Influence of feed additives and feed processing techniques on monogastric nutrition

by

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Abstract

A total of 5 experiments were conducted to evaluate the influence of feed additives and processing techniques on monogastric nutrition. First, 2 experiments were conducted to assess how multicarbohydrase inclusions affected the digestibility and growth performance of broiler chickens. A 150 kcal/kg and 151 kcal/kg increase in AME and AMEn, respectively, were observed with the inclusion of the proprietary enzyme blend 1 when compared to the control diet. Additional enzyme blends were tested in experiment 2, and no evidence of a growth response was observed.

The second objective pertained to determining the optimal conditioning temperature and die specifications when pelleting diets for nursery pigs. Treatments consisted of a mash control (MC) and 6 pelleted treatments manufactured using 2 different pellet dies (length/diameter [L:D]: 6.7 and 2.7) and 3 different conditioning temperatures (low, medium, high). Overall, pelleted diets showed poorer ADG (P = 0.049), decreased ADFI (P = 0.001) and improved G:F (P = 0.020) and no differences in final BW compared to the MC. There was also a decrease in pellet quality when treatments were manufactured on the 2.7 L:D die; however, these differences did not result in a growth performance response due to conditioning temperature or die. In conclusion, pelleting diets improves G:F but care should be taken when pelleting at high conditioning temperature when considering available lysine.

The third objective evaluated how changing variables when grinding corn influences subsequent corn particle size and flow ability. Experiment 1 determined the effects of whole corn moisture and hammermill screen size on subsequent ground corn particle size and flowability. As received (14.5% moisture) corn resulted in decreased (P < 0.029) particle size and an increased standard deviation compared to the high moisture (16.7% moisture) corn. Increased moisture content of corn increased ($P < 0.038$) composite flow index and tended to decrease ($P < 0.055$) angle of repose and critical orifice diameter ($P = 0.056$). Decreasing hammermill screen size increased moisture loss by 0.55%, corn particle size by 126 µm, and resulted in poorer flowability as measured by percent compressibility and angle of repose. High moisture corn increased subsequent particle size by 89 µm, therefore improving flowability as measured by CFI. For experiment 2, the effect of hammermill tip speed, assistive air flow rate and screen hole diameter on hammermill throughput and characteristics of the ground corn material was determined. Treatments were arranged in a 3 × 3 × 3 factorial design with 3 tip speeds (755, 995, 1,235 m/s), 3 screen hole diameters (2.3, 3.9, 6.3 mm) and 3 air assist system settings (60, 80, and 100% of fan motor load). Increasing screen hole diameter linearly increased ($P = 0.001$) corn particle size whereas increasing hammer tip speed linearly decreased ($P = 0.001$) particle size. The main effect of assistive air flow did not significantly impact corn particle size. In conclusion, adjusting hammer tip speed is a viable method of reducing particle size. With increased hammer tip speed come flowability concerns but these can be lessened with increased air assist.

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Acknowledgements

I would like to dedicate this thesis to the many, many people who supported me over the last 2 years. To my dad and sister, thank you for pretending to know what I was working on and letting me be the black sheep in a family of engineers. To the friends who are basically family at this point, thank you for always being there for when I needed you and being patient with me when I had to check chickens instead of making plans together. To all of my grad student cohorts, nothing in this thesis would be possible without all of you and the willingness to help at the drop of a hat. And of course, thank you to my dog Oakley for always letting me know when it was time to stop writing and play ball.

Chapter 1 - Effect of multicarbohydrase inclusion on the growth performance and digestibility of broilers

ABSTRACT

Two experiments were conducted to evaluate the effect of multicarbohydrase inclusion on broiler growth performance, AME and AMEn. In Exp. 1, a total of 600 one-day old, male (Cobb 500; initial BW 41 g) broiler chicks were housed in 6 Petersime batteries and used in an 18-d digestibility study. Birds were randomly assigned to battery cages with 5 birds per cage. Cages were then randomly allotted to 1 of 8 treatments within location block and balanced by BW with 15 replicates per treatment. Treatment diets consisted of a control and the control plus 1 of 7 multicarbohydrase enzyme blends (200 g/tonne). There was an overall effect ($P < 0.026$) for AME and AMEn. The diet containing enzyme 1 had a 150 kcal/kg and 151 kcal/kg increase in AME and AMEn respectively when compared to the control diet. In Exp. 2, a total of 1,260 one-day old, male (Cobb 500; initial BW 44g) broiler chickens were used in a 42-d growth study. Birds were randomly assigned to floor pens with 15 birds per pen. Pens were then randomly assigned to 1 of 6 treatments within location block and balanced by BW with 14 replications per treatment. Treatment diets consisted of a positive control (PC), negative control (NC), and the NC with 1 of 4 multicarbohydrase enzyme blends. The NC was formulated to have 111 kcal/kg less metabolizable energy [ME]than the PC. Enzyme blends A, B, C, and D were added at a rate of 200, 200, 200, and 100 g/tonne, respectively. From d 0 to 42, no differences were detected for ADG or ADFI. Broilers fed the PC diet had improved ($P < 0.01$) FCR compared to those fed the NC and the NC containing enzymes A, B, or C, with birds fed NC plus D being intermediate. There were no significant differences in the calculated productivity index. In conclusion, the

addition of an enzyme blend produced an increase in AME and AMEn in experiment 1 but no response in growth was observed with the addition in experiment 2.

KEY WORDS

Multicarbohydrase, broiler, digestibility, growth performance

INTRODUCTION

As time and feed additive technology has progressed, the interest in exogenous enzyme supplementation in animal feed has grown tremendously. The swine and poultry industries have investigated ways to utilize these enzymes to improve animal performance. Carbohydrase enzymes specifically have value for their ability to aid in the digestion of corn-based diets. A carbohydrase can be defined as any enzyme that can catalyze a reduction in the molecular weight of a polymeric carbohydrate (Adeola and Cowieson, 2011). There are many different variations of these carbohydrase enzymes such as xylanase, amylase, and glucanase. These enzymes can be added individually or in combination in attempts to improve nutrient digestion and poultry performance. Cowieson and Ravindran (2008) previously demonstrated an increase in broiler BW gain and feed intake when diets were supplemented with a blend of xylanase, amylase, and protease. A similar response of increased gain, feed intake and feed efficiency was observed by Olukosi et al. (2007a) when broilers were fed a wheat and rye based diet supplemented with xylanase. However, contradicting data reported by Olukosi and Adeola (2008) as well as Olukosi et al. (2008a, b) observed no response in growth performance to the supplementation of carbohydrases. These studies utilized diets formulated with either corn or wheat and varying energy densities with blends of xylanase, amylase, protease, and phytase. The variability in responses to enzyme supplementation may depend on various factors, such as diet energy density, enzyme type and combination, and feed manufacturing process. There is evidence that suggests broiler diets supplemented with a combination of enzymes could further increase nutrient utilization (Khattak, 2006). Therefore, two studies were conducted to evaluate the effects of the addition of multicarbohydrase enzymes in broilers. The first experiment was conducted to evaluate the effect of 7 multicarbohydrase enzyme blends on the AME and AMEn of broilers over an 18-day period. The second experiment examined the influence of 4 multicarbohydrase enzyme blends on growth performance of broilers fed diets with decreased energy density.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at Kansas State University (United States) reviewed and approved the protocol for all experiments discussed.

Exp. 1 Multi-Carbohydrase Enzymes on Broiler Nitrogen-Corrected Apparent Metabolizable Energy

Animals and Management

A total of 600 one-day old, male Cobb 500 broiler chickens were randomly assigned to pens within 6 Petersime batteries at the Kansas State University Poultry Facility (Manhattan, KS). Pens were randomly assigned to 8 treatments within location block and balanced by BW with 15 replicates per treatment and 5 birds per replica. The treatments were replicated in 16 blocks, and each treatment was randomized within each block. Each pen [dimensions, 96.5 × 33 cm] was therefore constituted as the experimental unit. The stocking density was 0.637m^2/bird.

Illumination was provided by fluorescent bulbs for the duration of the experiment. The total duration of the study was 18 days with a 2-phase feeding program, as follows: starter (1 to 8 d), grower (9 to18 d). Feed was provided *ad libitum* in a one pan feeder (capacity – 2 kg) per pen. Water was provided *ad libitum* through water troughs.

Standard battery management practices were used throughout the experiment. Animals and housing facilities were inspected twice daily, and general health status was recorded. Any mortalities were immediately removed and weighed. Feed and water supply and battery room temperature were also monitored. Body weight and feed consumption were measured on day 0, 8, 15 and 18. Feed conversion was adjusted for mortality on day 8, 15, and 18.

Experimental Diets and Processing

A total of 8 dietary treatments were produced at the Kansas State University feed mill. Dietary treatments consisted of a negative control (NC) and the NC plus enzyme 1, 2, 3, 4, 5, 6, or 7. The NC was formulated to meet requirements and composed of corn, soybean meal, DDGS, soy oil and mineral-vitamin premix (Table 1), and was formulated to 2,937 kcal/kg during the starter period and 2,988 kcal/kg during the grower period. Titanium dioxide was supplemented into the diet at 0.5% to serve as the indigestible marker for AME and AMEn analysis. Enzymes 1, 2, 3, 4, 5, 6, and 7 were added at a rate of 200 g/tonne respectively. No zootechnical additives (e.g. AGP, organic acids, essential oils, etc.) or coccidiostats were used in experimental feed. Chemical analysis of experimental diets is reported in Table 2.

Starter diets were fed in crumble form and grower diets were fed in pellet form. Corn particle size for all diets was approximately 700 µ. All diets were steam conditioned and pelleted on a 1 ton 30-horsepower pellet mill (1012-2 HD Master Model, California Pellet Mill, Crawfordsville, IN) with a 4 x 24 mm pellet die. Diets were conditioned to a target temperature of 82°C and conditioning time was approximately 25 s. After cooling, starter diets were crumbled (CME EcoRoll7). Additional, processing characteristics are reported in Table 3.

Digestibility Procedures

On d 16, 17 and 18 of the study, pans beneath each individual battery pen were lined with aluminium foil and excreta samples were collected for analysis. Pooled excreta samples were dried at 55°C for 24 hours, finely ground, and divided for analysis. Samples were analysed for crude protein, gross energy, and titanium dioxide to determine the apparent metabolizable energy (AMEn). Crude protein and gross energy were analysed by bomb calorimeter at Carolina Analytical Services, LLC (Bear Creek, North Carolina). Titanium dioxide was analysed by ash digestion (AOAC 942.05) and assayed according to Leone et al. (1973).

Digestibility Calculations

Apparent metabolizable energy and coefficient of nitrogen digestibility were defined by the following equations, where GE_{diet} was the gross energy of the diet, $GE_{excreta}$ was the gross energy of the excreta, $TiO_{2,\ diet}$ was the concentration of titanium dioxide in the diet, $TiO_{2,\ excreta}$ was the concentration of titanium dioxide in the excreta, and N represents the concentration of nitrogen either in the feed or excreta.

$$AME_n = GE_{diet} - \left[GE_{excreta} \times \left(\frac{TiO_{2,diet}}{TiO_{2,excreta}}\right)\right] - 8.22 \times \left\{N_{diet} - \left[N_{excreta} \times \left(\frac{TiO_{2,diet}}{TiO_{2,excreta}}\right)\right]\right\}$$

Exp. 2 Multi-Carbohydrase Enzymes on Broiler Growth Performance

Animal Management

A total of 1,260 one-day old, male Cobb 500 broiler chickens were randomly assigned to floor pens at the Kansas State University Poultry Facility (Manhattan, KS). Pens were randomly assigned to 1 of 6 treatments within location block and balanced by BW with 14 replicates per treatment and 15 birds per replica. The treatments were replicated in 14 location blocks, and each treatment was randomized within each block. Each pen [dimensions, 100 × 73 cm] was the experimental unit. The stocking density was 11 bird/m^2 and wood shavings were used as litter material.

