Effects of wheat source and particle size in meal and pelleted diets on finishing pig growth performance, carcass characteristics, and nutrient digestibility[1,2]

J. A. De Jong,* J. M. DeRouchey,* M. D. Tokach,* S. S. Dritz,† R. D. Goodband,*[3] C. B. Paulk,*[4] J. C. Woodworth,* C. K. Jones,‡ and C. R. Stark‡

*Department of Animal Sciences and Industry, College of Agriculture, †Department of Diagnostic Medicine/Pathobiology, College of Veterinary Medicine, and ‡Department of Grain Sciences and Industry, College of Agriculture, Kansas State University, Manhattan 66506-0201

ABSTRACT: Two experiments were conducted to test the effects of wheat source and particle size in meal and pelleted diets on finishing pig performance, carcass characteristics, and diet digestibility. In Exp. 1, pigs (PIC 327 × 1050; n = 288; initially 43.8 kg BW) were balanced by initial BW and randomly allotted to 1 of 3 treatments with 8 pigs per pen (4 barrows and 4 gilts) and 12 pens per treatment. The 3 dietary treatments were hard red winter wheat ground with a hammer mill to 728, 579, or 326 µm, respectively. From d 0 to 40, decreasing wheat particle size decreased (linear, $P < 0.033$) ADFI but improved (quadratic, $P < 0.014$) G:F. From d 40 to 83, decreasing wheat particle size increased (quadratic, $P < 0.018$) ADG and improved (linear, $P < 0.002$) G:F. Overall from d 0 to 83, reducing wheat particle size improved (linear, $P < 0.002$) G:F. In Exp. 2, pigs (PIC 327 × 1050; n = 576; initially 43.4 ± 0.02 kg BW) were used to determine the effects of wheat source and particle size of pelleted diets on finishing pig growth performance and carcass characteristics. Pigs were randomly allotted to pens, and pens of pigs were balanced by initial BW and randomly allotted to 1 of 6 dietary treatments with 12 replications per treatment and 8 pigs/pen. The experimental diets used the same wheat–soybean meal formulation, with the 6 treatments using hard red winter or soft white winter wheat that were processed to 245, 465, and 693 µm and 258, 402, and 710 µm, respectively. All diets were pelleted. Overall, feeding hard red winter wheat increased ($P < 0.05$) ADG and ADFI when compared with soft white winter wheat. There was a tendency ($P < 0.10$) for a quadratic particle size × wheat source interaction for ADG, ADFI, and both DM and GE digestibility, as they were decreased for pigs fed 465-µm hard red winter wheat and were greatest for pigs fed 402-µm soft white winter wheat. There were no main or interactive effects of particle size or wheat source on carcass characteristics. In summary, fine grinding hard red winter wheat fed in meal form improved G:F and nutrient digestibility, whereas reducing particle size of wheat from approximately 700 to 250 µm in pelleted diets did not influence growth or carcass traits. Finally, feeding hard red winter wheat improved ADG and ADFI compared with feeding soft white winter wheat.

Key words: finishing pig, growth, hard red wheat, particle size, pellet, soft white wheat

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INTRODUCTION

Cereal grains for pigs historically have been ground to reduce particle size to improve digestibility and pig growth (Hancock and Behnke, 2001). Grinding currently occurs through a variety of different mill types ranging from roller mills to hammer mills with varying sizes of screens capable of producing a wide variety of particle sizes (Hancock and Behnke, 2001).

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[3]Corresponding author: goodband@ksu.edu

[4]Present address: Department of Animal Science, 230 Kleberg, Texas A&M University, College Station, TX 77843.

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Mavromichalis et al. (2000) observed that G:F was improved when wheat particle size was reduced either from 1,300 to 600 μm or from 600 to 400 μm. Murphy et al. (2009) also reduced the particle size of wheat from 639 to 552 μm and found that decreasing particle size of a pelleted wheat diet tended to improve G:F. Using estimated grinding costs, Healy et al. (1994) concluded that costs associated with grinding are justified through improvements in feed efficiency. Although numerous experiments have been conducted that investigated particle size reduction of corn (Wondra et al., 1995) and sorghum (Paulk et al., 2015), few studies have determined the effects of fine-grinding hard red or soft white wheat. In addition, little work has compared the feeding value of soft white wheat with that of hard red wheat.

Pelleting is another feed processing technology used throughout the swine industry. Stark et al. (1994) and Wondra et al. (1995) have shown that pelleting diets improved ADG and feed efficiency of finishing pigs, but data is limited in regards to the effect of reducing grain particle size in a pelleted diet. Therefore, the objectives of these experiments were to determine the effects of particle size of hard red and soft white wheat in pelleted diets and hard red winter wheat in meal diets on finishing pig performance, carcass characteristics, and nutrient digestibility.

