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Use of feed technology to improve the nutritional value of feed ingredients

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Abstract. Two experiments were conducted to test the hypothesis that reduced particle size of corn will improve the caloric utilisation of corn fed to weanling pigs and to determine effects of pelleting, extrusion and extrusion and pelleting on energy and nutrient digestibility in diets containing low, medium or high levels of fibre. In Experiment 1, 128 pigs were used (initial bodyweight (BW) of 9.41 ± 1.54 kg). Pigs were randomly allotted to four diets in a randomised complete block design. There were four pigs per pen and eight replicate pens per treatment. The corn used was ground to different particle sizes (i.e. 865, 677, 485 or 339 µm). In Experiment 2, three diets were formulated, including a low-fibre diet, a medium-fibre diet-, and a high-fibre diet. Each diet was divided into four batches after mixing and either fed in a meal form without further processing or pelleted, extruded, or extruded and pelleted. In total, 24 growing pigs (initial BW: 26.5 ± 1.5 kg) with a T-cannula installed in the distal ileum were allotted to the diets in a split-plot design, with eight pigs allotted to each level of fibre. Ileal digesta and faecal samples were collected and the apparent ileal digestibility of energy, crude protein and dry matter were calculated as was the metabolisable energy in each diet. Results of Experiment 1 indicated that final BW and average daily gain were not affected by corn particle size. However, average daily feed intake decreased (linear, $P < 0.05$) as mean particle size decreased from 865 to 677, 485 and 339 µm. Likewise, gain to feed ratio increased (linear, $P < 0.05$) from 0.65 to 0.66, 0.70 and 0.69 for pigs fed diets containing corn ground to a mean particle size of 865, 677, 485 and 339 µm, respectively. In Experiment 2, results indicated that pelleting, extrusion, or pelleting and extrusion improved ($P < 0.05$) the apparent ileal digestibility of energy and dry matter, but in most cases, there were no differences among the pelleted, the extruded, and the extruded and pelleted diets. Medium- and high-fibre diets that were extruded had greater metabolisable energy ($P < 0.05$) than the meal diets. In conclusion, results indicated that gain to feed of pigs fed diets containing corn with the smaller particle size was increased compared with diets containing corn with a greater particle size. In addition, energy utilisation may be improved by pelleting or extrusion or by a combination of the two technologies, but the response seems to be greater for extrusion in diets that are relatively high in fibre.

Additional keywords: energy, feed processing, particle size, pig, starch.

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Introduction

In the US swine industry, a conventional diet based on corn and soybean meal fed to pigs is provided in a mash form and, in most cases, processing other than grinding and mixing is not practiced. However, due to the high cost of energy in pig diets, use of high-fibre ingredients such as soybean hulls, distillers dried grains with solubles (DDGS), and wheat middlings has increased. A high level of fibre in the diet usually results in reduced energy and nutrient digestibility (Noblet and Le Goff 2001) that negatively affects growth performance and carcass composition of pigs (Lee *et al*. 2012).

However, feed-processing technologies such as changes in grinding procedures, extrusion, expansion and pelleting may be used to modify the structure of the ingredients and increase nutrient availability (Wondra *et al*. 1995*c*; Hancock and Behnke 2001; Emiola *et al*. 2009). This may have a positive effect on pig growth performance and carcass composition, but effects of different feed technologies on the nutritional value of feed ingredients and diets fed to pigs are not fully understood. Therefore, the objectives of these experiments were (1) to test the hypothesis that feed efficiency is improved if corn particle size is reduced and (2) to determine effects of fibre level on responses to pelleting and extrusion of diets fed to growing pigs.

Materials and methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for the experiments. Pigs used in the experiments were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN, USA).

Effects of reducing particle size of corn on growth performance of weanling pigs

In Experiment 1, the corn that was used in all diets was from the same batch and the corn was grown in Iowa in 2011. The whole batch of corn was first rolled to a mean particle size of 2000 µm with an automatic roller mill (Model CSU 500, 2 stage; Automatic Equipment Mfg. Co., Pender, NE, USA). The rolled grain was then divided into four batches to obtain a mean particle size of 865, 677, 485 and 339 µm by using a hammer mill (Model #EL-9506-TF; Bliss Industries, Ponca City, OK, USA) with 15.88, 9.53, 3.97 or 1.19 mm screens, respectively.

