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Summary

Two experiments were conducted to determine the processing characteristics of yellow corn and three varieties of sorghum grain: red non-waxy, red waxy, and white waxy. Experiment 1 was conducted with consistent hammermill parameters to determine the impact of each respective grain source on subsequent particle size (d_{gw}), standard deviation (S_{gw}), and angle of repose (AoR). The four grain sources ground within the first experiment were then formulated into diets to be manufactured into pelleted feed. All pelleting parameters were held consistent throughout the duration of the experiment to determine the effects of different grain sources on the pelleting process and subsequent pellet durability index (PDI). Results within exp. 1 determined the four grain sources to have different d_{gw} values. To account for the confounding factor of particle size, exp. 2 was conducted with the same experimental design, however, aimed to achieve a consistent target d_{gw} within each of the four grain types. Data were analyzed as a randomized block design using the GLIMMIX procedure in SAS v9.4. When grinding with consistent hammermill parameters, d_{gw} was greater (P=0.001) in both waxy varieties of sorghum when compared to red non-waxy sorghum and yellow corn. Yellow corn had a greater (P<0.001) S_{gw} when compared to that of the sorghum grain varieties. Waxy sorghum grain had improved ($P < 0.001$) AoR in comparison to the other grain sources. When grinding to a consistent particle size, the sorghum varieties had improved AoR values ($P < 0.001$) when compared to yellow corn. Finally, both red and white waxy sorghum-based diets had improved PDI ($P < 0.05$) within both experiment 1 and 2 when compared to red non-waxy and yellow corn-based diets. In conclusion, waxy sorghum grain had significant impacts in feed processing characteristics such as a greater d_{gw} and an improved PDI when compared to yellow corn, thus representing possible improvements for feed processing quality when using these respective varieties of sorghum grain.

Introduction

Cereal grains are utilized within livestock feed production as the main source of dietary energy. Yellow corn is the most common starch source available for livestock

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feed, however the use of sorghum grain is becoming increasingly popular as a feed commodity as it becomes more available for producers. Like many other cereal grains grown throughout the world, sorghum grain has many varieties that comprise total production. Within livestock production and feed manufacturing, an aspect of interest is the difference between waxy and non-waxy sorghum grain varieties. Non-waxy, or traditional grain sorghum, is reported as having a composition of 25% amylose and 75% amylopectin, which is very similar to yellow corn, while waxy sorghum hybrids have been found to consist of almost entirely amylopectin.[2] The absence of amylose within waxy starches produces added benefits to food processing properties including gelling, viscosity, and stability, but also benefits to starch digestibility due to the branched structure of amylopectin increasing surface area for enzymatic activity.[3] The added benefits observed in waxy starches give the possibility to improve livestock performance, as well as feed processing characteristics; however, little research has been conducted to understand the key feed manufacturing characteristics of sorghum grain varieties. Therefore, the objective of this study is to determine the effects of grinding and pelleting different sorghum grain varieties with a hammermill on subsequent particle size, standard deviation, and pellet durability index.

Materials and Methods

Experiment 1: Grinding, constant hammermill parameters

Four grain sources, yellow corn and red non-waxy, red waxy, and white waxy sorghum were split into three 45 lb batches and ground with a laboratory-scale 1.5 horsepower bliss hammermill (Bliss Industries LLC., Ponca City, OK). All hammermill parameters were held consistent throughout the duration of this experiment including a constant feeder rate, a tip speed of 21677 ft/s, and a screen hole diameter of 0.156 in (#10). Each treatment was ground at three separate time points to produce three replications for each grain source. At each period a complete batch was ground before a sample was collected for further analysis. All samples in this study were collected using a sample probe, before being analyzed for geometric mean diameter (d_{gw}), standard deviation (S_{gw}), and angle of repose (AoR).

Experiment 2: Grinding, constant target mean particle size (d_{gw})

The four grain sources were split into three 45 lb batches and ground with a laboratory-scale 1.5 horsepower (HP) bliss hammermill (Bliss Industries LLC., Ponca City, OK). A target particle size of 550 µm was achieved by changing the screen hole diameter for each grain source. Yellow corn was ground with a 0.172 in (#11) screen, while red non-waxy sorghum was ground with a 0.156 in (#10) screen. Both the red and white waxy sorghum gains were ground using a 1.25 in (#8) screen. Each treatment was ground at three separate time points to produce three replications for each grain source. At each period, a complete batch was ground before a sample was collected for further analysis. All samples in this study were collected using a sample probe, before being analyzed for geometric mean diameter (d_{gw}), standard deviation (S_{gw}), and flowability characteristics through angle of repose (AoR).