Illumination was provided by fluorescent bulbs for the first 3 days and then changed to incandescent lights for the remainder of the experiment. The total duration of the study was 42 days with a 3-phase feeding program, as follows: starter (1 to 10 d), grower (10 to 21 d), finisher (21 to 42 d). Feed was provided *ad libitum* in a one pan round feeder (capacity – 13.6 kg). Water was provided *ad libitum* through nipple drinkers.

Standard floor pen management practices were used throughout the experiment. Animals and housing facilities were inspected twice daily, and general health status was recorded. Any mortalities were immediately removed and weighed. Feed, water supply, and battery room temperature were also monitored. Pen weights and feed consumption was measure on d 0, 10, 21, and 42. Feed conversion was adjusted for mortality on d 10, 21, and 42.

Experimental Diets and Processing

A total of 6 dietary treatments were produced at the Kansas State University feed mill. Dietary treatments consisted of a positive control (PC), negative control (NC), and the NC plus enzyme combination A, B, C, or D. The PC was composed of corn, soybean meal, DDGS, soy oil and mineral-vitamin premix (Table 4), and was formulated to meet the birds nutrient recommendations. The NC was formulated to have lower energy density (111 kcal/kg less metabolizable energy [ME]) than the PC diet by reducing the content of added soy oil and increasing DDGS in the starter diets and reducing the content of added soy oil in the grower and finisher diets. Enzymes A, B, C, and D were added to the NC at 200, 200, 200, and 100 g/tonne respectively. No zootechnical additives (e.g. AGP, organic acids, essential oils, etc.) or coccidiostats were used in experimental feed. Starter feed was provided from d 1 to 10, grower feed from d 10 to 21 and finisher feed from d 21 to 42. The chemical analysis of experimental diets is reported in Table 5.

Starter diets were fed as crumbles and grower and finisher diets were fed in pelleted form. Corn particle size for all diets was approximately 700 µ. All diets were steam conditioned and pelleted on a 5 ton 30-horsepower pellet mill (PM3016-4, California Pellet Mill, Crawfordsville, IN) with a 4 x 22 mm pellet die. Diets were conditioned to a target temperature of 88°C and conditioning time was approximately 25 s. After cooling, starter diets were crumbled (EcoRoll 7, CME). Further processing characteristics are reported in Table 6.

Body weights were recorded on d 0, coinciding with the change of feeding phase, on d 10 and d 21, and at the end of the study on d 42. Feed disappearance was recorded at d 10, 21 and 42 to calculate feed consumption. Feed conversion ratio (FCR) (mortality corrected) was calculated using BWG and FI data. Productivity index (PI) was also calculated as follows:

$$PI = \frac{BW, kg}{FCR, \frac{g}{g} \times age, d} \times (100 - mortality, \%) \times 100$$

STATISTICAL ANALYSIS

Exp. 1 Multi-Carbohydrase Enzymes on Broiler Nitrogen-Corrects Apparent Metabolizable Energy

Data were analyzed using the MIXED procedure in SAS 9.4(SAS Institute Inc., Cary, NC), with pen as the experimental unit and pen location as the blocking factor. Analysis was performed using Dunnett's multiple comparison for all parameters. Results were considered significant if $P \leq 0.05$ and were considered tendencies between $P > 0.05$ and $P \leq 0.10$.

Exp. 2 Multi-Carbohydrase Enzymes on Broiler Growth Performance

Data were analyzed using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc., Cary, NC), with pen as the experimental unit and pen location as the blocking factor. Difference of treatments were examined using Tukey's test. Results were considered significant if $P \leq 0.05$ and were considered tendencies between $P > 0.05$ and $P \leq 0.10$.

Results

Exp. 1 Multi-Carbohydrase Enzymes on Broiler Nitrogen-Corrected Apparent Metabolizable Energy

For the starter, grower, and overall results, there was no evidence for differences ($P > 0.206$) in ADG, FCR, or ADFI. However, there was an overall effect for ($P < 0.026$) AME and AMEn. The diet containing enzyme 1 had increased ($P < 0.05$) AME and AMEn compared to the control diet. However, diets containing the other enzymes had similar AME and AMEn compared to the control diet. Diets containing enzyme 1 had a 150 kcal/kg and 151 kcal/kg increase in AME and AMEn compared to the control diet.

Exp. 2 Multi-Carbohydrase Enzymes on Broiler Growth Performance

During the starter phase, there was a (*P* = 0.015) treatment effect on BW. Birds fed the NC and NC containing enzyme B or D were heavier compared to those fed the PC. However, d 10 BW was similar between birds fed the NC and those fed diets with added enzymes. There were no significant differences for ADFI or FCR during the starter period. During the grower phase (d 10 to 21), there were no significant differences in BW between the PC, NC, or any of the diets containing enzymes used in this experiment. There were no differences in ADG or FCR. However, there was an increase (*P* = 0.040) in ADFI for birds fed the diet containing enzyme D compared to those fed the PC with all other treatments being intermediate. For the finisher phase (d 21 to 42), there were no treatment effects for BW or ADG. There was an increase (*P* = 0.044) in ADFI of broilers fed the NC compared to the PC with all diets containing enzymes being intermediate. Overall from d 0 to 42 there were no significant effects for ADG or ADFI. However, broilers fed the PC had improved (*P* = 0.002) FCR compared to those fed the NC. During the grower and finisher phase broilers fed diets with added enzymes performed similar to the NC. There were no differences in productivity index of broilers fed different dietary treatments.

Discussion

Two experiments were conducted to measure the impact of multicarbohydrase blends on the performance of broilers. In experiment 1, the supplementation of 1 multicarbohydrase blend to a corn-soybean meal diet increased AME and AMEn by 150 and 151 kcal/kg, respectively; however, the addition of the other 6 blends did not result in any differences. These results are consistent with previous studies such as those completed by Stefanello et al. (2019) which reported an increase in AME and AMEn of 125 and 136 kcal/kg, respectively, when α-amylase was supplemented in a corn-soy diet fed to broilers. Jasek et al. (2018) also reported an improvement of 130 kcal/kg in ileal digestible energy when a blend including α-galactosidase and xylanase were included in a corn-soybean meal-based diet.

Corn contains approximately 71% starch (NRC, 1982) composed of amylose and amylopectin which is broken down by pancreatic α-amylase into simple sugars that can be used as energy (Moran, 1982). However, in addition, corn also contains multiple non-starch polysaccharides (NSP) such as mannose, glucose, arabinose, galactose, and xylose (Bacic et al., 1988; Knudsen, 2014). Slominski (2011) demonstrated how these NSP structures decrease nutrient utilization as a result of broiler chickens lacking the ability to hydrolyze the NSP components due to the absence of endogenous enzymes.

Ingredients with lower energy densities and price points show promise with enzyme additions. Zhu et al. (2014) conducted a study supplementing a multicarbohydrase blend to corn and soybean meal-based diets of varying energy levels. Zhu did not see improvement in growth performance, but analysis of pancreatic digestive enzymes noted that the enzyme activity significantly increased when added in low energy diets. Gallardo et al. (2016) demonstrated an increase in AME and AMEn as well as increase in amino acid digestibility by including a multicarbohydrase blend of α-galactosidase, galactomannanase, β-xylanase, and β-glucanase in a diet formulated with canola meal. Meng et al. (2004) utilized a multicarbohydrase blend of xylananse, glucanase, and cellulase in wheat-based diets producing a similar a response in AMEn. A majority of these studies hypothesized that the increase in available energy would lead to an improvement in growth performance over a full growout cycle but did not see any improvement in the 21-d studies they conducted.

It is hypothesized that the increase in AMEn provided by added multicarbohydrase enzymes demonstrated herein and in previous research would lead to an improvement in growth performance. However, there were no growth performance improvements observed when a multicarbohydrase blend was added to a diet formulated to have a lower energy density in the study conducted herein. Lu et al. (2013) contradicted these results in a similar study where broilers were fed an energy deficient corn-soybean meal diet and observed increased BW, FI, and improved feed efficiency when a carbohydrase enzyme blend was included. However, Ravindran (2013) noted that in most cases the addition of exogenous enzymes resulted in highly variable impacts on growth performance. An improvement in digestibility or growth performance of broilers elicited by the addition of exogenous enzymes is more pronounced when the nutrient density of the diet is decreased, the target ingredient quality is notably low, or there is a health challenge present. Jia et al. (2009) demonstrated that the inclusion of a pectinase, xylanase, glucanase, and mannanase blend minimized any growth suppressions that was associated with the health challenge in birds consuming both the wheat and corn diet but a more pronounced effect was observed in birds fed the wheat-based diet.

In experiment 2, there was no significant effects of adding exogenous carbohydrase blends to a diet formulated to have 111 kcal/kg less than the positive control diet. Birds fed the PC diet had decreased ADFI as well as improved FCR compared to the NC and diets containing supplemental carbohydrase blends. These results contrast a recent study by Amerah et al. (2017) which demonstrated an improvement in FCR when broilers were fed a low energy corn-based diet supplemented with a mixture of xylananse, amylase, and protease. Both the diets reported by Amerah as well as those used in exp. 2 decreased the level of fat in the negative control diets to decrease available energy.

In conclusion, the addition of an enzyme blend produced an increase in AME and AMEn in experiment 1. However, there were no observed benefits in growth performance with supplementing a blend of multicarbohydrase enzymes to a corn, soybean meal, and DDGS based diet.