MATERIALS AND METHODS

General

All practices and procedures used in this experiment were approved by the Kansas State University Institutional Animal Care and Use Committee. Both experiments were conducted at the Kansas State University Swine Teaching and Research Center, Manhattan, KS. Each pen (2.44 by 3.05 m) contained a 2-hole, dry self-feeder (Farmweld, Teutopolis, IL) and a nipple-cup waterer to provide ad libitum access to feed and water. Pens had concrete slatted flooring with a deep pit for manure storage. Pigs were fed a common corn–soybean meal diet for approximately 10 d on entering the facility until pigs from both experiments reached their respective starting weights.

There were 8 pigs per pen, allowing for 0.93 m^2/pig. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens. All diets for both experiments were manufactured at the O.H. Kruse Feed Technology Innovation Center at Kansas State University (Manhattan, KS).

Chemical Analysis

For both experiments, samples of wheat and soybean meal were collected at the feed mill. Samples of each diet were also collected from the farm, combined within phase, and subsampled. All ingredient and feed samples were analyzed for DM (method 934.01; AOAC, 2006), CP (method 990.03; AOAC, 2006), ether extract (method 920.39 A; AOAC, 2006), crude fiber (method 978.10; AOAC, 2006), ash (method 942.05; AOAC, 2006), Ca (method 965.14/985.01; AOAC, 2006), P (method 965.17/985.01; AOAC, 2006), starch method 15914; ISO, 2004), and ADF and NDF (Van Soest, 1963) at Ward Laboratories, Inc. (Kearney, NE). Initial samples of both of the wheat sources were analyzed for a complete AA profile (method 994.1247; AOAC, 2006) at University of Missouri Analytical Services (Columbia, MO).

Physical Diet Analysis

During both experiments, bulk density (Seedburo model 8800; Seedburo Equipment, Chicago, IL), particle size, and angle of repose of major ingredients and all meal diets were measured. Bulk density was determined for all ingredients using methods from Clementson et al. (2010). Particle size was determined using U.S. sieves, with numbers 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, and 270 and a pan. A Ro-Tap shaker (W.S. Tyler, Mentor, OH) was used to sift the 100-g samples for 10 min. Particle size was conducted without or with a flow agent (amorphous silica powder; Gilson Company Inc., Middleton, WI), which was added at 0.5 to 100 g of feed. A geometric mean particle size and the log normal SD were calculated by measuring the amount of grain remaining on each screen (ASAE, 2008). Angle of repose was measured by allowing feed to flow freely over a flat circular platform of a known diameter (Appel, 1994). The diameter of the platform and height of the resulting pile were used to calculate the angle of repose. For pelleted diets, pellet durability index (**PDI**) was determined using a Holmen NHP100 (Tekpro Limited, Norfolk, UK) for 30 s. Percentage fines were also determined with fines characterized as material that would pass through a number 6 Tyler sieve (3,360-μm opening) during 15 sec of manual shaking (ASAE, 1987).

Animals and Diets

For both experiments, pigs were weighed approximately every 2 wk and feed disappearance was measured to determine ADG, ADFI, and G:F. On d 7 of phase 3 (d 67 in Exp 1 and d 61 and 59 in Exp. 2), fecal samples were collected from 2 pigs per pen. Phase 3 diets contained 0.5% titanium dioxide as an indigestible marker. After collection, fecal samples were dried at 50°C in a forced-air drying oven (Precision Scientific Inc., Chicago, IL) and then ground for analysis of GE and titanium concentration. The digestibility values were calculated using the index method (Kong and Adeola, 2014).

In Exp. 1, a total of 288 pigs (PIC 327 × 1050; initially 43.8 kg BW) were used in an 83-d study. Pigs were balanced by initial BW and randomly allotted to 1 of 3 treatments with 8 pigs per pen and 12 pens per treatment. Diets were fed in 3 phases in meal form from d 0 to 27, d 27 to 60, and d 60 to 83. The 3 dietary treatments were hard red winter wheat ground to 728, 579, and 326 μm, respectively. Wheat was ground to the 3 particle sizes using a full-circle teardrop hammer mill (Bliss 22115; Bliss Industries LLC, Ponca City, OK) equipped with a number 12, 8, or 4 screen (4.83, 3.30, and 1.52 mm, respectively).