Particle size analysis

Particle size analysis was conducted according to the ANSI/ASAE S319.2 standard particle size analysis method as described by Kalivoda.[4] Samples were analyzed in duplicate for geometric mean diameter (d_{gw}) using a Tyler Ro-Tap machine (Model

1116, Tyler Industrial Products Inc., Mentor, Ohio) with flow agent, balls, and brushes (ANSI/ASAE S319.2 standard). Each ground grain sample was split using a riffle divider before weighing 0.220 lb of product. The 0.220 lb sample was then placed on the top sieve of a 13-sieve stack where 0.001 lb of silica flow agent was added. The sieve stack was then placed in the Tyler Ro-Tap machine for 10 minutes before individually weighing each sieve. This procedure was completed for all treatment samples in duplicate to calculate particle size and standard deviation for grinding results.

Flowability analysis

The flowability characteristics of ground grain treatment samples were evaluated using angle of repose (AoR). The AoR was estimated by allowing a sample to flow from a vibratory conveyor above a free-standing platform until it reached 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). Results of angle of repose values can be used to determine the flowability properties of a material. A range of 25-30 degrees represents an excellent flowing product, 31-35 degrees is a good flowing product, 36-40 degrees is a fair flowing product, 41-45 degrees represents a passable result, 46-55 degrees describes a poor flowing product, 56-55 degrees is considered very poor flowing product, and >66 degrees is a very, very poor flowing material.

Statistical analysis: Grinding

Data were analyzed as a randomized block design using the GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC). The experimental unit was the 45 lb batch of grain. The fixed effect was the treatment, while the blocking factor was set at day of grinding.

Experiment 1 and 2: Feed processing

Feed was manufactured in accordance with Current Good Manufacturing Practices at the Kansas State University O.H. Kruse Feed Technology Innovation Center, Manhattan, KS.

Diets were formulated as a late-finishing swine ration, balancing digestible amino acids throughout each treatment. Diets were designed by replacing the starch source with each of the four respective grain sources used within the grinding portion of these experiments. Formulation parameters were held consistent including 83.15% of the respective grain source, 13.7% soybean meal, and 1.0% added soybean oil throughout all treatments. All ingredients were weighed on a certified scale. Each diet was mixed in a 200 lb Davis paddle mixer to produce a total of 150 lb per treatment. Once the feed was mixed (150 lb), it was discharged and sacked off into 50 lb bags to produce three replications per treatment. Every bag was sampled and composited as a retained mash feed sample. Bags were then emptied into the hopper of the pellet mill to be manufactured into pelleted diets in a randomized block design. Treatments were steam conditioned for approximately 30 seconds with a target conditioning temperature of 180°F and pelleted on a pellet mill (Model CL-5, California Pellet Mill) equipped with a 0.157 in x 0.087 in pellet die (L:D 5.6). Production rates were targeted at 2.2 lb/min and held constant for all treatments. When pelleting, once target throughput and conditioning temperature were achieved the pelleting data and sample collection began. Temperature readings were recorded for conditioned mash feed and hot pellets. Hot pellets collected for temperature measurement were then compared to the original conditioning temperature. This change in temperature (Δ Temp) allowed for the frictional heat from the pellet mill die to be measured. During pelleting, hot pellets were collected directly off the pellet mill die chamber and set in trays at three different time points. Pellet samples were cooled in an experimental counter-flow cooler for 10 minutes to ensure cooled pellets were within 5°F of ambient room temperature. The sample pellets collected were then used to determine the pellet durability index (PDI) for each treatment.

Pellet durability index analysis

For PDI analysis, each sample was analyzed in duplicate using the Holmen NHP100 machine. Each sample was riffle divided and sifted using a #6 screen to remove any broken-down pellet fragments or fines. Next, 0.220 lb of sifted pellet sample was weighed and placed into the Holmen 100 machine for 30 seconds. The sample was then removed and sifted using the #6 screen to remove pellet fragments or fines and weighed. Samples were tested for each pelleted treatment in duplicate. The PDI values were calculated using the equation below:

$$\text{PDI Value} = (\text{final weight} / \text{initial weight}) \times 100$$

Statistical analysis: Pelleting

Data were analyzed as a randomized block design using the PROC GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC). Experimental unit was pelleting run. Fixed effects were the dietary treatment, while the blocking factor was set at time period of pelleting.

