, and 6.3 mm), and three air flow rates (1062, 1416, and 1770 fan revolutions per minute). Corn was ground on three separate days to create three replications and treatments were randomized within day. Samples were collected and analyzed for moisture, particle size, and flowability characteristics. There was a 3-way interaction ($p = 0.029$) for standard deviation (S_{gw}). There was a screen hole diameter × hammer tip speed interaction ($p < 0.001$) for geometric mean particle size d_{gw} ($p < 0.001$) and composite flow index (CFI) ($p < 0.001$). When tip speed increased from 3774 to 6176 m/min, the rate of decrease in dgw was greater as screen hole diameter increased from 2.3 to 6.3 mm. For CFI, increasing tip speed decreased the CFI of ground corn when ground using the 3.9 and 6.3 mm screen. However, when grinding corn using the 2.3 mm screen, there was no evidence of difference in CFI when increasing tip speed. In conclusion, the air flow rate did not influence d_{gw} of corn, but hammer tip speed and screen size were altered and achieved a range of d_{gw} from 304 to 617 µm.

Keywords: corn; hammermill; moisture content; particle size

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1. Introduction

Particle size reduction is one of the basic steps in processing grains [1]. Animal feed undergoes particle size reduction for many reasons such as expediting feed consumption, improving nutrient absorption, and reducing material handling and labor costs by facilitating easier transport of products [2,3]. As more information has become available on particle size and its influence, the knowledge of what is needed to optimize animal performance has also grown. This increase in understanding along with improved capabilities of grinding equipment has led to interest for targeting specific particle sizes for various species and growth stages. While this may seem a reasonable ask of the feed mill, there are limitations to what can be achieved.

Hammermills have become a cost-effective choice that offer the flexibility to create a wide range of particle sizes [4]. Hammermills consist of a rotor assembly within a screened chamber that houses hammers that rotate with the rotor assembly [5]. Particle size reduction is achieved by utilizing a combination of impact, shear, and compression forces exerted by the hammers in the grinding chamber with the largest proportion because of impact [6–8]. The most common method to alter the particle size when grinding with a hammermill would be to change the screens. The screen prevents ground material from leaving the chamber before it is properly sized to the size of the perforation holes of the screen. However, while screen changes are the most common, there are other options that can make smaller and more precise particle size adjustments without the added down time. Alternative solutions to controlling corn particle size and characteristics of the ground material are tip speed and air assist adjustments via a variable frequency drive (VFD). Adjusting the hammer tip speed allows for a range of particle sizes to be achieved with the same screen hole diameter being in place. Additionally, air assist systems are commonly installed in combination with hammermills to aid with removing sized particles from the grinding chamber. Adjusting the rate at which the air assist system is operating could also impact the final particle size by manipulating the time material spends in the grinding chamber [9]. As more air passes through the grinding chamber, sized particles will be removed from the chamber faster before more reduction occurs. All of these factors can potentially affect the particle size, standard deviation, and flowability characteristics of the resulting ground material. There is the potential to allow for a range of particle sizes to be achieved from one screen hole diameter, however with these changes a decrease in handling characteristics may be possible. Therefore, the objective of this study was to evaluate the effect of hammermill tip speed, assistive airflow rate, and screen hole diameter on hammermill throughput and characteristics of the ground material.

2. Materials and Methods

Whole yellow dent #2 corn was ground, and samples were collected at the JBS Live Pork LLC feed mill in Fremont, IA. Corn was ground using two 1-m Andritz hammermills (Model: 4330-6, Andritz Feed & Biofuel, Muncy, PA, USA). Both mills discharged to a shared plenum where samples were collected via a sample port. Each mill was equipped with 72 hammers and 300 HP motors on a VFD. Corn was ground on 3 separate days to create 3 replications per treatment and treatments were randomized within replication. A new lot of corn was used each day and corn moisture content was 15.4, 13.8, and 14.05% for day 1, 2, and 3, respectively. Treatments were arranged in a $3 \times 3 \times 3$ factorial design with 3 tip speeds (3774, 4975, and 6176 m/min), 3 screen hole diameters (2.3, 3.9, and 6.3 mm), and 3 air assist system fan RPM (1062, 1416, and 1770 fan RPM).