In Exp. 2, a total of 576 pigs (PIC 327 × 1050; initially 43.4 ± 0.02 kg BW) from 2 consecutive finishing groups were used. Pigs were randomly allotted to pens on entry into the finisher facility. Pens of pigs were balanced by initial BW and randomly allotted to 1 of 6 dietary treatments with 12 replications per treatment and 8 pigs per pen. The experimental diets all had the same wheat–soybean meal formulation, with the 6 treatments formed by including the wheat from 1 of 2 sources (hard red winter, the same batch as in Exp. 1, vs. soft white winter) that were processed to 3 different mean particle sizes (245, 465, and 693 μm and 258, 402, and 710 μm, respectively). All diets were fed in pelleted form.

The 3 particle sizes of the hard red winter wheat were created with a number 2, 10, or 16 screen (1.00, 4.06, and 6.35 mm, respectively). The hard red wheat ground to 245 μm was first ground through a 3-high roller mill (model 924; RMS Roller-Grinder, Harrisburg, SD) to ensure a fine enough grind was achieved through the hammer mill. Soft white wheat was ground through number 4, 12, and 16 hammer mill screens (1.52, 4.83, and 6.35 mm, respectively). Diets were all pelleted through pellet mill (30 HD Master Model; California Pellet Mill, San Francisco, CA). Pellets were steam conditioned at 85°C. Pellets were approximately 4 mm in diameter and 15 mm in length. During the grinding and pelleting process, electrical consumption and throughput were measured.

Before marketing, all pigs were individually weighed and tattooed for carcass data collection and transported approximately 200 km to a commercial abattoir (Triumph Foods LLC, St. Joseph, MO). All pigs were marketed on the same day within each experiment. Standard carcass characteristics including HCW, percentage carcass yield, backfat, loin depth, and percentage lean were measured. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Jowl fat samples were collected and analyzed by near-infrared spectroscopy (MPA, Bruker Corp., Bremen, Germany) for iodine value using the equation of Cocciardi et al. (2009).

Table 1. Chemical and AA analysis of wheat sources (as-fed basis)[1]

Item, %	Hard red winter wheat	Soft white winter wheat
DM	90.86	91.80
CP	11.8	11.2
ADF	3.2	2.8
NDF	8.1	8.6
Ca	0.07	0.13
P	0.38	0.40
Ether extract	1.8	1.6
Ash	1.81	1.89
Starch[2]	55.4	56.9
AA, %		
Lys	0.40	0.40
Ile	0.41	0.44
Met	0.21	0.20
Met + Cys	0.48	0.48
Thr	0.36	0.34
Trp	0.17	0.15
Val	0.47	0.52

[1]A composite sample consisting of 6 subsamples was used for analysis. The same batch of hard red winter wheat was used in both Exp. 1 and 2.

[2]Measured only available starch.

Statistical Analysis

Data were analyzed as a completely randomized design using PROC MIXED in SAS (SAS Inst. Inc., Cary, NC) with pen as the experimental unit. All treatment means were analyzed using the LSMEANS statement. For Exp. 1, linear and quadratic contrasts were completed to determine the effects of decreasing wheat particle size. For Exp. 2, linear and quadratic contrasts were completed to determine the main effects of decreasing wheat particle size as well as the interaction with wheat source. The main effect of wheat source was also determined. Linear and quadratic contrasts within wheat source for particle size were also tested. Lastly, there was no interaction between the 2 groups of pigs used and, therefore, group was used as a random effect. For both experiments, polynomial contrast coefficients were adjusted for unequally spaced treatments using the IML procedure of SAS. Results were considered significant at $P \leq 0.05$ and were considered tendencies between $P > 0.05$ and $P \leq 0.10$.

RESULTS

Chemical Analysis

Chemical and AA analysis were generally similar for the hard red and soft white winter wheat (Table 1). Due to the similarities in AA analysis between sources, the values for the hard red winter wheat were used for both wheat sources in formulation using NRC (2012) standardized ileal digestibility AA coefficients. Analysis of the treatment diets showed that formulated values and chemical analysis (Tables 2 and 3) were similar.

Physical Analysis

Physical analysis of ground wheat and complete diets in Exp. 1 (Table 4) revealed that, as expected, as the wheat particle size decreased, the particle size of the diet decreased as well, which led to an increase in the diet angle of repose. Using a flow agent during particle size analysis revealed a numerical reduction of up to 40 μm when compared with analysis without a flow agent. Diet analysis from Exp. 2 (Table 5) revealed that increasing the particle size of wheat regardless of the source worsened PDI values but had no effect on bulk density or percentage fines of the diets. Grinding hard red winter wheat required more kilowatt hours per tonne than grinding soft white winter wheat (Table 6). Finely ground wheat increased kilowatt hours per tonne for hard red wheat during pelleting but did not influence kilowatt hours per tonne for soft white wheat. Throughput during pelleting was improved by increasing wheat particle size as well as by pelleting soft white wheat compared with hard red wheat.