Results and Discussion

For exp. 1, when grinding grains with consistent hammermill parameters, there was an overall effect ($P < 0.001$) on d_{gw}, S_{gw}, AOR, percent < 212 µm, and percent < 150 µm. Red and white waxy sorghum grain had increased ($P < 0.05$) d_{gw} when compared to that of the red non-waxy sorghum and yellow corn. In addition, red non-waxy sorghum resulted in increased ($P < 0.05$) d_{gw} compared to corn (Table 1). Yellow dent corn had increased ($P < 0.05$) S_{gw} compared to all sorghum varieties, with red and white waxy sorghum grains decreased S_{gw} compared to non-waxy sorghum. A greater quantity of coarse material and decreased quantity of fine material observed in the waxy varieties of sorghum led to a larger subsequent d_{gw} and decreased S_{gw} value. Both S_{gw} and d_{gw} can have a significant impact on the flowability characteristics of ground grain. Within this experiment, the yellow dent corn had an AoR (53.1°) greater ($P < 0.05$) than that of the red non-waxy sorghum (45.6°). However, both the yellow dent corn and red non-waxy sorghum had an increased ($P < 0.05$) AoR compared to both the red (43.4°) and white (43.3°) waxy sorghum grains. Therefore, sorghum grains had an improvement in flowability characteristics when compared to that of the yellow corn. There was a significantly larger ($P < 0.001$) quantity of fine material, percent < 212 µm, and percent < 150 µm, within ground yellow dent corn, while the red waxy and white waxy sorghum grains had significantly lower quantities. Red non-waxy sorghum was intermediate within both categories, however it was still found to be significantly greater than that of the waxy sorghum varieties. These differences in fine material within respective grain sources likely led to the observed changes within flowability due to granular powders having higher cohesiveness and stronger binding properties.

Diet composition and formulation parameters from exp. 1 are represented in table 2. Pelleting results (Table 3) indicated that there was no significant difference (P=0.407) between grains in the change in temperature (Δ temp.) from the conditioning system to the final pellet exiting the die chamber. For exp. 1, there was an overall treatment effect observed (P < 0.01) for PDI. The corn-based diet had the poorest PDI (P < 0.05) compared to that of the sorghum-based diets. However, both the red and white waxy sorghum-based diets had greater (P < 0.05) PDI compared to the non-waxy sorghum-based diets. Therefore, pelleting waxy sorghum-based diets resulted in improved pellet quality compared to the non-waxy sorghum and corn-based diets; however, this response was confounded with d_{gw} and S_{gw} of the cereal grains. Traditionally, it is considered that reducing the particle size of cereal grains should aid in the pelleting process resulting in improved PDI. In the data reported herein, the increased d_{gw} of waxy sorghum grains did not negatively affect the PDI of these diets but conversely had improved PDI compared to the non-waxy sorghum and corn-based diets.

For exp. 2, changing the screen size for each respective grain source allowed for targeting the d_{gw} of 550 µm. Although a consistent d_{gw} was targeted, there were observed changes in particle distribution as denoted by an overall effect (P = 0.002) on S_{gw}. Yellow dent corn and red non-waxy sorghum had increased Sgw when compared to both waxy varieties of sorghum (Table 4). Greater quantities of fine material and less coarse material found within the yellow dent corn and red non- waxy sorghum grains led to a larger Sgw, while a consistent particle size was achieved. Thus, leading to the overall effects on (P < 0.05) AOR, percent < 212 µm, and percent < 150 µm. Within this experiment yellow dent corn had an AOR (50.2°) greater (P < 0.05) than that of the red non-waxy (46.7°), red waxy (46.0°), and white waxy sorghum grains (46.0°). However, no significant improvements are observed within flowability characterization of the four grain sources, representing similar flowability characteristics when ground to a consistent particle size. For exp. 2, there was a significantly larger (P < 0.05) quantity of fine material, percent < 212 µm, and percent < 150 µm, within ground red non-waxy sorghum when compared to that of the red and white waxy sorghum. Yellow dent corn was found to be similar (P > 0.05) to that of the red non-waxy sorghum, while white waxy sorghum was similar to that of the yellow dent corn. Red waxy sorghum represented the lowest quantity of fine material within both percent < 212 µm, and percent < 150 µm, however when observing the percent < 150 µm, both waxy varieties of sorghum become more similar.