Motor load and outlet temperatures were recorded for both mills at three separate time points during each grinding run via the Repete operating system (Repete Corp., Sussex, WI, USA). Air flow was measured using a hot wire anemometer (PerfectPrime Model WD9829) and taken between the baghouse and grinders. Samples of each treatment were collected and analyzed for moisture, particle size, and flowability characteristics. Ground corn samples were analyzed for moisture according to the AOAC method [10].

Particle size analysis was conducted according to the ANSI/ASAE [11] standard particle size analysis method as described by Kalivoda [12]. 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 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 tapped 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 d_{gw} and S_{gw} according to the equations described in ANSI/ASAE standard S319.2 [10]. The weight of the dispersing agent was not subtracted from the weight of the pan as specified in the ANSI/ASAE S319.2 [10]. 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 previously described [13].

$$CFI = y_1 + y_2 + y_3$$

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 [14]. 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 it was then 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 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 [12].

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 was 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 [12].

Data were analyzed as a $3 \times 3 \times 3$ factorial using the PROC GLIMMIX procedure of SAS (SAS Institute Inc., Cary, NC) with grinding run serving as the experimental unit and day of sample collection serving as the block. Contrast statements were used to separate treatment means with the comparison of the main effects screen (2.3 vs. 3.9 vs. 6.3), tip speed (3774 vs. 4975 vs. 6176), and air flow rate (1062 vs. 1416 vs. 1770). Linear and quadratic polynomials were used to test increasing parameters within each main effect. Results were considered significant if $p \leq 0.05$.

3. Results

There were no 3-way interactions for screen hole diameter $\times$ hammer tip speed $\times$ air flow for the d_{gw} or any flowability characteristics of ground corn (Table 1). However, there was a screen hole diameter $\times$ hammer tip speed $\times$ air flow interaction for S_{gw} ($p = 0.029$). When corn was ground using the 2.3 mm screen, increasing hammer tip speed decreased S_{gw} when the air assist setting was 1062 RPM. However, increasing tip speed did not influence S_{gw} when the air assist was set at 1416 or 1770 RPM. Furthermore, there was no evidence of difference in the S_{gw} when air assist was increased and corn was ground using hammer tip speeds of 3774, 4975, or 6176 m/min. When grinding with the 3.9 mm screen, increasing hammer tip speed reduced S_{gw}. However, the rate of S_{gw} reduction was greater when the air flow was increased. In addition, increasing the air flow rate from 1062 to 1770 RPM increased S_{gw} when corn was ground using a tip speed of 3774 m/min; however, there was no difference in air flow when a tip speed of 6176 was used. When corn was ground using the 6.3 mm screen, there was no evidence of difference in S_{gw} when increasing hammer tip speed when the air assist was set at 1062 RPM. Increasing hammer tip speed increased S_{gw} when the air assist was set at 1416 RPM, and increasing hammer tip decreased S_{gw} when the air assist motor was set at 1770 RPM. Furthermore, increasing air flow at hammer tip speeds of 3774 and 4975 m/min increased S_{gw} but no difference was observed at 6176 m/min.