Growth, Carcass, and Digestibility

In Exp. 1, from d 0 to 40, decreasing wheat particle size decreased (linear, $P < 0.038$) ADFI but improved (quadratic, $P < 0.006$) G:F (Table 7). From d 40 to 83, decreasing wheat particle size increased (quadratic, $P < 0.013$) ADG and increased (linear, $P < 0.001$) G:F. Overall from d 0 to 83, reducing wheat particle size increased (linear, $P < 0.002$) G:F with no difference in ADG or ADFI observed. Finally, reducing wheat particle size increased (linear, $P < 0.05$) DM and GE digestibility.

In Exp. 2, feeding hard red winter wheat improved ($P < 0.05$) ADG and ADFI when compared with pigs fed soft white winter wheat (Table 8). There was a tendency ($P < 0.10$) for a quadratic particle size × wheat source interaction for ADG and ADFI and a significant interaction ($P < 0.05$) for both DM and GE digestibility because ADG, ADFI, and both DM and GE digestibility values decreased in pigs fed 465-μm hard red winter wheat but increased for those fed 402-μm soft white

Table 2. Diet composition, Exp. 1 (as-fed basis)

	BW range, kg		
Item	44 to 63	63 to 82	82 to 120
Ingredient, %			
Hard red wheat	81.26	87.43	92.18
Soybean meal (46.5% CP)	15.84	10.14	4.94
Calcium phosphate (21.5% P)	0.28	0.03	–
Limestone	1.43	1.28	1.30
Salt	0.35	0.35	0.35
Vitamin and trace mineral premix[1,2]	0.30	0.25	0.20
Phytase[3]	0.08	0.08	0.05
L-Lys HCl	0.33	0.33	0.35
DL-Met	0.04	0.02	0.02
L-Thr	0.09	0.09	0.11
Titanium dioxide[4]	–	–	0.50
Calculated analysis			
Standard ileal digestible (SID) AA, %			
Lys	0.94	0.81	0.71
Ile:Lys	64	63	61
Met:Lys	30	30	30
Met + Cys:Lys	61	63	66
Thr:Lys	62	63	66
Trp:Lys	23.1	23.7	23.7
Val:Lys	68	69	67
Total Lys, %	1.05	0.91	0.79
ME,[5] kcal/kg	3,154	3,163	3,163
NE,[6] kcal/kg	2,323	2,358	2,385
SID Lys:ME, g/Mcal	2.98	2.56	2.24
Available P, %	0.30	0.25	0.24
Chemical analysis, %[7]			
DM	90.28	89.91	89.16
CP	19.7	18.4	16.1
ADF	2.9	2.8	2.5
NDF	9.3	8.2	7.8
Crude fiber	2.6	2.2	2.3
Ca	0.74	0.89	0.74
P	0.51	0.48	0.41
Ether extract	1.4	1.5	1.6
Ash	4.41	4.79	3.70
Starch	44.1	45.0	51.3

[1]Provided, per kilogram of premix, 4,409,200 IU vitamin A, 551,150 IU vitamin D_3, 17,637 IU vitamin E, 1,764 mg vitamin K, 3,307 mg riboflavin, 11,023 mg pantothenic acid, 19,841 mg niacin, and 15.4 mg vitamin B_{12}.

[2]Provided, per kilogram of premix, 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulfate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[3]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 450.3 phytase units/kg feed, with a release of 0.11% available P.

[4]Titanium was included in the Phase 3 diet as an indigestible marker and was fed for the first 7 d of the phase at a level of 0.5% at the expense of corn.

[5]NRC, 2012.

[6]Sauvant et al., 2004.

[7]A composite sample consisting of 6 subsamples was used for analysis.