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Table 1.1 Effect of multicarbohydrase supplementation on broiler digestibility as measured by AME and AMEn diet composition (as-fed basis)[1, 2, 3]

	Starter	Grower
Ingredient, %	NC	NC
Corn	57.06	61.14
Soybean Meal 46.5 %	31.75	26.70
Dried Distillers Grains with Solubles (7% oil)	6.00	7.00
Choice White Grease	0.50	0.69
L-lys HCl	0.22	0.20
DL- Met	0.28	0.21
L- Thr	0.08	0.07
Mono Cal	1.30	1.20
Limestone	1.50	1.48
Salt	0.23	0.23
Vitamin Mineral Premix[4]	0.25	0.25
Sodium Bicarbonate	0.23	0.23
Choline Cl	0.10	0.10
Titanium Dioxide	0.50	0.50
Total	100	100
Calculated Analysis		
MEn (kcal/kg)	2937	2988
CP %	2925	2975
Digestible AA, %	1.39	1.46
Lys	1.19	1.05
Arg:Lys	0.43	0.44
His:Lys	0.68	0.70
Ile:Lys	1.46	1.55
Leu:Lys	1.73	1.63
Met:Lys	0.76	0.76
TSAA:Lys	0.77	0.75
Phe:Lys	0.22	0.91
Thr:Lys	0.18	0.18
Trp:Lys	0.77	0.79
Val:Lys	0.90	0.86
Ca	0.71	0.68
P	0.45	0.43
Available P	0.18	0.18
Na	0.19	0.1
Cl	0.22	0.21

[1]Experimental diets were fed in 2 phases from d 0 to 8 and d 9 to 18 for the starter and grower respectively.
[2]Enzymes 1, 2, 3, 4, 5, 6, and 7 were added to the negative control (NC) at 200 g/tonne to create dietary treatments.
[3]NC = Negative Control

[4] Providing per gram 9703 IU of Vitamin A, 1212 IU of Vitamin D3, 38 IU of Vitamin E, 3.8 mg of Vitamin K, 43 mg of Niacin, 24 mg of Pantothenic acid, 7.2 mg of Riboflavin, and 33 Is of Vitamin B12

Table 1.2 Effect of multicarbohydrase supplementation on broiler digestibility as measured by AME and AMEn chemical analysis of experimental diets (as-fed basis)[1, 2, 3, 4]

		Enzyme						
Item, %	NC	1	2	3	4	5	6	7
Starter								
Dry matter	88.7	88.5	88.4	87.9	88.0	87.8	88.5	88.3
Crude protein	21.8	22.4	20.6	20.4	21.1	21.4	22.0	19.9
Crude fiber	2.4	2.2	2.0	2.4	2.2	2.3	2.4	2.4
Crude fat	3.5	3.3	3.3	3.5	3.3	3.7	3.2	3.1
Grower								
Dry matter	88.7	89.1	88.9	89.3	89.0	89.3	89.2	89.4
Crude protein	21.8	22.4	20.6	20.4	21.1	21.4	22.0	19.9
Crude fiber	2.7	3.2	2.7	2.3	3.4	3.0	2.9	2.3
Crude fat	4.2	4.5	4.3	4.2	4.3	4.3	4.5	4.1

[1]Analysis was performed by Ward Laboratories, Inc. (Kearney, NE) on pooled diet samples collected from the feeders.
[2]Experimental diets were fed in 2 phases from d 0 to 8 and d 9 to 18 for the starter and grower respectively.
[3]Enzymes 1, 2, 3, 4, 5, 6, and 7 were added to the negative control (NC) at 200 g/tonne to create dietary treatments
[4]NC = Negative Control

Table 1.3 Effect of multicarbohydrase supplementation on broiler digestibility as measured by AME and AMEn feed processing data[1, 2, 3]

		Enzyme						
Item	NC	1	2	3	4	5	6	7
Starter								
Production rate, kg/min	10.2	15.6	14.9	15.7	15.7	15.0	15.6	15.8
Conditioning Temp., °C	76.7	81.0	82.8	77.9	78.8	81.9	77.0	82.9
Hot Pellet Temp., °C	74.6	83.5	86.1	83.5	85.9	87.5	81.2	86.0
Pellet Durability Index,[2] %	75.7	75.3	73.7	74.0	71.0	75.2	75.5	78.2
Percent Fines,[2] %	51.7	47.3	49.9	48.2	49.6	47.5	44.7	46.3
Grower								
Production rate, kg/min	15.8	15.8	15.9	15.6	15.7	16.0	16.1	16.0
Conditioning Temp., °C	81.5	81.7	79.4	82.2	78.3	84.1	78.9	82.4
Hot Pellet Temp., °C	81.8	85.9	83.5	86.3	80.0	86.7	82.5	86.2
Pellet Durability Index,[1] %	74.4	72.2	71.7	70.1	69.6	76.2	65.5	61.0
Percent Fines,[2] %	7.1	7.7	7.5	7.4	7.8	6.9	7.9	8.2

[1]Diets were manufactured using a 1-ton 30 horsepower pellet mill (1012-2 HD Master Model, California Pellet Mill, Crawfordsville, IN) equipped with a 4 x 24 mm pellet die Add feed form here
[2]Pellet durability analysis was performed using a Holmen 100 for 60 seconds on samples collected from the pellet mill cooler prior to additional fat application.
[3]Analysis was performed on samples collected from the feeder using a #6 sieve.

Table 1.4 Effect of multicarbohydrase supplementation on broiler growth performance diet composition (as-fed basis)[1, 2, 3]

	Starter		Grower		Finisher	
Ingredient, %	PC	NC	PC	NC	PC	NC
Corn	54.50	53.46	51.67	53.72	55.41	57.45
Soybean Meal 46.5 %	36.00	34.75	33.00	33.00	29.00	29.00
Dried Distillers Grains with Solubles (7% oil)	4.00	8.00	10.00	10.00	10.00	10.00
Soy oil	1.84	0.18	2.52	0.49	3.08	1.04
L-lys HCl	0.22	0.24	0.09	0.08	0.08	0.08
DL- Met	0.31	0.29	0.20	0.19	0.18	0.18
L- Thr	0.13	0.12				
Mono Cal	0.76	0.70	0.43	0.43	0.26	0.26
Limestone	1.42	1.44	1.27	1.27	1.17	1.17
Salt	0.23	0.23	0.23	0.23	0.23	0.23
Vitamin Mineral Premix[4]	0.25	0.25	0.25	0.25	0.25	0.25
Sodium Bicarbonate	0.23	0.23	0.23	0.23	0.23	0.23
Choline Cl	0.10	0.10	0.10	0.10	0.10	0.10
Phytase[5]	0.011	0.011	0.011	0.011	0.011	0.011
Total	100	100	100	100	100	100
Calculated Analysis						
MEn (kcal/kg)	3000	2890	3025	2915	3100	2990
CP %	23.63	24.10	23.40	23.55	21.75	21.91
Fat	5.56	4.11	6.29	4.37	7.17	5.25
Digestible AA, %						
Lys	1.28	1.28	1.12	1.12	1.02	1.02
Arg:Lys	1.04	1.04	1.15	1.16	1.16	1.16
His:Lys	0.42	0.42	0.47	0.48	049	0.49
Ile:Lys	0.68	0.68	0.76	076	0.77	0.77
Leu:Lys	1.40	1.44	1.62	1.64	1.70	1.71
Met:Lys	0.49	0.48	0.46	0.46	0.47	0.48
TSAA:Lys	0.74	0.73	0.75	0.75	0.78	0.78
Phe:Lys	0.79	0.80	0.90	0.91	0.92	0.93
Thr:Lys	0.67	0.67	0.64	0.65	0.66	0.66
Trp:Lys	0.18	0.18	0.20	0.20	0.20	0.20
Val:Lys	0.75	0.76	0.85	0.86	0.88	0.88
Ca	0.96	0.96	0.85	085	0.77	0.77
P	0.61	0.62	0.56	0.57	0.51	0.51
Avail P	0.48	0.48	0.43	0.43	0.39	0.39
Na	0.18	0.18	0.19	0.19	0.19	0.19
Cl	0.19	0.20	0.20	0.20	0.20	0.20

Table 1.4a Effect of multicarbohydrase supplementation on broiler growth performance diet composition (as-fed basis) *continued*

[1]Experimental diets were fed in 3 phases from d 0 to 10, d 10 to 20 and d 20 to 42 for the starter, grower and finisher, respectively.
[2]Enzymes A, B, C, and D were added to the negative control (NC) at 200, 200, 200, and 100 g/MT to create dietary treatments.
[3] PC = Positive Control, NC = Negative Control
[4] NB3000 was used as the vitamin and mineral premix providing per gram 9703 IU of Vitamin A, 1212 IU of Vitamin D3, 38 IU of Vitamin E, 3.8 mg of Vitamin K, 43 mg of Niacin, 24 mg of Pantothenic acid, 7.2 mg of Riboflavin, and 33 Is of Vitamin B12
[5]Quantum Blue 5G, AB Vista, Plantation, FL 2500 FTU/kg

Table 1.5 Effect of multicarbohydrase supplementation on broiler growth performance chemical analysis of experimental diets (as-fed basis)[1, 2, 3, 4]

			Enzyme			
Item, %	PC	NC	A	B	C	D
Starter						
Dry matter	88.43	89.6	89.4	89.0	89.5	89.7
Crude protein	23.0	22.7	23.1	22.9	23.0	23.1
Crude fiber	3.1	3.5	4.5	4.5	4.5	5.0
Crude fat	4.8	2.7	2.7	3.0	3.1	2.9
Grower						
Dry matter	88.1	88.1	88.1	88.5	88.1	88.5
Crude protein	22.7	23.0	22.8	22.5	22.5	23.1
Crude fiber	3.7	2.6	3.0	3.6	3.2	2.4
Crude fat	5.4	3.5	3.6	3.5	3.6	3.6
Finisher						
Dry matter	88.4	88.6	88.1	88.2	87.5	88.0
Crude protein	21.6	21.3	21.0	21.3	21	21.3
Crude fiber	4.1	3.6	4.1	4.0	3.7	3.4
Crude fat	6.2	4.3	4.4	4.1	4.0	4.2

[1]Analysis was performed by Ward Laboratories, Inc. (Kearney, NE) on pooled diet samples collected from the feeders.
[2]Experimental diets were fed in 3 phases from d 0 to 10, d 10 to 20 and d 20 to 42, respectively.
[3]Enzymes A, B, C, and D were added to the negative control (NC) at 200, 200, 200, and 100 g/tonne to create dietary treatments
[4] PC = Positive Control, NC = Negative Control

Table 1.6 Effect of multicarbohydrase supplementation on broiler growth performance feed processing data[1]

			Enzyme			
Item[2,3]	PC	NC	A	B	C	D
Starter						
Production rate, kg/min	61.9	63.1	67.0	63.3	60.2	57.9
Conditioning Temp., °C	84.6	86.4	85.8	83.9	84.7	84.2
Hot Pellet Temp., °C	82.9	85.2	85.1	84.8	84.7	85.0
Pellet Durability Index, % [4]	86.2	93.2	94.6	93.8	92.6	93.0
Percent Fines, % [5]	47.8	50.4	51.1	49.8	49.6	45.7
Grower						
Production rate, kg/min	59.4	61.6	59.2	60.1	60.6	61.8
Conditioning Temp., °C	86.3	86.5	85.6	86.6	85.2	85.4
Hot Pellet Temp., °C	87.7	88.1	87.6	87.0	87.3	87.6
Pellet Durability Index, % [4]	89.6	93.6	92.5	92.0	93.9	93.3
Percent Fines, % [5]	11.3	7.8	8.4	9.1	8.8	8.6
Finisher						
Production rate, kg/min	60.2	58.5	58.2	57.8	58.1	59.1
Conditioning Temp., °C	85.4	86.2	85.7	85.5	85.8	86.0
Hot Pellet Temp., °C	85.4	87.9	86.9	88.7	89.1	90.0
Pellet Durability Index, % [4]	86.8	94.7	93.3	94.0	94.8	94.7
Percent Fines, % [5]	7.9	8.4	8.1	7.9	8.7	8.8

[1]Diets were manufactured using a 5-ton 30 horsepower pellet mill (PM3016-4, California Pellet Mill, Crawfordsville, IN) equipped with a 4 x 22 mm pellet die add feed form here

[2]Enzymes A, B, C, and D were added to the negative control (NC) at 200, 200, 200, and 100 g/tonne to create dietary treatments

[3] PC = Positive Control, NC = Negative Control

[4]Pellet durability analysis was performed using a Holmen 100 for 60 seconds on samples collected from the pellet mill cooler prior to additional fat application.