There was a linear screen hole diameter × linear hammer tip speed interaction ($p = 0.001$) for d_{gw} (Table 2). When tip speed increased from 3774 to 6176 m/min the rate of decrease in d_{gw} was greater as screen hole diameter increased from 2.3 to 6.3 mm resulting in a 67, 111, and 254 µm decrease in d_{gw} for corn ground using the 2.3, 3.9, and 6.3 mm screen hole diameter, respectively. There was a linear screen hole diameter × linear hammer tip speed interaction was also observed for COD ($p = 0.018$). When grinding using a hammer tip speed of 3774 m/min a decrease in COD was observed as screen hole diameter increased from 2.3 mm to 6.3 mm, but as tip speed increased to 4975 and 6176 m/min no differences in COD were observed with increasing screen hole diameter. Additionally, an interaction of screen hole diameter and hammer tip speed was observed for percent compressibility (Quadratic × Linear, $p = 0.015$). Increasing screen hole diameter had a quadratic effect on percent compressibility and increasing hammer tip speed decreased percent compressibility when using the 2.3 mm screen but increased with the 3.9 mm and 6.3 mm screens. Furthermore, an interaction of screen hole diameter and hammer tip speed was also observed for the composite flow index (Linear × Linear, $p = 0.040$). Composite flow index results increased with increasing screen hole diameter when corn was ground using a hammer tip speed of 3774 m/min but no differences were observed as tip speed increased to 4975 and 6176 m/min. An interaction of screen hole diameter and hammer tip speed was observed for mill motor load (Quadratic × Quadratic, $p = 0.001$). Mill motor load was decreased as screen hole diameter increased from 2.3 mm to 6.3 mm but increased as hammer tip speed was increased with the most significant reductions being observed as tip speed was increased from 3774 m/min to 4975 m/min on the 2.3 mm screen. Last, an interaction of screen hole diameter and hammer tip speed was observed for mill outlet temp (Linear × Linear, $p < 0.036$), where mill outlet temperature decreased as screen hole diameter was increased. However, as hammer tip speed was increased on the 2.3 mm screen mill outlet temperature decreased, where on the 3.9 mm and 6.3 mm screens increasing hammer tip speed resulted in increased outlet temperatures.

A significant interaction of screen hole diameter and air flow was observed for the compressibility (Quadratic × Linear, $p < 0.046$) and composite flow index (Linear × Linear, $p < 0.026$) results (Table 3). Compressibility results increased as air flow rate was increased on the 2.3 mm and 6.3 mm screens but decreased as air flow was increased on the 3.9 mm screen. Furthermore, screen hole diameter increased percent compressibility in a quadratic fashion with the highest measurements resulting from the 3.9 mm screen. The CFI increased as screen hole diameter was increased and increased as air flow was increased on the 2.3 mm and the 3.9 mm but decreased with increasing air flow on the 6.3 mm screen. There were no hammer tip speed by air flow interactions.

Table 1. Influence of 3-way interaction of screen hole diameter × hammer tip speed × air flow on the particle size and standard deviation of hammermilled corn [1].

Screen Hole Diameter, mm [2]		**2.3**			**3.9**			**6.3**			**Probability, $p <$** [6]
Hammer Tip Speed, m/min [3]	**3774**	**4975**	**6176**	**3774**	**4975**	**6176**	**3774**	**4975**	**6176**	**SEM**	
Particle size, μm [5]											
Air flow [4]											
1062	344	341	296	443	395	334	580	437	380		
1416	361	314	273	477	390	336	652	437	357	25.26	0.227
1770	408	330	342	433	389	349	620	452	351		
Standard deviation, S_{gw} [5]											
Air flow											
1062	3.07	2.97	2.86	3.25	3.03	2.93	3.10	3.21	3.23		
1416	2.97	2.82	2.89	3.05	2.91	2.87	2.89	3.07	3.24	0.086	0.029
1770	3.13	2.97	2.97	3.47	3.13	2.97	3.54	3.46	3.27		

[1] Treatments were arranged in a 3 × 3 × 3 factorial design with main effects of tip speed, screen hole diameter, and air flow rate. Each treatment was replicated 3 times. [2] Corn was ground using screen hole diameters of 2.3, 3.9 or 6.3 mm. [3] Corn was ground using three motor speeds: 1100, 1450, or 1800 rpm. Hammer tip speed was then calculated by multiplying π by the hammermill diameter (m) and motor speed (rpm). [4] Corn was ground using three air flow settings of 1062, 1416, or 1770 fan RPM. [5] Particle size and standard deviation (S_{gw}) are determined according to ASABE 319.2 methods. [6] For the standard deviation result, a linear screen hole diameter × linear tip speed × linear air flow response was observed.