Table 3. Diet composition, Exp. 2 (as-fed basis)

	Wheat source and BW range, kg					
	Hard red winter wheat			Soft white winter wheat		
Item	43 to 63	63 to 82	82 to 120	43 to 63	63 to 82	82 to 120
Ingredient, %						
Wheat	78.44	85.01	89.43	78.44	85.01	89.43
Soybean meal (46.5% CP)	17.31	11.15	6.33	17.31	11.15	6.33
Choice white grease	1.50	1.50	1.50	1.50	1.50	1.50
Calcium phosphate (21.5% P)	0.25	–	–	0.25	–	–
Limestone	1.38	1.28	1.25	1.38	1.28	1.25
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[1,2]	0.26	0.20	0.16	0.26	0.20	0.16
Phytase[3]	0.08	0.08	0.05	0.08	0.08	0.05
L-Lys HCl	0.29	0.30	0.32	0.29	0.30	0.32
DL-Met	0.05	0.05	0.01	0.05	0.05	0.01
L-Thr	0.09	0.08	0.10	0.09	0.08	0.10
Titanium dioxide[4]	–	–	0.50	–	–	0.50
Calculated analysis						
Standard ileal digestible (SID) AA, %						
Lys	0.94	0.81	0.71	0.94	0.81	0.71
Ile:Lys	66	65	63	68	67	67
Met:Lys	31	30	30	30	30	30
Met + Cys:Lys	62	63	66	62	64	66
Thr:Lys	63	63	66	62	63	66
Trp:Lys	23.5	24.0	24.3	22.1	22.1	22.1
Val:Lys	70	70	70	74	75	75
Total Lys, %	1.05	0.91	0.80	1.05	0.91	0.80
ME,[5] kcal/kg	3,233	3,240	3,240	3,286	3,299	3,302
NE,[6] kcal/kg	2,422	2,455	2,475	2,519	2,559	2,587
SID Lys:ME, g/Mcal	2.91	2.50	2.19	2.86	2.45	2.15
Available P, %	0.28	0.23	0.22	0.28	0.23	0.22
Chemical analysis, %[7]						
DM	89.8	90.5	90.0	91.4	91.5	90.4
CP	20.3	18.3	16.0	19.6	17.5	15.4
ADF	2.5	2.3	1.9	3.0	2.9	2.2
NDF	7.7	7.3	6.9	8.6	8.4	7.6
Ca	0.72	0.68	0.62	0.81	0.67	0.63
P	0.50	0.43	0.45	0.50	0.42	0.41
Ether extract	2.7	2.6	2.40	2.6	2.7	2.40
Ash	3.8	3.4	3.7	4.1	3.6	3.5
Starch	39.9	45.4	47.4	41.8	44.7	49.3

[1]Provided, per kilogram of premix, 4,409,200 IU vitamin A, 551,150 IU vitamin D_3, 17,637 IU vitamin E, 1,764 mg vitamin K, 3,307 mg riboflavin, 11,023 mg pantothenic acid, 19,841 mg niacin, and 15.4 mg vitamin B_{12}.

[2]Provided, per kilogram of premix, 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulfate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[3]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 450.3 phytase units/kg feed, with a release of 0.11% available P.

[4]Titanium was included in the Phase 3 diet as an indigestible marker and was fed for the first 7 d of the phase at a level of 0.5% at the expense of corn.

[5]NRC, 2012.

[6]Sauvant et al., 2004.

[7]A composite sample consisting of 6 subsamples was used for analysis.

Table 4. Physical analysis of diets and wheat, Exp. 1[1,2]

	Particle size, µm		
Item	728	579	326
Wheat			
Particle size (no flow agent)[3], µm	728	579	326
Particle size (with flow agent), µm	714	554	284
Bulk density, g/L	767	767	763
Angle of repose, °	42.4	45.8	50.9
Diet[4]			
Bulk density, g/L	765	763	733
Particle size (no flow agent), µm	650	504	374
Angle of repose, °	44.7	46.4	50.7

[1]A composite sample consisting of 6 subsamples was used for analysis.

[2]All treatments were analyzed and values were averaged as all treatments were identically formulated.

[3]Particle sizes were determined using Tyler sieves, with numbers 6, 8, 10, 14, 20, 28, 35, 48, 65, 100, 150, 200, and 270 and a pan. A Ro-Tap shaker (W.S. Tyler, Mentor, OH) was used to sift the 100-g samples for 10 min. Particle sizes were run with and without flow agent at an inclusion level of 0.5 g.

[4]Diet samples from phases were averaged; no differences existed between phases.

winter wheat. Finally, dietary treatments did not affect any carcass characteristics; however, feed efficiency on a carcass weight basis tended to be improved ($P < 0.10$) when hard red winter wheat was fed compared with when soft white winter wheat was fed.

DISCUSSION

Although wheat production has decreased in recent years in the United States, it is still used in livestock diets domestically and across the world (USDA, 2016). Wheat can be categorized into 5 main classifications including hard red winter, hard red spring, soft red winter, white, and durum (USDA, 2013). Of these, hard red winter wheat represents 40% of total production in the United States in a given year, making it the most common wheat used for livestock diets (USDA, 2013). White wheat, although less common, is more widely grown in the western United States (USDA, 2013) and, therefore, is used for swine located in that region.