[5]Analysis was performed on samples collect from feeders using a #6 sieve

Table 1.7 Effect of enzyme supplementation on broiler growth performance and digestibility as measure by AME and AMEn, Exp 1[1, 2]

		Enzyme								
Item[3,4]	NC	1	2	3	4	5	6	7	SEM	P-Value
BW, g										
d 0	41.6	41.5	41.8	41.5	41.6	41.7	41.5	41.6	0.11	0.492
d 8	205.0	202.4	205.7	207.4	204.1	201.3	200.7	203.9	2.40	0.532
d 18	771.6	765.7	771.6	767.0	751.2	751.4	757.2	749.6	12.3	0.786
d 0 to 18										
ADG, g	39.7	39.2	40.0	39.1	39.4	38.6	39.2	38.3	0.86	0.921
ADFI, g	58.9	57.1	58.1	57.2	56.0	55.6	55.7	53.9	1.69	0.566
FCR	1.48	1.45	1.45	1.46	1.42	1.43	1.41	1.40	0.02	0.435
AME, kcal/kg	3151	3301*	3175	3149	3194	3115	3150	3176	36.0	0.025
AMEn, kcal/kg	3126	3277*	3151	3126	3171	3092	3126	3153	36.0	0.026

[1]A total of 600 broilers (Cobb 500) were used in a 18-d experiment with 5 broilers per pen and 15 pens per treatment.

[2]Data were analyzed using the MIXED procedure in SAS 9.4 (SAS Institute Inc., Cary, NC), with pen as the experimental unit and pen location as the blocking factor. Analysis was performed using Dunnett's multiple comparison for all parameters.

[3]Enzymes A, B, C, and D were added to the negative control (NC) at 200, 200, 200, and 100 g/tonne to create dietary treatments

[4] PC = Positive Control, NC = Negative Control

* Denotes significantly different from the Negative Control at $P < 0.05$

Table 1.8 Effect of multicarbohydrase supplementation on growth performance of broilers, Exp. 2[1]

Item[2,3]	PC	NC	Enzymes A	Enzymes B	Enzymes C	Enzymes D	SEM	P-Value
BW, g								
d 0	44.0	43.9	43.8	43.7	43.7	43.4	0.16	0.207
d 10	300.1[d]	307.1[abc]	302.1[bcd]	309.6[a]	301.0[cd]	308.2[ab]	2.54	0.015
d 21	1107.6	1122.2	1119.0	1131.2	1117.6	1139.2	11.9	0.414
d 42	3401.5	3483.5	3407.4	3449.8	3459.2	3491.6	28.0	0.053
d 0 to 10								
ADG, g	25.1	25.8	25.3	26.1	25.1	25.7	0.38	0.052
ADFI, g	27.6	28.5	28.3	28.1	28.2	28.5	0.50	0.776
FCR	1.09	1.10	1.11	1.07	1.12	1.10	0.015	0.331
d 10 to 21								
ADG, g	73.3	72.9	72.7	73.8	72.7	75.3	0.93	0.267
ADFI, g	92.2[b]	95.3[ab]	94.9[ab]	95.9[ab]	94.6[ab]	97.4[a]	1.15	0.040
FCR	1.26	1.29	1.30	1.30	1.30	1.29	0.011	0.176
d 21 to 42								
ADG, g	110.5	108.0	107.3	109.2	109.7	110.6	1.34	0.317
ADFI, g	177.1[b]	184.9[a]	180.3[ab]	182.4[ab]	182.6[ab]	183.2[ab]	1.72	0.044
FCR	1.64	1.67	1.68	1.67	1.66	1.65	0.011	0.073
d 0 to 42								
ADG, g	78.2	79.2	77.3	79.4	78.4	80.1	0.84	0.225
ADFI, g	117.6	121.5	119.2	121.5	120.1	121.9	1.22	0.122
FCR	1.50[b]	1.53[a]	1.54[a]	1.53[a]	1.53[a]	1.52[ab]	0.007	0.002
Productivity Index	4.81	4.50	4.39	4.73	4.47	4.47	0.13	0.167
Mortality Count	22	34	35	34	35	38	---	---

[1]A total of 1,260 broilers (Cobb 500) were used in a 42-d experiment with 15 broilers per pen and 14 pens per treatment.
[2]Enzymes A, B, C, and D were added to the negative control (NC) at 200, 200, 200, and 100 g/tonne to create dietary treatments
[3] PC = Positive Control, NC = Negative Control
[a,b,c,d] Means within a row with different superscripts differ ($P < 0.05$)

Chapter 2 - Evaluation of conditioning temperature and die specifications on nursery pig performance

ABSTRACT: A total of 315 barrows (DNA; 200 × 400; initial BW 5.9 kg) were used in a 35d growth trial. Upon arrival, pigs were weighed and assigned to pens in a completely randomized design with 5-pigs/pen, and each pen was randomly assigned to 1 of 7 dietary treatments with 9 replications per treatment. Treatments consisted of a mash control (MC) and 6 experimental pelleted treatments manufactured using 2 pellet dies (length/diameter [L:D]: 6.7 and 2.7) and 3 conditioning temperatures (low, med, high). Conditioning temperatures for phase 1 diets pelleted using the 6.7 L:D die were approximately 27, 38, and 49°C and for the 2.7 L:D die were 38, 49, and 60°C for the low, med, and high respectively. Phase 2 conditioning temperatures for diets pelleted using the 6.7 L:D die were approximately 49, 60, and 71°C and for the 2.7 L:D die were 60, 71, and 82°C for the low, med, and high respectively. Diets were fed in three phases: Phase 1: d 0-10, Phase 2: d 11-25, and Phase 3: d 26-35. During phase 3 all pigs were fed a common mash diet. Overall from d 0 to 35, similar ADG was observed for pigs fed the MC or pelleted treatments, except the diet pelleted at the low conditioning temperature using the 6.7 L:D die which had decreased (*P* = 0.049) ADG compared to the MC. There was a tendency for increased (*P* = 0.088) ADG in pigs fed diets pelleted using the L:D 2.7 die compared to the L:D 6.7 die. This was driven by a tendency for a quadratic increase (*P* = 0.077) in ADG in pigs fed diets pelleted using the 2.7 L:D die with the med conditioning temperature showing the greatest improvement. Pigs fed pelleted treatments, except the med temperature on the 2.7 L:D die, had decreased (*P* = 0.001) ADFI compared to the MC. However, treatments pelleted using the 6.7 L:D die as well as the treatment manufactured at the med conditioning temperature on the 2.7 L:D die had improved (*P* = 0.030) G:F compared to the MC diet. Pigs fed

diets manufactured using the 6.7 L:D die had decreased (*P* = 0.030) ADFI compared to those fed diets pelleted using the 2.7 L:D die. In summary, pelleted diets showed poorer ADG but decreased ADFI and improved G:F and no differences in final BW compared to the MC. There was a tendency for a quadratic (*P* = 0.077) response of ADG as well as an increase (*P* = 0.026) in ADFI on the 2.7 L:D die. A decrease in pellet quality was observed when treatments were manufactured on the 2.7 L:D die but these differences did not result in a growth performance response.

Key Words: Nursery pigs, Pellet, Pellet Die Thickness, Conditioning temperature

INTRODUCTION

Pelleting swine feed is a common industry practice as it can lead to improved animal performance, decreased feed wastage, and improved feed handling characteristics (Behnke, 1994). The pelleting process begins by feeding dry mash feed into a conditioning chamber where heat and moisture is applied via steam. As the feed exits the conditioner it is compressed through a die to form pellets and then cooled before being stored prior to shipment. While the pelleting process is widely understood, there are many factors that can be manipulated and produce a vastly different final product. These factors include diet formulation, conditioning temperature, and die selection. These choices can impact the overall performance of the mill and the quality of the feed being produced (Behnke, 2001).

Nursery pig diets can specifically benefit from pelleting as they typically contain a high percentage of milk-based products such as spray dried whey or whey permeate. When nursery diets contain high concentrations of whey products and are fed in a meal form, they have poor flowability characteristics (Carney et al., 2005). Improving the flowability of finished feed not only improves handling in the feedmill but also reduces bridging in bins and feeders on farms.

In addition to improved handling, it has been shown that pelleting can also improve performance in nursery pigs. Wondra et al. (1995) reported a 7% improvement in G:F in finishing pigs fed a pelleted diet compared to mash diets. While pelleting improves handling and performance in nursery pigs, high quality pellets are necessary to encourage these responses (Stark, 1994). Stark (1994) detailed how the benefits of pelleting are dependent on the quality of the pelleted feed and will decline if quality is not maintained. It is widely accepted that there are many different factors that affect pellet quality such as formulation, conditioning via steam, and pellet die selection (Behnke, 1994). However, most trials have tested only 1 factor at a time and data showing the interactive effects of different factors is lacking. Therefore, the objective of this study was to evaluate the interactive effects of conditioning temperature and die specifications when pelleting diets on pellet quality and subsequent growth performance of nursery pigs.

Materials and Methods

All experimental procedures were approved by Institutional Animal Care and Use Committee at Kansas State University.

A total of 315 barrows (DNA 200 × 400; initial BW of 5.9 kg) were used in a 35-d growth trial at the KSU Segregated Early Weaning (SEW) facility. Pigs were housed in 1.2 × 1.2-m pens containing a three-hole dry self-feeder and one cup waterer to provide *ad libitum* access to feed and water. Pigs were weaned at approximately 21-d of age and upon arrival to the weaning facility, pigs were weighed and assigned to pens in a completely randomized design with 5-pigs/pen, and each pen was assigned to 1 of 7 treatments. There were 63 total pens that provided 9 replications per treatment. Effort was made to minimize difference in average weight and variance between pens, and care was taken to prevent clustering of pens for the same treatment within a certain location in the facility.

Dietary treatments consisted of a basal diet fed as a mash control (MC) or 6 diets pelleted with different pelleting parameters. The mash control diet was mixed at Hubbard Feeds (Beloit, KS) and transferred to Kansas State University, Manhattan, KS and pelleted using the CL-5 experimental pellet mill (Model CL5 California Pellet Mill Co., Crawfordsville, IN). Diets were steam conditioned (12.7 cm diameter x 91.4 cm length) to 3 target conditioning temperatures for approximately 30-s and pelleted using one of two pellet dies. Both pellet dies had holes that were 4.7 mm in diameter and two different die thicknesses, to create lengths:diameter (L:D), of 2.7 and 6.7. Phase 1 feed was conditioned to approximately 27 (Low), 38 (Med), and 49°C (High) using the 6.7 L:D die and 38 (Low), 49 (Med), and 60°C (High) using the 2.7 L:D die. The feeder was set at a constant rate to achieve approximately 48.8 kg per hour. Phase 2 feed was conditioned to approximately 49 (Low), 60 (Med), and 71°C (High) using the 6.7 L:D die and 60 (Low), 71 (Med), and 82°C (Low) using the 2.7 L:D die. The feeder was set at a constant rate to achieve approximately 108 kg per hour for Phase 2. Pellets were then cooled in an experimental cooler for 15 minutes. After cooling, pellets were sifted to remove fines to mitigate effects of pellet quality on pig performance. Pellet samples were taken at the die as well as after cooling and analyzed for pellet quality using a Holmen NHP37.7 (TekPro Ltd, Norfolk, UK) for 60 seconds at 70 mbar. The basal diet formulation was a standard nursery diet that was formulated to meet or exceed the recommended nutrient requirement for nursery pigs (NRC, 2012)[1]. Diets were fed in three phases (Phase 1: d 0 to 10; Phase 2: d 11 to 25; Phase 3: d 26 to 35). Phase 3 was offered in the form of a common mash diet to all treatment pens. Twice

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[1] NRC, 2012. Nutrient Requirement for Swine, 11th rev. ed. National Academy Press, Washington, DC.

daily barn checks were done to assess pig health and feeder adjustments to prevent bridging or wastage. Pens of pigs were weighed, and feed disappearance calculated on d 0, 10, 17, 25, and 35 of the experiment to determine growth performance (average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F)). Feed additions were recorded for each individual pen. Feed samples were taken from the feeders and appropriately stored until proximate analysis was performed at Ward Laboratories (Kearney, NE).