Diet composition and formulation parameters from experiment 2 are represented in table 2. Pelleting results (Table 5) indicated that there was no significant difference between grains in the change in temperature (Δ temp) from the conditioning system to the final pellet exiting the die chamber (P=0.348). For exp. 2, there was an overall treatment effect observed (P < 0.01) for PDI. The corn and red non-waxy sorghum-based diets had the poorest PDI (P < 0.05) compared to that of the waxy sorghum-based diets. The white waxy sorghum-based diet had greater (P < 0.05) PDI compared to the corn and non-waxy sorghum-based diets, however, the red waxy sorghum-based diet had an improved PDI when compared to all other treatments. Therefore, pelleting waxy sorghum-based diets resulted in improved pellet quality compared to the non-waxy sorghum and corn-based diets.

Differences in endosperm composition of the four grain sources likely led to the waxy sorghum varieties having less fine material within grinding, subsequently changing the characteristics of particle size reduction in these specific grains. Within applied feed manufacturing, producers will need to account for differences in grinding characteristics when changing grain sources and understand that significant differences can be found in mean particle size, particle distribution, and flowability traits when no grinding parameters are changed between different grain sources. Differences in chemical properties found between waxy and non-waxy starch grains may have led to greater binding properties within the pelleting system, thus a greater pellet quality was achieved. Producers utilizing different sources of grain may see improvements in pellet quality, depending on processing parameters and grain variety. To most effectively utilize these grain sources, it will be important to determine the exact impact waxy sorghum grains have on feed manufacturing, as well as further understanding their impact on starch digestibility within swine diets.

Table 1. Effect of grinding corn and different sorghum grain varieties with constant hammermill settings on subsequent particle size (d_{gw}), standard deviation (s_{gw}), angle of repose (AoR), and percentage of fine particles[1,2]

	Grain Type					
Item	Yellow Corn	Red Non-waxy	Red Waxy	White Waxy	SEM	*P* <
Particle Size (d_{gw})[3]	438[c]	567[b]	664[a]	688[a]	21.1	0.001
Standard Deviation (s_{gw})[4]	3.34[a]	2.84[b]	2.39[c]	2.39[c]	0.059	0.001
AoR (°)[5]	53.1[a]	45.6[b]	43.4[c]	43.3[c]	0.468	0.001
<212µm (%)[6]	25.94[a]	18.78[b]	11.39[c]	11.26[c]	0.924	0.001
<150µm (%)[7]	21.15[a]	15.18[b]	8.55[c]	8.53[c]	0.822	0.001

[1]Four grain sources were ground in a randomized block design using a laboratory-scale bliss hammermill with constant parameters including feeder rate, a tip speed of 21677 ft/s and a screen size 0.156 in (#10).
[2]Means within a row followed by a different letter ([a-c]) are significantly different ($P \leq 0.05$).
[3]Geometric mean diameter was determined using ASABE S319.2 standard particle size method.
[4]Standard deviation of the geometric mean diameter was determined using ASABE S319.2 standard particle size method.
[5]Flowability characteristics were determined using a Flowdex machine to estimate angle of repose values.
[6]Fine particle were determined as a percentage of material below the d_{gw} of 212µm.
[7]Fine particle were determined as a percentage of material below the d_{gw} of 150µm.

Table 2. Corn and sorghum grain-based diet composition[1]

		Sorghum Variatey		
Ingredients, %	Yellow Corn	Red Non-waxy	Red Waxy	White Waxy
Corn	83.11	0	0	0
Soybean meal, 46.5% CP	13.68	13.68	13.68	13.68
Sorghum	0	83.17	83.17	83.17
Soybean oil	1.00	1.00	1.00	1.00
Calcium carbonate	0.60	0.61	0.61	0.61
Monocalcium P, 21% P	0.10	0.02	0.02	0.02
Salt	0.50	0.50	0.50	0.50
L-Lys	0.35	0.39	0.39	0.39
DL-Met	0.07	0.08	0.08	0.08
L-Thr	0.12	0.11	0.11	0.11
L-Trp	0.03	0.02	0.02	0.02
L-Val	0.03	0.00	0.00	0.00
Trace mineral premix	0.15	0.15	0.15	0.15
Vitamin premix	0.25	0.25	0.25	0.25
Phytase[2]	0.02	0.02	0.02	0.02

[1]Diets were formulated for finishing pigs weighing 220- 280 lb.
[2]Quantum Blue 10g (AB Vista., Plantation, FL) provided 10,000 units of phytase FTU/g of diet with an assumed release of 0.14 available P.