In total, 128 weaned pigs (initial bodyweight (BW) 9.41 ± 1.54 kg) were randomly allotted, after they had been fed a common diet for 14 days, to a randomised complete block design with four experimental diets that were fed for 3 weeks to test the hypothesis that the gain to feed ratio (G : F) is improved if diets fed to weanling pigs contain corn ground to a smaller rather than a greater particle size. All pigs were fed a diet that contained corn (61.56%), soybean meal (32.00%), fish meal (3.00%), soybean oil (1.00%) and vitamins, minerals and crystalline amino acids to meet requirements for weanling pigs (NRC 2012). The only difference among diets was that corn ground to 865, 677, 485 or 339 µm was used in the diets. Analysis of mixed diets (as-fed basis) indicated that values for gross energy (GE) were 3966, 3951, 3974 and 3971 kcal per kg for diets containing corn ground to 865, 677, 485 or 339 µm, respectively. Analysed lysine, methionine and threonine (as-fed basis) were 1.36%, 0.44% and 0.86% in diets containing corn ground to 865 µm; 1.39%, 0.43% and 0.86% in diets containing corn ground to 677µm; 1.43%, 0.43% and 0.90% in diets containing corn ground to 485 µm; and 1.41%, 0.49% and 0.91% in diets containing corn ground to 339 µm. There were four pigs per pen and eight replicate pens per treatment. Feed and water were provided on an *ad libitum* basis throughout the experiment and daily feed allotments were recorded. Individual pig bodyweights were recorded at the beginning of the experiment and pig bodyweights as well as feed left in the feeders were recorded at the end of the experiment. On the last day of the experiment, a faecal sample was obtained from each pig to determine faecal pH. At the conclusion of the experiment, data were summarised to calculate average daily gain, average daily feed intake (ADFI) and G : F for each pen and treatment group, and data for caloric efficiency were summarised within treatment group. The pen was the experimental unit and an α-level of 0.05 was used to assess significance among means.

Effects of pelleting and extrusion on energy digestibility in diets fed to pigs

In Experiment 2, 24 growing barrows (initial BW: 26.5 ± 1.5 kg) were equipped with a T-cannula in the distal ileum. Pigs were allotted to treatment diets in a split-plot design, with eight pigs allotted to diets containing low (8% neutral detergent fibre, NDF), medium (12% NDF) or high (20% NDF) levels of fibre. Diets were fed to the pigs during four 14-day periods. Within each type of diet, the eight pigs were fed the diets produced using four processing technologies in such way that two pigs were fed each diet in each period and no pig received the same diet twice. Therefore, eight replicate pigs per diet were used. Pigs were housed individually in metabolism crates in an environmentally controlled room. A feeder and a nipple drinker were installed in each crate, and a screen and a funnel were placed below the slatted floor of the crates allowing for the total, but separate, collection of faeces and urine from each pig. The low-fibre diet was based on corn (69.70%) and soybean meal (27.50%), the medium-fibre diet was based on corn (47.95%), soybean meal (24.50%) and 25.00% DDGS, and the high-fibre diet was based on corn (29.90%), soybean meal (22.80%), 25.00% DDGS and 20.00% soybean hulls. Titanium dioxide was included as an indigestible marker at 0.5%. Vitamins and minerals were included in all diets to meet or exceed current nutrient requirements (NRC 2012). All ingredients were ground using a Bühler horizontal hammer mill, Model DFZC 655 (Bühler AG, Uzwil, Switzerland) to a mean particle size of 600 µm. Diets were mixed using a Bühler Speedmix DFML paddle mixer. One batch of each diet was mixed, and this batch was then divided into four sub-batches. One sub-batch of each diet was fed in meal form without further processing. One sub-batch of each diet was pelleted at 85°C after conditioning for 120 s using a Bühler DNSA short-term conditioner with a length of 800 mm and a diameter of 250 mm; pelleting took place at a temperature of 85°C using a 55 kW pellet press model Bühler DPDB 304.75 with a die of 4 × 70 mm. Pelleted diets were cooled in a Bühler Model DFKG counter flow cooler. One sub-batch was extruded at a temperature of 115°C using a Bühler Model AHSF 133 single screw extruder with a diameter of 133 mm. The last sub-batch was first extruded at 115°C and then pelleted at 85°C. Pigs were adapted to the level of fibre within each type of diet for 14 days before starting the experiment. This was accomplished by feeding the pigs with a mixture of the four batches within the level of fibre.