Statistical analyses

Data were analyzed using the PROC-GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC) with pen serving as the experimental unit. Analysis was performed using Dunnett's multiple comparison to compare each pelleted treatment to the MC. Contrast statements were used to separate treatment means with comparison of die (6.7 vs 2.7) and linear and quadratic polynomials were used to test increasing conditioning temperature within each die. Results were considered significant $P \leq 0.05$, and marginally significant at $P \leq 0.10$.

RESULTS

All treatment diets were analyzed for crude protein, fiber, fat, phytase content, as well as total and available lysine. Phase 1 diets pelleted using the 6.7 L:D die had an approximately 10% decrease (Table 2) in available lysine as conditioning temperature increased. Diets pelleted using the 2.7 L:D die had an even larger 25% decrease in the available lysine of phase 1 diets as conditioning temperature increased. A similar trend was seen in phase 2 diets pelleted using the 2.7 L:D die where available lysine decreased by 15% as conditioning temperature increased. However, phase 2 diets pelleted with the 6.7 L:D die had similar available lysine at all of the conditioning temperatures evaluated in this experiment.

Conditioning and hot pellet temperatures were recorded periodically throughout each pelleting run and the difference (Δ T) calculated. Conditioning temperatures averaged within 2°C of the target and the Δ T decreased as conditioning temperature increased as shown in Table 3. This is an expected result as frictional heat will decrease when conditioning temperature increase as steam provides moisture and therefore acts as a lubricant as feed passes through the die. There was approximately a 10% decrease in PDI (pellet durability index) of the phase 1 diet when pelleted with 2.7 L:D die compared the 6.7 L:D die but no large differences in PDI when comparing conditioning temperatures. However, the phase 2 diet pelleted at the low or medium conditioning temperature on the 2.7 L:D die was analyzed to have a PDI value approximately 30% poorer than all other pelleted treatments. This decrease in pellet quality was improved as conditioning temperature increased.

From d 0 to 10 there were no differences in ADG or ADFI for each pelleted treatment compared to the mash control diet. There was a tendency for pigs fed the mash control (MC) to have decreased ($P = 0.068$) G:F compared to pigs fed pelleted diets. When diets were pelleted using the 6.7 L:D die, pigs fed diets conditioned at the medium temperature (38°C) tended to have increased (quadratic, $P = 0.077$) ADFI compared to the low and high temperatures. There was no difference in d 10 BW for any treatment.

From d 10 to 25, pigs fed the MC had increased ($P = 0.021$) ADG compared to those fed the diets pelleted using the low and medium conditioning temperatures on the 6.7 L:D die. Pigs fed all other pelleted diets had ADG similar to those fed the MC. When pelleting using the 6.7 L:D die, there was a tendency for a linear increase ($P = 0.098$) in ADG in pigs fed diets pelleted with increasing conditioning temperature. Pigs fed the MC or the treatment pelleted at the medium conditioning temperature on the 2.7 L:D die performed similarly while all other pelleted treatments had decreased (*P* < 0.05) ADFI during this phase. Furthermore, pigs fed diets pelleted on the 6.7 L:D die had decreased (*P* = 0.026) ADFI compared to the 2.7 L:D die. There were no differences in G:F or d 25 BW during this period.

From d 25 to 35 all treatments were fed a common mash diet. There were no differences in ADG, ADFI, or G:F between pigs previously fed the MC and each pelleted diet. However, there was a tendency for increased (*P* = 0.083) ADG in pigs previously fed diets pelleted on the 2.7 L:D die compared to the 6.7 L:D die. Pigs fed diets pelleted using the die with a L:D of 2.7 also had increased (*P* = 0.039) ADFI compared to pigs fed diets manufactured with the 6.7 L:D die.

From d 0 to 25 there was no difference observed in ADG when comparing each pelleted treatment to the MC. Pigs fed diets pelleted on the 6.7 L:D die at any of the conditioning temperatures and diets pelleted using the 2.7 L:D at the low and high conditioning temperatures had decreased (*P* = 0.001) ADFI during this phase compared to those fed the MC. All pelleted treatments manufactured on the 6.7 L:D die as well as the medium conditioning temperature on the 2.7 L:D die showed improved (*P* = 0.027) G:F compared to those fed the MC. There were no differences between pigs fed diets pelleted using the different dies.

Overall from d 0 to 35, pigs fed the MC had increased (*P* = 0.049) ADG compared to diet manufactured using the 6.7 L:D die at the low conditioning temperature with all other pelleted treatments performing similarly to the MC. When pelleting diets using the 2.7 L:D die, there was a tendency for increased (quadratic, *P* = 0.077) ADG in pigs fed diets conditioned at increasing temperatures, with the medium temperature having the greatest ADG. There was a tendency for increased (P = 0.088) ADG in pigs fed diets pelleted using the 2.7 L:D die compared to the 6.7 L:D die. Pigs fed diets pelleted on the 6.7 L:D die and diets pelleted using the 2.7 L:D at the low and high conditioning temperatures had decreased (*P* = 0.001) ADFI during this phase compared to the MC. Pigs fed pelleted diets using the 6.7 L:D die at any conditioning temperature or the 2.7 L:D die at the medium conditioning temperature had improved (*P* = 0.020) G:F compared to the MC. Additionally, pigs fed diets manufactured using the 6.7 L:D die had decreased (*P* = 0.030) ADFI compared to those fed diets pelleted using the 2.7 L:D die. There was a tendency for increased (*P* = 0.088) d 35 BW in pigs fed diets pelleted using the 2.7 L:D die compared to the 6.7 L:D die.

DISCUSSION

Pelleting swine diets has been shown to improve growth performance and feed handling as well as decrease feed wastage. Vanschoubrok et al. (1971) summarized 66 experiments evaluating the effects of pelleting swine diets on production costs, handling characteristics, as well as animal performance and the advantages of pelleting include increased bulk density and improved transportation characteristics, reduced ingredient segregation, decreased dust production, reduced feed intake, increased rate of gain, and improved feed efficiency. Hanke et al. (1972) saw an improvement in G:F as well as an increase in ADG. Stark (1994) observed an 8 and 15% improvement in ADG and G:F respectively when nursery pigs were fed pelleted diets compared to mash. Wondra et al. (1995) also found that pelleting increased ADG and improved G:F by 5 and 7% respectively. More recent work by Nemechek et al. (2015) observed a similar improvement in ADG and G:F in nursery pigs fed pelleted diets compared to a mash diet with poor quality pellets performing intermediately. In the experiment reported herein, a similar improvement in G:F as well as a decrease in ADFI was observed in pigs fed pelleted diets compared to the mash control treatment. However, pigs fed the mash control treatment had similar ADG to all pelleted treatments except the low temperature using the 6.7 L:D die.

While pelleting has been shown to improve performance, there are many different parameters during the pelleting process that could alter the final product. In the experiment reported herein two different pellet dies were evaluated at three different conditioning temperatures to evaluate the growth performance of nursery pigs. The optimum moisture of conditioned mash is from 16 to 17.5% with 4 to 5% coming from the added moisture from steam applied during the conditioning process (Behnke and Gilpin, 2014). Schofield (2005) further developed the understanding of steam addition to mash finding a 1% increase in moisture for every 12.5°C increase in temperature. The increase in temperature and moisture affects both the performance of the mill as well as the nutritional components of feed. Nutritional components such as starch, fiber, and protein will react to the heat and moisture during conditioning. Ultimately the way these nutrients behave during thermal processing determines the overall performance of the animal receiving the feed. Rojas et al., (2016) determined that processing feed via pelleting, extrusion, or a combination of the two improves the apparent ileal digestibility of starch as well as most amino acids. However, while thermal processing can positively impact digestibility and feed efficiency there are possible negative implications. The addition of moisture coupled with increased temperature and mechanical energy placed on feed as it moves through the pellet die can lead to the occurrence of the Maillard reaction. During the Maillard reaction, free amine groups are permanently bound to a reducing sugar (Stein et al., 2006). Lysine is particularly susceptible to the Maillard reaction as it contains two free amine groups (Carpenter and Booth, 1973). Lysine that has been used in the Maillard reaction is no longer available to the animal (Mavromichalis, 2001). However, the quantity of Lysine remaining relies on varying processing characteristics. Noguchi et al. (1982) extruded feed with 20% added sucrose and found reactive Lysine to range from 0 to 40%. The amount of Lysine lost to the Maillard reaction was due to the additional reducing sugars present which cause a larger proportion of the free amine groups of Lysine to react with the sugars. Beaufrand et al. (1978) concluded that 32 to 80% of available Lysine was lost when feed was extruded at 170°C and 10 to 14% moisture content. While these results are intended for extrusion, they prove the importance of maintaining mash moisture to provide lubrication across the die and reduce mechanical friction to prevent the Maillard reaction and preserve Lysine availability. In the experiment reported herein a numerical decrease in analyzed total and available lysine was observed from the low to high conditioning temperature regardless of die.

Pellet quality is dependent on formulation components as well as processing variables. Retention time in the pellet die possibly has a positive impact on pellet quality but is reliant on initial ingredient density, production rate, and die L:D ratio (Fahrenholz, 2012). Stevens (1987) suggested that a longer exposure to the heat in the die, or die retention time, to have a relationship to pellet durability due to an increase in starch gelatinization as feed moves through the die. Saensukjaroenphon (2019) demonstrated a linear increase in pellet quality as L:D ratio increased because it increased the die retention time. In the experiment reported herein, an approximate 30% decrease in pellet quality from 89 to 61% was observed on the 2.7 L:D die compared to the 6.7 L:D die. This decline was observed in the phase 2 diet and improved as conditioning temperature increased. The phase 1 diet showed a similar 10% decrease in pellet quality from 95 to 85% on the 2.7 L:D die compared to the 6.7 L:D but did not improve with increased conditioning temperature. However, while a larger L:D ratio will improve pellet quality, it was noted that production rate may need to be decreased to avoid plugging

(Saensukjaroenphon, 2019). Pellet quality also plays a key role in the performance of animals fed pelleted diets. Stark (1994) evaluated the effects of pellet quality on the growth performance and feed efficiency of nursery pigs in two experiments. In the first experiment, no differences were observed in ADG but the addition of 25% fines tended to negatively impact G:F. In experiment 2 a similar improvement in G:F as well as a tendency for increased ADG were observed when feeding pellets versus mash diets. In both experiments, daily fines accumulation more than doubled when fines were included in the treatment to simulate poor quality pellets. This increase in fines accumulation suggests possible increased feed wastage. This possible increase in feed wastage as a result of poor pellet quality was seen in phase 2 of the experiment reported herein. During phase 2 a large decrease in pellet quality was observed in combination with an increase in ADFI of pigs fed diets manufactured using the 2.7 L:D die. It is possible that the increase in ADFI was a result of increased feed wastage as a result of poor-quality pellets.