Previous work has shown the concentration of energy in wheat to be 91 to 97% that of corn and the concentration of AA to be greater than that of corn (Stein et al., 2010). In numerous studies when diets were balanced for dietary energy and AA, wheat- and corn-based diets produced similar growth performance and carcass characteristics when fed during the nursery phase (Erickson et al., 1980) or the finisher phase (Han et al., 2005). This suggests corn can be replaced with wheat in diet formulation with few or no negative effects on performance. Jha et al. (2011) fed 6 Canadian wheat varieties for 21 d to weanling pigs and found that wheat variety had no effect on ADG, ADFI, or G:F. They also noted no difference for pelleting throughput or PDI between the 6 wheat varieties. Bhatty et al. (1974) fed 17 cultivars of hard and soft spring wheat and found that soft white had a greater GE and less fiber than hard red wheat. In the current study, pigs fed hard red winter wheat had increased ADG and ADFI compared with those fed soft white winter wheat. Values for feed per kilogram carcass tended to be poorer for pigs fed soft white winter wheat than hard red winter wheat in the current experiment, suggesting that the source of soft white winter wheat used may have been slightly lower in energy than what would normally be expected (Sauvant et al., 2004).

In Exp. 1, particle size reduction of hard red winter wheat from 728 to 326 µm initially resulted in reduced ADFI and numerically lower ADG. However, pigs appeared to adjust to the finely ground diets during the second half of the trial, as reducing wheat particle size improved ADG and G:F, which led to similar improvements

Table 5. Physical analysis of diets and wheat, Exp. 2[1,2]

	Wheat source and particle size, µm					
	Hard red winter wheat			Soft white winter wheat		
Item	693	465	245	710	402	258
Wheat						
Particle size (no flow agent)[3], µm	693	465	245	710	402	258
Particle size (with flow agent), µm	631	415	201	638	341	210
Bulk density, g/L	1,134	1,224	1,088	1,192	1,133	1,125
Angle of repose, °	45.8	49.5	50.8	43.6	58.2	58.1
Diet[4]						
Bulk density, g/L	870	860	875	853	876	883
Pellet durability index, %	74.2	81.2	88.5	48.7	50.9	54.5
Pellet fines, %	26.9	22.9	24.0	24.1	27.2	22.2

[1]A composite sample consisting of 3 subsamples was used for analysis.

[2]All values are averages of samples taken from the 2 groups.

[3]Particle sizes were determined using Tyler sieves, with numbers 6, 8, 10, 14, 20, 28, 35, 48, 65, 100, 150, 200, and 270 and a pan. A Ro-Tap shaker (W.S. Tyler, Mentor, OH) was used to sift the 100-g samples for 10 min. Particle sizes were run with and without flow agent at an inclusion level of 0.5 g.

[4]Diet samples from phases were averaged; no differences existed between phases.

Table 6. Feed manufacturing electrical consumption and throughput, Exp. 2[1]

	Wheat source and particle size, μm					
	Hard red winter wheat			Soft white winter wheat		
Item	693	465	245	710	402	258
Wheat grinding						
kW[2]	8.4	9.3	11.0	7.6	8.5	8.6
kWh[3]	7.0	7.0	7.9	4.4	4.9	5.0
Throughput, t/h	4.1	3.6	3.3	4.1	4.3	4.7
kWh/t	2.0	2.6	3.3	1.6	2.0	2.1
Pelleting						
kW	21.0	20.6	20.6	22.7	22.8	22.6
kWh	12.3	12.7	14.1	14.9	13.8	13.6
Throughput, t/h	1.2	1.1	1.0	1.2	1.2	1.2
kWh/t	17.5	18.7	20.6	18.9	19.0	18.8

[1]Voltage was recorded during each manufacturing run and then averaged across the dietary phases

[2]kW was calculated by the formula kW = amperage × voltage/1,000.

[3]kWh was calculated by the formula kWh = kW × hours used.