The four low-fibre diets prepared as meal, pelleted, extruded, or extruded and pelleted analysed (as-fed basis) 3919, 3920, 4112 and 4083 kcal GE per kg, respectively, and 1.03%, 1.06%, 1.14% and 1.10% lysine. The four medium-fibre diets prepared as meal, pelleted, extruded, or extruded and pelleted analysed (as-fed basis) 4168, 4154, 4415 and 4400 kcal per kg GE, respectively, and 1.10%, 1.09%, 1.13% and 1.13% lysine. The four high-fibre diets prepared as meal, pelleted, extruded, or extruded and pelleted analysed (as-fed basis) 4180, 4144, 4363 and 4184 kcal GE per kg, respectively, and 1.17%, 1.10%, 1.24% and 1.20% lysine.

The initial 5 days of each period were considered an adaptation period to the diet. Faecal and urine samples were quantitatively collected from Day 6 to Day 11, using the marker to marker approach (Adeola 2001), and ileal digesta were collected for 8 h on Day 13 and Day 14 using standard operating procedures (Stein *et al*. 1998). Values for the apparent ileal digestibility (AID) of crude protein (CP), GE and dry matter (DM) and the apparent total tract digestibility (ATTD) of GE and DM were calculated for each diet (Adeola 2001). Likewise, the metabolisable energy (ME) of each diet was also calculated.

Data were analysed as a 3 × 4 factorial, with fibre level and post-mixing processing as factors, using the mixed procedure of SAS (SAS Institute Inc., Cary, NC, USA). The model included fibre level, post-mixing processing, and the fibre level × post-mixing processing interaction as fixed effects and period and pig as random effects. The pig was the experimental unit for all analyses and an α level of 0.05 was used to assess significance among means.

Results and discussion

Effects of reducing particle size of corn on growth performance of weanling pigs

Diets were formulated to be equal in CP and digestible lysine. There were no differences in the initial or the final BW among pigs fed the four diets and average daily gain was also not different among treatments (Table 1). In contrast, ADFI decreased and values for G : F increased as the particle size of corn was reduced (linear, $P < 0.05$). This result is in agreement with previous data (Healy *et al*. 1994; Wondra *et al*. 1995*b*). The reduced ADFI observed in pigs fed diets containing corn ground to a smaller particle size was likely a result of pigs eating to meet their energy requirement and indicated that more energy was obtained from diets with reduced particle size. The increased G : F that was observed as particle size of corn was reduced was expected because corn ground to a smaller particle size contains more ME than corn ground to a greater particle size (Wondra *et al*. 1995*a*; Rojas and Stein 2015).

The increase (linear, $P < 0.01$) in pH of faecal samples that was observed as particle size of corn decreased indicated that synthesis of volatile fatty acids (VFA) decreases as particle size decreases. This observation is in agreement with data from growing–finishing pigs fed corn ground to a finer particle size, indicating that pH increases and VFA concentration in cecal samples decreases as corn particle size is reduced (Rojas *et al*. 2016). The reason for the reduced synthesis of VFA is most likely that reduced corn particle size results in increased prececal digestibility of starch (Rojas and Stein 2015), which in turn results in reduced substrate for fermentation in the hindgut. Thus, the increased pH in the faeces of pigs observed as particle size decreased indicates that less VFA is synthesised in the hindgut when pigs are fed diets that contain finely ground corn than when they are fed diets that contain coarsely ground corn (Callan *et al*. 2007; Rojas *et al*. 2016).

Caloric efficiency represents the relationship between daily energy intake and daily BW gain. In other words, it is the amount of energy needed to gain 1 kg of BW. The increase (linear, $P < 0.05$) in caloric efficiency that was observed as corn particle size was reduced indicated that pigs fed diets containing corn ground to a finer particle size need less feed to gain 1 kg of BW (i.e. 3.7% more efficient) than pigs fed diets containing corn ground to a coarser particle size. This observation is in agreement with data by de Jong *et al*. (2013). Overall, results of the experiment indicated that a reduction in corn particle size results in improved utilisation of energy in corn. However, it is possible that reduced particle size of corn may result in increased risk of pigs developing stomach ulcers, but these effects were not assessed in the present research.