CONCLUSION

In the experiment reported herein, numerical decreases in available lysine were observed as conditioning temperature increased on both dies when hot pellet temperatures surpassed 57°C on the phase 1 diet and 65°C for phase 2. In addition, there was also a 10% and 30% decrease in pellet quality for phase 1 and 2 diets respectively when treatments were manufactured on the 2.7 L:D die compared to the 6.7. Pellet quality during phase 2 improved as conditioning temperature increased but no such increase was observed in phase 1. However, these differences did not result in a growth performance response due to conditioning temperature or die. Furthermore, pigs fed pelleted diets had poorer ADG but decreased ADFI and improved G:F compared to those fed the MC. Based on the experiment reported herein, it would be recommended that hot pellet temperatures be measured to appropriately evaluate possible deficits incurred by extreme thermal processing. It is recommended that phase 1 diet hot pellet temperatures remain below 45°C and 55°C for the 6.7 and 2.7 L:D dies respectively and below 75°C for phase 2 diets die L:D.

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Table 2.1 Diet composition (as-fed basis)[1, 2, 3]

Ingredient, %	Phase 1	Phase 2	Phase 3
Corn	38.81	56.91	65.47
Whey, spray dried	25.00	10.00	---
Soybean meal	17.65	25.95	28.30
DDGS	5.00	---	---
Fish meal, menhaden	4.50	2.50	---
Choice White Grease	3.00	1.00	2.00
Enzymatically treated Soybean meal[4]	2.50	---	---
MHA methionine	0.24	0.23	0.25
L-Threonine	0.18	0.21	0.23
L-Lysine	0.48	0.48	0.55
L-Valine	0.10	0.15	0.16
L-Tryptophan	0.05	0.04	0.05
Monocalcium P, 21%	0.40	0.60	1.10
Limestone	0.50	0.75	0.75
Sodium chloride	0.30	0.50	0.60
Vitamin premix[5]	0.25	0.25	0.25
Trace mineral premix[6]	0.15	0.15	0.15
Zinc oxide	0.39	0.25	---
Choline chloride	0.04	---	---
Sodium metabisulfite	0.25	---	---
Alltech Viligen	0.15	---	---
Vitamin E 44,092 IU/kg	0.05	---	---
Vitamin AD 10:1	0.01	---	---
Phytase[7]	0.02	0.03	---
Total	100	100	100

continued

Table 2.2 *continued*. Diet composition (as-fed basis)[1,2,3]

Ingredient, %	Phase 1	Phase 2	Phase 3
Calculated analysis			
Standard ileal digestible (SID) AA, %			
Lysine	1.38	1.35	1.35
Isoleucine:lysine	56	54	60
Leucine:lysine	108	109	106
Methionine:lysine	37	37	37
Methionine and cysteine: lysine	58	56	54
Threonine:lysine	64	63	60
Tryptophan:lysine	18.4	18.9	18.0
Valine:lysine	68	70	67
Histidine:lysine	30	34	32
Total Lysine, %	1.55	1.50	1.41
ME, kcal/kg	3,322	3,366	3,324
NE, kcal/kg	2,389	2,464	2,638
SID Lys:NE, g/Mcal	5.77	5.37	5.12
CP, %	19.5	20.9	19.0
Ca, %	0.70	0.75	0.80
P, %	0.60	0.60	0.50
Available P, %	0.47	0.47	0.32

[1]Experimental diets were fed in 3 phases from d 0 to 10, 11 to 25 with a common diet fed from d 26 to 35.

[2]All treatment diets were mixed at Hubbard Feeds (Beloit, KS) and transported to be pelleted using the CL-5 experimental pellet mill at Kansas State University.

[3]AA = Amino acids. ME = metabolizable energy. NE = net energy.

[4] HP300 (Hamlet Protein, Findlay, OH)

[5] Provided per kg of premix: 4,375 IU vitamin A; 1,000 IU vitamin D; 30,000 IU vitamin E; 3,306 mg vitamin K; 3.3 mg vitamin B12; 49.6 mg niacin; 27.5 mg pantothenic acid; 8.2 mg riboflavin.

[6] Provided per kg of premix: 2931 ppm Zn from zinc sulfate; 110 ppm Fe from ferrous sulfate; 33 ppm Mn from manganese oxide; 16 ppm Cu from copper sulfate; 0.29 ppm I from calcium iodate; 0.29 ppm Se from sodium selenite.

[7] During Phase 1 Quantum Blue (AB Vista, Plantation, FL) was used as the phytase source supplying 333 FTU/kg. Axtra PHY 2500 TPT (Dupont, Wilmington, DE) was used as the phytase source for Phase 2 supplying 434 FTU/g.

Table 2.3 Chemical analysis of experimental diets (as-fed basis).[1,2]

Pellet Die[3]		6.7			2.7		
Conditioning Temperature[4]	MC[5]	Low	Med	High	Low	Med	High
Phase 1							
Moisture, %	8.24	9.5	10.38	11.01	9.44	10.8	11.14
Crude Protein, %	17.2	19.2	17.8	18.9	18.8	19.2	17.1
Crude Fiber, %	2.2	1.9	1.7	1.7	2.0	2.2	1.9
Fat, %	5.5	5.9	5.4	5.1	6.0	6.2	5.1
Total Lysine, %	1.42	1.40	1.32	1.32	1.47	1.33	1.25
Available Lysine, %[6]	1.18	1.37	1.29	1.26	1.44	1.30	1.21
Lysine:Crude Protein, %	7.20	7.29	7.41	6.98	7.81	6.92	7.30
Phase 2							
Moisture, %	10.45	10.93	11.48	11.51	11.56	11.66	12.06
Crude Protein, %	18.3	19.5	20.0	19.5	20.3	19.2	18.1
Crude Fiber, %	1.9	1.8	2.0	1.9	1.7	2.0	1.9
Fat, %	3.7	3.6	3.7	3.8	3.5	4.1	4.0
Total Lysine, %	1.51	1.40	1.43	1.46	1.52	1.45	1.38
Available Lysine, %[6]	1.47	1.36	1.40	1.40	1.49	1.42	1.35
Lysine:Crude Protein, %	8.25	7.17	7.15	7.48	7.48	7.55	7.62

[1]Moisture, crude protein, crude fiber, and fat analysis was performed by Ward Laboratories, Inc. (Kearney, NE) on pooled diet samples collected from the feeders.
[3]Diets pelleted at KSU were manufactured using a model CL-5 experimental on two pellet dies with a pellet diameter of 4.7 mm with and Length:Diameter ratio of either 6.7 or 2.7.
[4] Conditioning temperatures for phase 1 feed was approximately 27 (Low), 38 (Med), and 49°C (High) using the 6.7 L:D die and 378 (Low), 49 (Med), and 60°C (High) using 2.7 L:D die. Phase 2 feed was conditioned to approximately 49 (Low), 60 (Med), and 71°C (High) using the 6.7 L:D die and 60 (Low), 71 (Med), and 82°C (Low) using the 2.7 L:D die.
[5] MC = Mash Control.
[6] Total and available lysine analysis was performed using official analytical methods at the Agricultural Experiment Station Chemical Laboratories, University of Missouri according to AOAC Official Method 975.44, chp. 45.4.03, 2006

Table 2.4 Effect of pellet die and conditioning temperature on feed processing [1,2]

Pellet Die[3]		6.7			2.7		
Conditioning Temp[4]	MC[5]	Low	Med	High	Low	Med	High
Phase 1							
Production rate, kg/min	---	0.98	1.03	1.08	0.96	0.96	0.92
Conditioning Temp., °C	---	26.9	38.2	49.1	39.3	50.4	60.2
Hot Pellet Temp., °C	---	47.8	58.7	65.9	57.6	63.5	64.6
Δ T, °C[5]	---	20.9	20.5	16.8	18.3	13.1	4.4
Pellet Durability Index,[1] %[6]	---	95.5	94.5	94.3	84.7	82.5	83.6
Phase 2							
Production rate, kg/min	---	1.79	1.94	1.64	1.66	1.78	1.88
Conditioning Temp., °C	---	49.6	60.2	72.2	60.7	71.9	80.0
Hot Pellet Temp., °C	---	66.0	72.1	79.0	68.0	73.8	81.5
Δ T, °C	---	16.4	11.9	6.8	7.3	1.9	1.5
Pellet Durability Index, %	---	86.7	89.0	92.2	66.9	61.5	82.4

[1]All diets were mixed at Hubbard Feeds (Beloit, KS) and transported to KSU for further processing.
[2] Diets pelleted at KSU were manufactured on two pellet dies with a pellet diameter of 4.7 mm with an L:D ratio of either 6.7 or 2.7 and sifted to control for differences in pellet quality.
[3] Conditioning temperatures for phase 1 feed was approximately 27 (Low), 38 (Med), and 49°C (High) using the 6.7 L:D die and 378 (Low), 49 (Med), and 60°C (High) using 2.7 L:D die. Phase 2 feed was conditioned to approximately 49 (Low), 60 (Med), and 71°C (High) using the 6.7 L:D die and 60 (Low), 71 (Med), and 82°C (Low) using the 2.7 L:D die.
[4] MC = Mash Control.
[5] Δ T = Hot Pellet temp – Conditioning Temp
[6] Pellet durability analysis was performed using a Holmen 100 for 60s for all pelleted samples