Table 2. Influence of 2-way interaction of screen hole diameter × hammer tip speed on the energy consumption, particle size, and flowability of hammermilled corn [1].

Screen Hole Diameter, mm [2]		**2.3**			**3.9**			**6.3**		**Probability, *p* <**
Tip Speed, m/min [3]	**3774**	**4975**	**6176**	**3774**	**4975**	**6176**	**3774**	**4975**	**6176**	**SEM**	
Physical Analysis											
Particle size, µm	371 ^{cd}	328 ^{ef}	304 ^{f}	451 ^{b}	391 ^{c}	340 ^{def}	617 ^{a}	442 ^{b}	363 ^{cde}	15.73	0.001 *
Standard deviation, S_{gw}	3.05 ^{b}	2.92 ^{a}	2.90 ^{c}	3.25 ^{c}	3.02 ^{bc}	2.92 ^{c}	3.17 ^{a}	3.24 ^{a}	3.24 ^{a}	0.064	0.002 *†
Critical orifice diamete r [4]	32.4 ^{ab}	31.7 ^{ab}	32.8 ^{a}	31.1 ^{b}	30.8 ^{b}	31.7 ^{ab}	29.1 ^{c}	31.5 ^{ab}	32.2 ^{ab}	0.576	0.018 *
Compressibility, % [5]	18.34 ^{abc}	19.01 ^{ab}	17.25 ^{bc}	16.96 ^{c}	19.75 ^{a}	19.33 ^{a}	18.96 ^{ab}	18.52 ^{abc}	19.49 ^{a}	0.641	0.015 †
Composite flow index [6]	46.14 ^{c}	45.91^{c}	45.75 ^{c}	49.34 ^{ab}	46.91 ^{bc}	45.43 ^{c}	51.53 ^{a}	47.58 ^{bc}	46.43 ^{bc}	1.264	0.040 *
Energy											
Motor Load, kW	147.07 ^{a}	102.41 ^{b}	99.39 ^{b}	89.58 ^{c}	88.96 ^{c}	89.73 ^{c}	76.01 ^{d}	76.16 ^{d}	78.21 ^{d}	2.677	0.001 ‡
Mill Temp, °C	29.81 ^{a}	27.58 ^{cd}	29.00 ^{abc}	27.46 ^{d}	28.06 ^{bcd}	29.67 ^{a}	27.01 ^{d}	28.34 ^{abcd}	29.21 ^{ab}	0.960	0.036 *¶

[1] Treatments were arranged in a 3 × 3 × 3 factorial design with main effects of tip speed, screen hole diameter, and air flow rate. Each treatment was replicated 3 times. [2] Corn was ground using screen hole diameters of 2.3, 3.9 or 6.3. [3] Corn was ground using three motor speeds: 1100, 1450, or 1800 rpm. Hammer tip speed was then calculated by multiplying π by the hammermill diameter (mm) and motor speed (rpm). [4] Critical orifice diameter was determined using a Flodex device to determine product mass flow characteristics through varying discharge outlet sizes. [5] Percent compressibility is calculated by using the Hausner ratio (PTapped/PBulk). [6] The composite flow index is calculated by the following equation CFI = (−0.667(AoR Result) + 50) + (−0.667(%C Result) + 36.667) + (−1.778(COD Result) + 37.778). * Denotes Linear Screen hole diameter × Linear Tip Speed response. ¶ Denotes Linear Screen hole diameter × Quadratic Tip Speed response † Denotes Quadratic Screen hole diameter × Linear Tip Speed response ‡ Denotes Quadratic Screen hole diameter × Quadratic Tip Speed response. ^{abcdef} Within a row, means without a common superscript differ ($p < 0.05$).