Table 7. Effects of wheat particle size on finishing pig performance, Exp. 1[1]

	Wheat particle size, μm				Probability, $P <$	
Item	728	579	326	SEM	Linear	Quadratic
d 0 to 40						
ADG, kg	0.92	0.93	0.90	0.01	0.274	0.313
ADFI, kg	2.29	2.24	2.20	0.03	0.035	0.713
G:F	0.400	0.413	0.409	0.003	0.038	0.006
d 40 to 83						
ADG, kg	0.92	0.90	0.95	0.01	0.013	0.042
ADFI, kg	2.87	2.80	2.84	0.04	0.608	0.196
G:F	0.319	0.322	0.336	0.003	0.001	0.406
d 0 to 83						
ADG, kg	0.92	0.91	0.93	0.01	0.415	0.571
ADFI, kg	2.59	2.53	2.53	0.03	0.166	0.319
G:F	0.354	0.361	0.367	0.003	0.002	0.464
Digestibility[2]						
DM, %	89.0	91.2	91.5	0.7	0.019	0.129
GE, %	65.5	70.3	73.5	1.9	0.004	0.387
BW, kg						
d 0	43.8	43.8	43.8	0.51	0.996	0.998
d 40	80.4	80.7	79.9	0.83	0.660	0.627
d 83	119.8	119.5	121.1	1.14	0.366	0.596

[1]A total of 288 pigs (PIC 327 ×1050) were used, with 12 pens per treatment and 8 pigs per pen.

[2]Fecal samples were taken on d 67 of the study via rectal massage from 2 pigs per pen.

in overall G:F. Seerley et al. (1988) also fed varying particle sizes of wheat to finishing pigs but found results contrasting to those reported herein. Their results suggest that a larger particle size (1,780 μm) increased ADG in the finishing period compared with finely ground (890 to 1,410 μm) wheat. The improvement in ADG with coarsely ground wheat is difficult to explain given that G:F was also numerically improved with the coarsely ground wheat in their study. Mavromichalis et al. (2000) conducted 2 separate experiments exploring particle size of wheat. In their first experiment, finishing pigs were fed wheat ground to either 1,300 or 600 μm. Pigs fed the finely ground wheat had improved G:F. In their second experiment, pigs were fed wheat ground to 600 or 400 μm. Again, pigs fed the finely ground wheat had improved G:F but also had a greater incidence of stomach ulcers.

In the current study, as hard red winter wheat was ground from coarse to fine in mash diets, pigs had improved DM and GE digestibility. This agrees with Choct et al. (2004), who conducted a weanling pig trial to determine the effect of wheat particle size on nutrient digestibility. The study used both a hammer mill and a roller mill to reduce wheat particle size. Fine, medium, and coarse ground treatments were created for each respective milling apparatus. Digestibility for GE was improved as particle size was reduced regardless of the processing method. In a similarly designed study by Mavromichalis et al. (2000), the apparent digestibility of DM and N was improved as wheat particle size was reduced when comparing 1,300- to 600-μm wheat and 600- to 400-μm wheat. l'Anson et al. (2012) observed that grinding wheat from 760 to 664 μm did not affect any growth criteria but did improve GE digestibility. The 96-μm decrease in particle size may not have been large enough to elicit a growth response, given the replication in the study, although differences in digestibility were realized. In general, it appears that as particle size is reduced, the nutrient digestibility improves in diets fed in meal form.

Conversely, in Exp. 2, nutrient digestibility was not improved as particle size was reduced when diets were fed in pelleted form. This is in contrast to work by Healy et al. (1994), who found improved digestibility of N, DM, and GE when corn and hard and soft sorghum with decreasing particle sizes (900, 700, 500, and 300 μm) were fed to weanling pigs in pelleted form. These differing results may be a result of the different grains fed, the different pig weight ranges used, or potential lack of precision due to sampling only once from 2 pigs per pen. The smaller particle sizes used in the current experiment compared with larger particle sizes being fed in the Healy et al. (1994) experiment also may have influenced the results. Therefore, our data would suggest that in pelleted diets, the improvement due to particle size reduction for nutrient digestibility may diminish as particle size is reduced below approximately 500 μm.

In tandem with improved digestibility, improvements in growth performance have been associated with decreased particle size of cereal when diets are fed in meal form (Hedde et al., 1985; Wu, 1985; Wondra et al., 1995). However, data is limited on the effect of particle size of wheat in pelleted diets with finishing pigs.