2.5 Effect of conditioning temperature and die specifications on nursery pig performance.

										Probability, $P <$[7,8]				
Die[4]		6.7			2.7					6.7		2.7		6.7 vs 2.7
Cond Temp[5]	MC[6]	Low	Med	High	Low	Med	High	SEM	Dunnett's	Linear	Quadratic	Linear	Quadratic	
BW, kg														
d 0	5.97	2.97	6.00	5.99	5.99	6.02	6.01	0.11	0.997	0.828	0.817	0.877	0.810	0.700
d 10	7.45	7.42	7.64	7.36	7.45	7.63	7.37	0.18	0.731	0.778	0.180	0.693	0.230	0.955
d 25	14.3	13.5	13.8	13.8	13.8	14.2	13.8	0.35	0.419	0.453	0.646	0.921	0.283	0.298
d 35	19.7	18.5	18.9	18.8	19.2	19.6	18.9	0.44	0.183	0.531	0.579	0.629	0.216	0.088
d 0 to 10														
ADG, kg	0.15	0.15	0.16	0.14	0.15	0.16	0.14	0.01	0.654	0.672	0.155	0.601	0.209	0.907
ADFI, kg	0.18	0.15	0.17	0.15	0.15	0.16	0.15	0.01	0.249	0.933	0.077	0.475	0.429	0.997
G/F	0.82	1.00	0.95	0.94	0.90	0.99	0.92	0.04	0.068	0.265	0.714	0.771	0.140	0.432
d 10 to 25														
ADG, kg	0.46	0.40*	0.40*	0.43	0.42	0.44	0.43	0.01	0.021	0.098	0.553	0.435	0.327	0.128
ADFI, kg	0.63	0.52*	0.53*	0.55*	0.55*	0.57	0.56*	0.01	0.001	0.211	0.353	0.334	0.308	0.026
G/F	0.73	0.76	0.77	0.78	0.76	0.76	0.77	0.01	0.395	0.376	0.804	0.636	0.947	0.413
d 25 to 35[9]														
ADG, kg	0.54	0.49	0.50	0.49	0.53	0.54	0.51	0.02	0.458	0.913	0.697	0.445	0.423	0.083
ADFI, kg	0.83	0.73	0.78	0.76	0.79	0.81	0.79	0.02	0.121	0.394	0.358	0.922	0.477	0.039
G/F	0.64	0.67	0.64	0.64	0.66	0.66	0.64	0.01	0.728	0.333	0.550	0.202	0.653	0.870
d 0 to 25														
ADG, kg	0.34	0.30	0.31	0.31	0.30	0.33	0.31	0.01	0.169	0.329	0.846	0.514	0.131	0.384
ADFI, kg	0.44	0.37*	0.38*	0.39*	0.39*	0.41	0.39*	0.01	0.001	0.304	0.805	0.636	0.196	0.126
G/F	0.75	0.80*	0.80*	0.80*	0.78	0.80*	0.79	0.01	0.027	0.911	0.898	0.645	0.510	0.214
d 0 to 35														
ADG, kg	0.39	0.35*	0.36	0.36	0.36	0.39	0.37	0.01	0.049	0.362	0.726	0.827	0.077	0.088
ADFI, kg	0.55	0.47*	0.49*	0.49*	0.50*	0.52	0.50*	0.01	0.001	0.201	0.517	0.627	0.153	0.030
G/F	0.70	0.74*	0.73	0.73*	0.73	0.74*	0.72	0.01	0.020	0.429	0.505	0.435	0.312	0.286

continued

Table 2.6 *continued* Effect of conditioning temperature and die specifications on nursery pig performance.

[1] A total of 360 barrows (DNA 200 × 400) with initial body weight (BW) of 5.9 kg, were used in a 35-d growth trial with 5 pigs per pen and 9 pens per treatment.
[2] All diets were mixed at Hubbard Feeds (Beloit, KS) and transported to KSU for further processing.
[3] Diets were fed as follows, phase 1 from d0-10, phase 2 from d10-25, and a common mash diet was fed to all test pigs from d 25 until the end of the study on d 35.
[4] Pelleted diets were manufactured on two pellet dies with a pellet diameter of 4.7 mm with an L:D ratio of either 6.7 or 2.7.
[5] Conditioning temperatures for phase 1 feed was approximately 27 (Low), 38 (Med), and 49°C (High) using the 6.7 L:D die and 378 (Low), 49 (Med), and 60°C (High) using 2.7 L:D die. Phase 2 feed was conditioned to approximately 49 (Low), 60 (Med), and 71°C (High) using the 6.7 L:D die and 60 (Low), 71 (Med), and 82°C (Low) using the 2.7 L:D die.
[6] MC = Mash Control
[7] Analysis was performed using Dunnett's multiple comparison for all parameters and contrasts were used to separate treatment means with comparison of die (6.7 vs 2.7) and temperature within die
[8] * denotes a $P < 0.05$ significant difference from the MC diet
[9] From day 25-35 of the study all pigs were given a common mash diet.

Chapter 3 - Effects of grinding corn with different moisture concentration on subsequent particle size and flowability characteristics

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. Whole yellow dent #2 corn was used for this experiment. Treatments were arranged as a 2 × 2 factorial design with two moisture concentrations (14.5 and 16.7% moisture) each ground using 2 hammermill screen sizes (3mm and 6mm). Corn was ground using a lab scale 1.5 HP Bliss Hammermill at 3 separate time points to create 3 replications per treatment. Increasing initial whole corn moisture was accomplished by adding 5% water and heating at 55ºC for 3 hours in sealed glass jars using a Fisherbrand Isotemp Oven (Model 15-103-051). 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 3mm screen resulted in decreased ($P < 0.041$) moisture content compared to corn ground using the 6mm screen. There was a decrease ($P < 0.031$) in particle size from the 6mm screen to the 3mm 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 3mm to 6mm. Angle of repose tended to decrease ($P < 0.056$) when corn was ground using a 6mm screen compared to a 3mm 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. 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 5.5 g/kg, 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, Grind, Moisture, Flowability, Particle Size

Introduction

Reducing the particle size of cereal grains is 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 consumes 70% of the total energy used during the feed production process (Dabbour, 2015). Hammermills are the most commonly used size-reduction equipment because of their high throughput rates and versatility in grinding of different materials (Bitra et al., 2009).

Hammermills achieve particle size reduction by utilizing impact forces to shatter larger particles into smaller particles (Austin, 2002). Overall mill performance is dependent on many different factors such as initial particle size, material, feed rate, machine configuration, and moisture content (Mani et al., 2004). Initial moisture content (MC) is one of the most important factors to consider. Yellow dent #2 corn at approximately 15% moisture content is the most common grain typically used for feed in the US. However, the MC of corn can vary greatly based on the region of origin, weather patterns, and harvest conditions. Changes in the MC can affect the performance of the grinding equipment, energy usage, and the characteristics of the ground material (Probst et al., 2013). Furthermore, MC influences the cohesion and adhesion of particles which can alter the flowability of materials (Fitzpatrick et al., 2004). Therefore, the overall 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.

Procedures

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 two moisture levels (14.5 and 16.7%) and ground using 2 hammermill screen sizes. The screen holes measures 3mm and 6mm in diameter. Increasing initial whole corn moisture was accomplished by adding 5% water and heating at 55ºC for 3 hours 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) 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 then were analyzed for moisture, particle size, and flowability characteristics. Ground corn samples were analyzed for moisture according to AOAC 930.15.

Particle Size Analysis

Particle size analysis was conducted according to the ANSI/ASAE S319.2 standard particle size analysis method as described by Kalivoda (2016). 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) 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. 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.

Physical and Flow Property Measurements

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 detailed by Horn (2008). 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 (Appel, 1994).

The critical orifice diameter was determined using a powder flowability test instrument (Flodex Model WG-0110, Paul N. Gardner Company, Inc., Pompano Beach, FL). 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 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 (Kalivoda, 2016).

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 (Kalivoda, 2016).

Statistical Analysis

Data were analyzed as 2 × 2 factorial using the PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC). Grinding run served as the experimental unit and each treatment was replicated 3 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.

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 3mm screen resulted in decreased ($P < 0.041$) MC compared to corn ground using the 6mm screen. There was a decrease ($P <= 0.031$) in particle size from the 6mm screen to the 3mm 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 3mm to 6mm. Angle of repose tended to decrease

(*P* < 0.056) when corn was ground using a 6mm screen compared to a 3mm 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* < 0.029) particle size and an increase (*P* < 0.038) in standard deviation 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.

Discussion

Corn particle size is a key quality measure when manufacturing feed. The experiment reported herein shows corn of different initial MC ground using two different screen sizes on a hammermill will have different physical characteristics post grinding. Koch (2002) details the basic characteristics of grinding with a hammermill and the use of screens to control grind size. The decrease in particle size observed from the 6mm screen to the 3mm is expected. To achieve the increased particle size reduction, material will spend more time in the grinding chamber to reach the desired particle size (Martin, 1981). The observed loss in MC observed 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 (Guo et al., 2016).

Jindal and Austin (1976) as well as Adapa et al. (2011) described how increased MC influences the breaking behavior of material during the grinding process. The results of the experiment reported herein suggest that as MC decreased the S_{gw} of the ground material increased. The increase in MC and subsequent reduction in S_{gw} 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 of the ground material. Probst et al. (2013) evaluated corn as well as corn cobs at three different moisture contents on grinding performance and the characteristics of the ground material. An increase in post-grinding moisture loss as well as an increase in S_{gw} 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 S_{gw} or a more uniform grind.

The particle size of material as well as its distribution can cause segregation during handling and affects the flowability of materials (Barbosa-Canovas et al., 2015). Kalivoda et al. (2016) reported a reduction in particle size corresponded with poorer flowability characteristics caused predominantly by fine particles. The shape of these fine particles may be the main cause for their negative impacts on flowability (Goodband et al., 2006). Horn (2008) details the characteristics of particles that may cause poor flowability such as particle size, shape, density, and surface among other factors. Small or fine particles are a significant flowability concern due to the attractive forces between particles. Smaller particles result a smaller distance between individual particles. Therefore, the cohesion forces between particles, primarily due to Van der Waals attraction, is stronger and results in poorer flowability (Yang et al., 2005). 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 (United States Pharmacopoeial Convention [USP], 2007). The percent compressibility is defined as an indication of the incremental, volumetric, structural and/or increasing of external forces (Harnby et al., 1987). Critical orifice diameter is a method that employs a cylinder with a series of interchangeable base plate discs that have 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. (Taylor et al., 2000). These measurements were then compiled into a composite flow index using the equations detailed by Horn (2008). A single value of flowability that considers all evaluations can be beneficial when evaluating flowability results as it can demonstrate and overall rating as well as individual characteristics of ground material and where problems may arise. A scale reported by Horn (2008) helps to further understand the results of the composite flow index. A score less than 15 corresponds to very, very poor flowability while 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 3mm screen which had a poor rating.

While energy consumption was not evaluated in the experiment reported here in, there is evidence MC impacts energy consumption. Tran et al. (1981) found a linear relationship between MC and grinding energy that decreased with increased moisture. This decrease in energy consumption is due to lower MCs resulting in a harder product to be ground (Tran et al., 1981). However, Armstrong et al. (2007) reported that changes in grinding energy consumption are more predictable in the region of 10 to 13% moisture content. Further research is needed on the impact of moisture content, energy consumption, as well as air assist systems on the particle size of corn.

Conclusion

This experiment shows corn samples of different initial moisture content, ground using two different screen sizes on a hammermill, will have different physical characteristics post-grinding. Decreasing screen size decreased particle size and resulted in poorer flowability. A CFI greater than 45 is considered passable and all treatments met this standard except 14.5% moisture corn that was ground using the 3mm screen. When corn was ground using the 3mm in screen, a 5.5 moisture loss was observed compared to the 6mm 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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Table 3.1 Effect of initial corn moisture and screen size on physical characteristics of ground corn

	3mm		6mm			Probability, *P* <		
Item	14.5%	16.7%	14.5%	16.7%	SEM	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}[1]	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, ° [2]	52.07	47.21	47.24	46.00	1.35	0.056	0.055	0.219
Critical orifice diameter[3]	30.0	26.0	27.3	23.3	1.79	0.175	0.056	1.00
Compressibility, %[4]	26.8	26.1	25.4	23.0	0.85	0.030	0.112	0.344
Composite flow index[5]	38.5	46.6	45.6	52.4	3.02	0.063	0.038	0.839

[1] Particle size and standard deviation (Sgw) are determined according to ASABE 319.2 methods.

[2] 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).