Table 3. Influence of 2-way interaction of screen hole diameter × air flow on the compressibility and composite flow index of hammermilled corn [1].

Screen Hole Diameter, mm [2]		**2.3**			**3.9**			**6.3**		**Probability, *p* <**
Air flow, RPM [3]	**1062**	**1416**	**1770**	**1062**	**1416**	**1770**	**1062**	**1416**	**1770**	**SEM**	
Physical Characteristic											
Compressibility, % [4]	17.52 ^{b}	18.37 ^{b}	18.71 ^{ab}	19.03 ^{ab}	18.65 ^{ab}	18.36 ^{b}	18.15 ^{b}	18.44 ^{b}	20.39 ^{a}	0.641	0.046 †
Composite flow index [5]	45.48 ^{cd}	44.62 ^{d}	47.69 ^{abc}	46.12 ^{bcd}	46.51 ^{bcd}	49.05 ^{ab}	50.07 ^{a}	47.72 ^{abc}	47.76 ^{abc}	1.264	0.026 *

[1] Treatments were arranged in a 3 × 3 × 3 factorial design with main effects of tip speed, screen hole diameter, and air flow rate. Each treatment was replicated 3 times. [2] Corn was ground using screen hole diameters of 2.3, 3.9, or 6.3 mm. [3] Corn was ground using three air flow settings of 1062, 1416, or 1770 fan RPM. [4] Percent compressibility is calculated by using the Hausner ratio (PTapped/PBulk). [5] The composite flow index is calculated by the following equation CFI = (−0.667(AoR Result) + 50) + (−0.667(%C Result) + 36.667) + (−1.778(COD Result) + 37.778). * Denotes Linear Screen hole diameter × Linear Air Flow response. † Denotes Quadratic Screen hole diameter × Linear Air Flow response. ^{abcd} Within a row, means without a common superscript differ ($p < 0.05$).

4. Discussion

Corn particle size, or geometric mean diameter (d_{gw}), and geometric standard deviation (S_{gw}) are key quality measures when manufacturing feed. The experiment reported herein shows that varying equipment and settings used during the grinding process will produce different physical characteristics post grinding. Previous research details the basic characteristics of grinding with a hammermill and the use of screens to control grind size [4]. The decrease in particle size observed from the 6.3 mm to the 2.3 mm screen is to be expected as decreasing screen hole diameter will increase the time material spends in the grinding chamber [15]. This decrease in screen hole diameter also increased energy consumption. This was also expected as grinding to obtain smaller particles will increase the amount of time spent in the grinding chamber and therefore energy consumption [16,17]. As the time spent in the grinding chamber increases friction becomes increasingly significant as particles contact the hammers as well as the surface of the screen which leads to increased fragmentation of particles [18]. Increased time spent in the grinding chamber can be a result of many factors. Decreased screen hole diameter as previously mentioned, as well as hammer tip speed and the rate of assistive air flowing through the grinding chamber can all effect the grinding time. As hammer tip speed is increased, the impact forces exerted by the hammers is increased and causes a more severe shatter pattern of the grain [19]. Research also found that increasing hammer tip speed and screen hole diameter increased hammermill through put [20]. While an interaction of the two factors was not evaluated in that study, an interaction of screen hole diameter and hammer tip speed on the energy used by the grinders was observed in the experiment reported herein. Furthermore, increasing screen hole diameter was shown to increase d_{gw} and S_{gw} as well as impact flow characteristics.