Table 3. Effect of corn and sorghum grain-based diets on subsequent change in temperature (Δ Temp.) across the die and pellet durability index (PDI) (Exp. 1)[1]

		Sorghum Variatey				
Item	Yellow Corn	Red Non- waxy	Red Waxy	White waxy	SEM	*P* =
Δ Temp., °F[3]	8.30	12.39	10.81	9.78	1.62	0.407
PDI, %[4]	68.6[b]	70.4[b]	92.1[a]	85.2[a]	4.15	0.006

[1]Four treatments were pelleted in a randomized block design using constant pelleting parameters throughout all treatments. Steam conditioning occurred for approximately 30 seconds with a temperature of 180°F before being pelleted using a CL-5, California Pellet Mill equipped with a 0.157 in x 0.087 in pellet die (L:D 5.6). Production rates were targeted at 2.2 lb/ min and held constant for all treatments.
[2]Means within a row followed by a different letter ([a-c]) are significantly different ($P \leq 0.05$).
[3]Change in temperature was determined by calculating the difference in conditioning temperature and hot pellet temperature directly from the die chamber.
[4]Pellet durability index was determined using a Holmen NHP100 machine at the 30 second setting. Pellet samples were screened before and after this process using a #6 sieve.

Table 4. Effect of grinding corn and different sorghum grain varieties with a hammermill to a consistent mean particle size on subsequent AoR and percentage of fine particles[1,2]

		Sorghum Variety				
Item	Corn	Red Non-waxy	Red Waxy	White Waxy	SEM	*P* =
Standard Deviation (S_{gw})[3]	2.95[a]	2.92[a]	2.44[b]	2.49[b]	0.054	0.002
AoR (°)[4]	50.2[a]	46.7[b]	46.0[b]	46.0[b]	0.609	0.001
<212 µm (%)[5]	17.70[ab]	20.04[a]	14.42[c]	14.96[bc]	1.142	0.016
<150 µm (%)[6]	13.76[ab]	16.42[a]	11.09[b]	11.96[b]	0.975	0.012

[1]Four grain sources were ground in a randomized block design with a laboratory-scale bliss hammermill to produce a target mean particle size of 550µm by changing the screen hole diameter (Corn- 0.172 in, #11 non-waxy red sorghum 0.156 in, #10; red and white waxy sorghum 0.125 in, #8). All other parameters were held consistent including feeder rate and tip speed (21677 ft/s).
[2]Means within a row followed by a different letter ([a-c]) are significantly different ($P \leq 0.05$).
[3]Standard deviation of the geometric mean diameter was determined using ASABE S319.2 standard particle size method.
[4]Flowability characteristics were determined using a flowdex machine to estimate angle of repose values.
[5]Fine particle were determined as a percentage of material below the d_{gw} of 212µm.
[6]Fine particle were determined as a percentage of material below the d_{gw} of 150µm.

Table 5. Effect of corn and sorghum grain-based diets on the pelleting process and subsequent change in temperature (Δ Temp) and pellet durability index (PDI)[1,2,3]

		Sorghum Variety				
Item	Yellow Corn	Red Non-waxy	Red Waxy	White Waxy	SEM	*P* =
Δ Temp., °F[4]	8.17	12.58	11.71	9.02	2.120	0.348
PDI, %[5]	80.91[c]	78.75[c]	93.07[a]	88.18[b]	2.47	0.001

[1]Four treatments were pelleted in a randomized block design using constant pelleting parameters throughout all treatments. Steam conditioning occurred for approximately 30 seconds with a temperature of 180°F before being pelleted using a CL-5, California Pellet Mill equipped with a 0.157 in x 0.087 in pellet die (L:D 5.6). Production rates were targeted at 2.2 lb./ min and held constant for all treatments.

[2]Means within a row followed by a different letter ([a-c]) are significantly different ($P \leq 0.05$).

[3]Grain ground from objective three, consistent mean particle size, was formulated into diets to be manufactured into pelleted feed.

[4]Change in temperature was determined by calculating the difference in conditioning temperature and hot pellet temperature directly from the die chamber.

[5]Pellet durability index was determined using a Holmen NHP100 machine at the 30 second setting. Pellet samples were screened before and after this process using a #6 sieve.