[3] Critical orifice diameter was determined using a Flodex device to determine product mass flow characteristics through varying discharge outlet sizes.

[4] 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

[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).

Chapter 4 - Evaluation of Hammermill Tip Speed, Air Assist, and Screen Size on Ground Corn Characteristics

Abstract

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 ground corn. Whole yellow dent #2 corn was ground and samples collected at the JBS Live Pork LLC feed mill in Fremont, IA. Corn was ground using two Andritz hammermills (Model: 4330-6, Andritz Feed & Biofuel, Muncy,PA) measuring 1-m in diameter. Each mill was equipped with 72 hammers and 300 HP motors on a variable frequency drive (VFD). Treatments were arranged in a 3 × 3 × 3 factorial design with 3 tip speeds (3,774, 4,975, and 6,176 m/min), 3 screen hole diameters (2.3, 3.9 and 6.3 mm), and 3 air flow rates (1,062, 1,416, and 1,770 fan RPM). Corn was ground on 3 separate days to create replication and treatments were randomized within replication. Samples of each treatment were collected and analyzed for moisture, particle size, and flowability characteristics. The flowability characteristics of finished diets were evaluated using a composite flow index (CFI), which includes percent compressibility, angle of repose (AoR), and critical orifice diameter (COD). There was a 3-way interaction for particle size standard deviation (S_{gw}), (linear screen hole diameter × linear hammer tip speed × linear air flow, $P = 0.029$). When corn was ground using the 2.3 mm screen, increasing hammer tip speed decreased particle size S_{gw}. Furthermore, increasing air flow rate increased the S_{gw} when corn was ground using a hammer tip speeds of 3,774 and 6,176 m/min but no difference was observed at 4,975 m/min. When grinding with the 3.9 mm screen, increasing hammer tip speed reduced particle size 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 1,062 to 1,770 RPM increased particle size S_{gw}

when corn was ground using a tip speed of 3,774 m/min; however, there was no difference in air flow when a tip speed of 6,176 m/min was used. Corn ground using the 6.3 mm screen showed increases in S_{gw} at the 1,062 and 1,416 RPM air flow settings and decreased S_{gw} at the 1,770 RPM air flow setting with increasing hammer tip speeds. Furthermore, increasing air flow at hammer tip speeds of 3,774 and 4,975 m/min increased S_{gw} but no difference was observed at 6,176 m/min.

Keywords: Corn, Grind, Air Assist, Flowability, Particle Size

Introduction

Particle size reduction is one of the basic steps in processing grains (Dziki, 2008). Animal feed undergoes particle size reduction for a number of reasons such as improving nutrient digestion and reducing material handling and labor costs by facilitating (Berk, 2013; Wennerstrum et al., 2002). 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 (Koch, 2002). Hammermills consist of a rotor assembly within a screened chamber that houses hammers that rotate with the rotor assembly (Heiman, 2005). 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 as a result of impact (Austin, 2002; Probst et al., 2013; Saravacos and Kostaropoulos, 2002). 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 to fit through the size of the perforated 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 hammer 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 (Lyu, 2020). 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 hammer tip speed and air flow rate. . 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.

Procedures

Whole yellow dent #2 corn was ground and samples 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). 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 replication and treatments were randomized within replication. Treatments were arranged in a 3 × 3 × 3 factorial design with 3 tip speeds (3,774, 4,975, and 6,176 m/min), 3 screen hole diameters (2.3, 3.9 and 6.3 mm), and 3 air assist system fan RPM's (1,062, 1,416, and 1,770 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). 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 AOAC 930.15.

Particle Size Analysis

Particle size analysis was conducted according to the ANSI/ASAE S319.2 standard particle size analysis method as described by Kalivoda (2016). 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) 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. 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.

Physical and Flow Property Measurements

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 described by Horn (2008). 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 (Appel, 1994).

The critical orifice diameter was determined using a powder flowability test instrument (Flodex Model WG-0110, Paul N. Gardner Company, Inc., Pompano Beach, FL). 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 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 (Kalivoda, 2016).

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 (Kalivoda, 2016).

Statistical Analysis

Data were analyzed as a 3 x 3 x 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 (3,774 vs 4,975 vs 6,176), and air flow rate (1,062 vs 1,416 vs 1,770). Linear and quadratic polynomials were used to test increasing parameters within each main effect. Results were considered significant if $P \leq 0.05$.

Results

There were no 3-way interactions for screen hole diameter × hammer tip speed × air flow for the d_{gw} or any flowability characteristics of ground corn (Table 1). However, there was a screen hole diameter × hammer tip speed × 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 1,062 RPM. However, increasing tip speed did not influence S_{gw} when the air assist was set at 1,416 or 1,770 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 3,774, 4,975, or 6,176 ft/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 1,062 to 1,770 RPM increased S_{gw} when corn was ground using a tip speed of 3,774 m/min; however, there was no difference in air flow when a tip speed of 6,176 was used. When corn was ground using the 6.3 in screen, there was no evidence of difference in S_{gw} when increasing hammer tip speed when the air assist was set at 1,062 RPM. Increasing hammer tip speed increased Sgw when the air assist was set at 1,416 RPM and increasing hammer tip decreased S_{gw} when the air assist motor was set at 1,770 RPM. Furthermore, increasing air flow at hammer tip speeds of 3,774 and 4,975 m/min increased S_{gw} but no difference was observed at 6,176 ft/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 3,774 to 6,176 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 critical orifice diameter (P = 0.018). When grinding using a hammer tip speed of 3,774 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 4,975 and 6,176 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 3,774 m/min but no differences were observed as tip speed increased to 4,975 and 6,176 ft/mmm 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 3,774 m/min to 4,975 m/min on the 2.3 mm screen. Lastly, 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.

An 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. 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

For the main effect of screen hole diameter, linear increases in particle size ($P < 0.001$) and standard deviation ($P < 0.001$) were observed with increasing screen hole diameter. A decrease in angle of repose (Linear, $P < 0.002$) was observed with increasing screen hole diameter. Furthermore, a similar decrease in critical orifice diameter ($P < 0.010$) was observed with increasing screen hole diameter. These decreases translated to an increase ($P < 0.018$) in the composite flow index corresponding with improved flowability. Lastly a linear decrease (P < 0.001) was observed in mill motor load with increasing screen hole diameter. There was no significant results of percent compressibility or moisture for any of the main effects of screen hole diameter, hammer tip speed, or air flow. For the main effect of hammer tip speed, a decrease (Linear, $P < 0.001$) in particle size was observed with increasing hammer tip speeds. Additionally, a decrease in standard deviation (Linear, $P < 0.001$) was also observed with increasing hammer tip speeds. For flowability metrics, increased hammer tip speeds resulted in increases in angle of repose (Linear, $P < 0.025$) as well as an increase in critical orifice diameter (Linear, $P < 0.014$). These decreases resulted in subsequent decrease in the composite flow index (Linear, $P < 0.002$) or poorer flowability. Lastly, linear increases in mill motorload ($P < 0.001$) and mill temp ($P < 0.007$) were also observed with increasing hammer tip speed. For the main effect of air flow, a significant increase (Quadratic, $P < 0.001$) in standard deviation was observed with increased air flow rate. There was also a quadratic decrease ($P < 0.004$) for angle of repose of corn ground using increased air flow rates. There was no significant results of percent compressibility or moisture for any of the main effects of screen hole diameter, hammer tip speed, or air flow.

Discussion

Corn particle size, or geometric mead 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. Koch (2002) details the basic characteristics of grinding with a hammermill and the use of screens to control grind size. 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 (Martin, 1981). 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 (Al-Rabadi, 2013; Miao et al., 2011). As the time spent in the grinding chamber increases friction becomes more and more significant as particles contact the hammers as well as the surface of the screen which leads to increased fragmentation of particles (Milanovic, 2018). 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 (Tran, 1981). Bochat et al. (2015) also found that increasing hammer tip speed and screen hole diameter increased hammermill through put. 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. (2016) 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. (2008), 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. The particle size of material as well as its distribution can cause segregation during handling and affects the flowability of materials (Barbosa-Canovas et al., 2015). Haque (2010) 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 (Haque, 2010).

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 is minimal published data that has evaluated 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. Lyu et al. (2020) stated 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}. 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.

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. (1994) observed improvement in the performance of pigs when corn was reduced from 1000 to 500 micron. Callan et al (2007) 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 (Deaton et al., 14,975; Charbeneau and Roberson, 2004). However, increasing the S_{gw} to include a larger portion of large particles was shown to improve broiler performance (Hetland et al., 2002). This improvement is driven by the larger particles stimulating gizzard development (Svihus, 2011).

Conclusion

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 3,774, 4,975, and 6,176 m/min as well as air flow settings of 1,062, 1,416, and 1,770 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 with 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.

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Table 4.1 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,
Hammer tip speed, m/min[3]	3,774	4,975	6,176	3,774	4,975	6,176	3,774	4,975	6,176	SEM	*P* <[6]
Particle size, µm[5]											
Air flow[4]											
1,062	344	341	296	443	395	334	580	437	380		
1,416	361	314	273	477	390	336	652	437	357	25.26	0.227
1,770	408	330	342	433	389	349	620	452	351		
Standard deviation, Sgw[5]											
Air flow											
1,062	3.07	2.97	2.86	3.25	3.03	2.93	3.10	3.21	3.23		
1,416	2.97	2.82	2.89	3.05	2.91	2.87	2.89	3.07	3.24	0.086	0.029
1,770	3.13	2.97	2.97	3.47	3.13	2.97	3.54	3.46	3.27		

[1] Corn was ground using two 43 mm Andritz hammermills (Model 4330-6, Andritz Feed & Biofuel, Muncy, PA) equipped with 72 hammers and 300 HP motors on variable frequency drives (VFD). 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 1,062, 1,416, or 1,770 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 4.2 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, in[2]	2.3			3.9			6.3				Probability,
Tip speed, m/min[3]	3,774	4,975	6,176	3,774	4,975	6,176	3,774	4,975	6,176	SEM	*P* <
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 diameter[5]	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, %[6]	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[7]	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] Corn was ground using two 43 mm Andritz hammermills (Model 4330-6, Andritz Feed & Biofuel, Muncy, PA) equipped with 72 hammers and 300 HP motors on variable frequency drives (VFD). 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] 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).

[5] Critical orifice diameter was determined using a Flodex device to determine product mass flow characteristics through varying discharge outlet sizes.

[6] Percent compressibility is calculated by using the Hausner ratio (PTapped/PBulk).

[7] 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

Table 4.3 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,
Air flow, RPM[3]	1,062	1,416	1,770	1,062	1,416	1,770	1,062	1,416	1,770	SEM	*P* <[5]
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] Corn was ground using two 43 mm Andritz hammermills (Model 4330-6, Andritz Feed & Biofuel, Muncy, PA) equipped with 72 hammers and 300 HP motors on variable frequency drives (VFD). 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 1,062, 1,416, or 1,770 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

Table 4.4 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	3,774	4,975	6,176	1,062	1,416	1,770	SEM	Screen	Tip	AS
Physical Analysis													
Particle size, 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] Corn was ground using two 43 mm Andritz hammermills (Model 4330-6, Andritz Feed & Biofuel, Muncy, PA) equipped with 72 hammers and 300 HP motors on variable frequency drives (VFD). 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 1,062, 1,416, or 1,770 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).