Increasing in grinding time and therefore fragmentation of particles results in a greater proportion of fine, flour-like particles. There is evidence that an increase in fine particles negatively impacts the flowability of ground material. Kalivoda et al. [12] reported a reduction in particle size that corresponded with poorer flowability characteristics caused predominantly by fine particles. A similar reduction in flow properties was observed with changes in screen hole diameter, hammer tip speed, and assistive air flow rate. According to a scale developed by Horn et al. [13], flowability decreases as CFI and angle of repose increases. In the experiment reported herein increasing screen hole diameter or air flow decreased the angle of repose while increasing tip speed increased AoR (Table 4). The particle size of material as well as its distribution can cause segregation during handling and affects the flowability of materials [21]. Haque [22] also suggested that flow properties are impacted more so by the physical characteristics of ground material rather than any chemical properties. This includes the d_{gw}, S_{gw}, particle shape, and electrostatic charge [22].

In the experiment reported herein, a three-way interaction of screen hole diameter, hammer tip speed, and assistive air flow rate was observed for the S_{gw} of corn ground using a hammermill. There are few published data evaluating screen hole diameter, hammer tip speed, and air assist simultaneously. There is a particular lack of understanding of the impact of air assist on ground material characteristics. Previous research determined that applying air flow through a hammer mill aids to improve the capacity of the mill as well as achieve a more uniform grind, or lower S_{gw} [9]. This was demonstrated in the experiment reported herein as a quadratic response of the main effect of air flow where the S_{gw} of corn ground using the median air flow setting resulted in the lowest S_{gw} value followed by the low and then high setting respectively. This result was unexpected as increased assistive air flow rate should aid to remove appropriately sized particles from the grinding chamber faster and therefore reduce the amount of time particles are subject to grinding forces. The magnitude of the response however was dependent on the screen hole diameter and hammer tip speed. Along with the response of S_{gw} to different air flows, a significant decrease in angle of repose was seen with an increase to the maximum air flow setting as well as an interaction of screen hole diameter and air flow on the CFI of ground corn. It can be hypothesized that an increase in fine particles created from increased time spent in the grinding chamber influenced the responses of S_{gw} and flowability characteristics as a result of assistive air flow rate.

Table 4. Influence of main effects of screen hole diameter, tip speed, and air flow on energy consumption, particle size, and flowability of hammermilled corn [1,2,3,4].

	Screen Hole Diameter, mm			Tip Speed, m/min			Air Flow, RPM				*p*-Value		
	2.3	**3.9**	**6.3**	**3774**	**4975**	**6176**	**1062**	**1416**	**1770**	**SEM**	**Screen**	**Tip**	**AS**
Physical Analysis													
Particle size d_{gw}, µm [5]	334 ^{c}	394 ^{b}	474 ^{a}	480 ^{a}	381 ^{b}	335 ^{c}	394	400	408	10.83	0.001 *	0.001 *	0.477
Standard deviation, S_{gw}	2.96 ^{c}	3.06 ^{b}	3.22 ^{a}	3.16 ^{a}	3.06 ^{b}	3.02 ^{b}	3.07 ^{b}	2.96 ^{c}	3.21 ^{a}	0.033	0.001 *	0.001 *	0.001 †
Angle of repose, ° [6]	45.57 ^{a}	45.01 ^{a}	43.26 ^{b}	43.55 ^{b}	44.98 ^{a}	45.30 ^{a}	44.84 ^{a}	45.75 ^{a}	43.25 ^{b}	1.034	0.002 *	0.025 *	0.004 †
Critical orifice diameter [7]	32.37 ^{a}	31.25 ^{b}	30.96 ^{b}	30.88 ^{b}	31.40 ^{ab}	32.29 ^{a}	31.62	31.77	31.18	0.337	0.010 *	0.014 *	0.424
Compressibility, % [8]	18.20	18.68	18.99	18.09	19.09	18.69	18.23	18.49	19.15	0.370	0.322	0.163	0.200
Composite flow index [9]	45.93 ^{a}	47.23 ^{ab}	48.52 ^{a}	49.00 ^{a}	46.80 ^{a}	45.87 ^{b}	47.23	46.28	48.17	0.912	0.018 *	0.002 *	0.109
Moisture, %	13.9	13.7	16.6	13.9	13.5	16.7	13.8	13.6	16.8	0.686	0.439	0.383	0.368
Energy													
Motor Load, kW	116.29 ^{a}	89.43 ^{b}	76.05 ^{c}	104.21 ^{a}	89.18 ^{b}	88.37 ^{b}	92.64	93.74	95.41	1.969	0.001 *	0.001 *	0.311
Mill Temp, °C	28.80	28.40	28.19	28.09 ^{b}	27.99 ^{b}	29.30 ^{a}	28.27	28.53	28.57	0.538	0.377	0.007 *	0.754
Fan Speed, m/min	17.39	19.10	17.45	17.72	18.45	17.78	13.87 ^{c}	17.79 ^{b}	22.27 ^{a}	1.309	0.380	0.842	0.001 *