Table 8. Effects of wheat source and particle size of pelleted diets on finishing pig growth performance and carcass characteristics, Exp. 2[1]

Item	Wheat source and particle size, µm: Hard red winter 693	465	245	Soft white winter 710	402	258	SEM	Probability, $P <$: Quadratic particle size × source[2]	Source main effect
ADG, kg	1.03	1.01	1.03	0.99	1.00	0.97	0.013	0.055	0.004
ADFI, kg	2.67	2.59	2.66	2.56	2.58	2.54	0.035	0.060	0.003
G:F	0.384	0.388	0.387	0.388	0.389	0.384	0.0029	0.881	0.941
Initial BW, kg	43.4	43.4	43.4	43.4	43.4	43.4	3.75	0.989	0.978
Final BW, kg	127.3	125.6	127.9	125.3	125.7	123.2	3.19	0.141	0.074
Digestibility									
DM, %	88.0	87.0	87.7	85.1	87.7	85.8	0.79	0.040	0.048
GE, %	66.3	64.5	68.3	64.9	67.5	62.3	1.95	0.041	0.360
Carcass traits									
Feed/carcass gain[3]	1.66	1.63	1.65	1.71	1.70	1.67	0.029	0.418	0.065
HCW, kg	91.77	90.31	91.36	90.44	91.10	89.42	1.439	0.302	0.479
Carcass yield, %	72.9	72.8	73	73.1	73.1	73.0	0.15	0.234	0.167
Backfat, mm	18.96	19.28	19.62	19.93	19.59	19.17	0.434	0.792	0.431
Loin depth, mm	58.71	57.97	57.14	57.75	58.21	56.40	1.300	0.426	0.445
Percentage lean, %	52.8	52.6	52.4	52.4	52.5	52.5	0.21	0.859	0.397
Jowl iodine value, mg/100 g	68.6	69.0	69.1	68.3	68.6	68.4	0.43	0.945	0.210

[1] total of 576 pigs (PIC 327 × 1050; initially 43.4 ± 0.02 kg BW) in 2 groups were used in 75- and 89-d studies with 8 pigs per pen and 12 replications per treatment.

[2] No source × particle size interactions, main effects of particle size, or linear or quadratic effects of particle size within wheat source ($P > 0.10$).

[3] Feed/carcass gain is expressed as total intake/kilograms carcass gain with an assumed initial yield of 75%.

In Exp. 2, reducing particle size of either wheat source in pelleted diets had no effect on performance of finishing pigs. Murphy et al. (2009) conducted a similar experiment with wheat diets finely ground to either 639 or 552 µm, where again all diets were fed in pelleted form. When wheat was finely ground, it tended to improve G:F; however, this may have been a result of the improved pellet quality of the finely ground wheat diets and not a direct effect of the decreased particle size. De Jong et al. (2012) investigated the effects of particle size of pelleted diets in nursery pigs using corn ground to 638 or 325 µm, respectively. When corn was finely ground to 325 µm and fed in pelleted form, there was no effect of particle size on growth performance of the nursery pigs. Pelleting has been shown to improve diet digestibility (Graham et al., 1989; Wondra et al., 1995; Xing et al., 2004), which, in addition to the current data, might suggest that a diet's digestibility may reach a theoretical "ceiling" when pelleting is used and additional effects of diet particle size may not be realized. This might suggest that particle size reduction in pelleted diets may be advantageous only when grain is coarsely ground (>500 µm) and not when grain is finely ground (<500 µm). Lahaye et al. (2008) also found that reducing the particle size of wheat from 1,000 to 500 µm improved DE, OM, and DM digestibility when fed in meal form but that pelleting did not further improve digestibility. This further demonstrates that pelleting and fine grinding of wheat diets does not produce an additive improvement in G:F.

Feed processing technologies have the ability to improve feed efficiency and growth in pigs, but they can also potentially increase the feed mill's cost of production. The improved animal performance needs to be balanced with the increased cost of production and reductions in feed mill throughput to justify the additional grain or complete diet processing. In Exp. 2, grinding hard red or soft white winter wheat from approximately 600 to approximately 200 µm increased kilowatts and kilowatt hours required for grinding and kilowatt hours per tonne. In addition, fine grinding reduced throughput by 0.08 and 0.06 t/h for hard red and soft white winter wheat, respectively. This was similar to results reported by Healy et al. (1994), who also reported increased kilowatt usage as particle size of either corn or sorghum was reduced from 900 to 300 µm. Paulk et al. (2015) also reported increased electrical usage as sorghum was ground from 724 to 319 µm. Both, Paulk et al. (2015) and Healy et al. (1994) reported reduced rates of production as grains were more finely ground. The reduced production rate and increased kilowatt usage during grinding, especially at the finer grinds, will increase the cost of manufacturing at the feed mill.

In conclusion, fine grinding hard red winter wheat improved G:F when diets were fed in meal form. When hard red winter or soft white winter wheat diets were finely ground and fed in pelleted form, no effect of particle size on growth was observed. It appears that very fine grinding (<500 μm) is not warranted if diets are to be pelleted, except as a means to improve pellet quality.

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