[1] Treatments were arranged in a 3 × 3 × 3 factorial design with main effects of tip speed, screen hole diameter, and air flow rate. Each treatment was replicated 3 times. [2] Corn was ground using screen hole diameters of 2.3, 3.9, or 6.3. [3] Corn was ground using three motor speeds: 1100, 1450, or 1800 rpm. Hammer tip speed was then calculated by multiplying π by the hammermill diameter (mm) and motor speed (rpm). [4] Corn was ground using three air flow settings of 1062, 1416, or 1770 fan RPM. [5] Particle size and standard deviation (Sgw) are determined according to ASABE 319.2 methods. [6] 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). [7] Critical orifice diameter was determined using a Flodex device to determine product mass flow characteristics through varying discharge outlet sizes. [8] Percent compressibility is calculated by using the Hausner ratio (PTapped/PBulk). [9] The composite flow index is calculated by the following equation CFI = (−0.667(AoR Result) + 50) + (−0.667(%C Result) + 36.667) + (−1.778(COD Result) + 37.778). * Denotes Linear Screen hole diameter × Linear Air Flow response. † Denotes Quadratic Screen hole diameter × Linear Air Flow response. ^{abc} Within a row and main effect, means without a common superscript differ ($p < 0.05$).

While no nutritional values were evaluated in this experiment, it is a significant consideration for optimum animal performance. The positive impacts reduced particle size have on swine has been widely reported. Healey et al. [23] observed improvement in the performance of pigs when corn was reduced from 1000 to 500 micron. Callan et al. [24] demonstrated improved feed conversion when finishing pigs were fed a complete diet ground through a 3 mm screen compared to a 6mm hammermill screen. For poultry, decreasing the d_{gw} of diets showed no effect when fed to broilers or turkey poults [25,26]. However, increasing the S_{gw} to include a larger portion of large particles was shown to improve broiler performance [27]. This improvement is driven by the larger particles stimulating gizzard development [28].

5. Conclusions

In summary, the results of the experiment reported herein show that hammer tip speed and air flow rate are viable options for adjusting ground material characteristics when grinding using a hammermill alongside the traditional screen variations. This experiment showed when using a 2.3, 3.9, and 6.3 mm screens at hammer tip speeds of 3774, 4975, and 6176 m/min as well as air flow settings of 1062, 1416, and 1770 that a wide range of particle sizes can be achieved. Along with the range of particle sizes capable of being produced, an increased level of accuracy can also be achieved with hammer tip speed and air flow adjustments with minimizing the down time necessary for screen changes. However, while increasing hammer tip speeds gives added flexibility, there are negatives that should be considered. Increasing the hammer tip speed with a VFD will increase the energy usage, as motor load will be increased especially on screens will smaller hole diameters. Furthermore, results of this study showed that when grinding using a 3.9 or 6.3 mm screen hole diameter, increasing hammer tip speed decreased the flowability of ground corn. However, increasing the air assist rate helped to improve the flowability characteristics.

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