Effects of pelleting and extrusion on energy and nutrient digestibility in diets fed to pigs

The AID of GE and DM was less ($P < 0.05$) for meal diets than for diets that were processed after mixing (Table 2). However, the AID of GE and DM was greater ($P < 0.05$) for extruded diets than for pelleted diets and the AID of GE and DM was also greater ($P < 0.05$) for extruded diets than for the combination of extruded and pelleted diets. The AID of CP was greater ($P < 0.05$) for extruded diets and diets that were extruded and pelleted than for meal diets or pelleted diets.

The AID of GE and DM was greater ($P < 0.05$) in the low-fibre diets than in the medium- or high-fibre diets, but medium-fibre diets had AID of GE and DM that were greater ($P < 0.05$) than for high-fibre diets. The AID of CP was greater ($P < 0.05$) for the low-fibre diets than for the medium- and high-fibre diets, but no differences were observed between medium- and high-fibre diets.

The ATTD of GE was less ($P < 0.05$) for meal diets than for pelleted diets or diets that were extruded and pelleted, but there were no differences among the post-mixing processed diets for the ATTD of GE and DM. The ATTD of GE and DM was greater ($P < 0.05$) for medium-fibre diets than for high-fibre diets, but less ($P < 0.05$) than that for low-fibre diets.

The ME (DM basis) was lower ($P < 0.05$) in the high-fibre diets than in the low- or medium-fibre diets (Table 3). The ME was greater ($P < 0.01$) in pelleted diets than in the meal diet for the medium-fibre diets, but the interaction between fibre and processing was significant ($P < 0.05$) for ME. Diets containing low or high fibre concentrations processed with a combination of extrusion and pelleting increased ME compared with the

Table 1. Growth performance and faecal pH of pigs fed diets containing corn ground to different particle sizes (Experiment 1)
ADFI, average daily feed intake; ADG, average daily gain; BW, bodyweight; G : F, gain to feed ratio; ME, metabolisable energy; s.e.m., standard error of the mean

Item	Corn particle size (μm)				Pooled s.e.m.	*P*-value	
	865	677	485	339		Linear	Quadratic
Growth performance and faecal pH							
Initial BW (kg)	9.42	9.43	9.43	9.36	0.52	0.20	0.14
Final BW (kg)	19.04	19.14	19.26	18.60	0.90	0.29	0.11
ADG (kg/day)	0.46	0.46	0.47	0.44	0.02	0.37	0.16
ADFI (kg/day)	0.71	0.71	0.67	0.64	0.03	0.02	0.34
G : F	0.65	0.66	0.70	0.69	0.01	<0.01	0.86
pH of faeces	5.84	5.97	6.09	6.24	0.05	<0.01	0.67
Energy efficiency							
ME intake (kcal/day)	2318	2325	2231	2136	116.34	0.05	0.40
Caloric efficiency (kcal ME/kg gain)	5040	5030	4752	4857	103.32	0.05	0.71

Table 2. Apparent ileal digestibility of gross energy, crude protein and dry matter and apparent total tract digestibility of gross energy and dry matter in experimental diets, as-fed basis (Experiment 2)

AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; CP, crude protein; DM, dry matter; GE, gross energy; EP, extruded and pelleted; Ext, extruded. Within a row, means followed by the same letter are not significantly different (at $P = 0.05$); s.e.m., standard error of the mean

Item	Type of processing				s.e.m.	*P*-value	Level of fibre			s.e.m.	*P*-value
	Meal	Pellet	Ext	EP			Low	Medium	High		
					AID (%)						
GE	66.2d	68.4c	72.7a	71.0b	0.60	<0.01	76.6x	72.5y	59.5z	0.52	<0.01
CP	72.5b	73.5b	77.9a	76.6a	0.90	<0.01	77.6x	77.1x	70.7y	0.84	<0.01
DM	63.5d	65.3c	69.6a	67.9b	0.67	<0.01	74.7x	69.2y	55.8z	0.60	<0.01
					ATTD (%)						
GE	84.7b	86.0a	85.5ab	86.4a	0.68	0.02	90.2x	85.7y	81.1z	0.65	<0.01
DM	84.9	85.6	85.4	86.2	0.67	0.14	90.0x	85.5y	81.1z	0.64	<0.01

Table 3. Concentration of metabolisable energy in experimental diets

EP, extruded and pelleted; Ext, extruded; ME, metabolisable energy. Means followed by the same letter are not different (at $P = 0.05$); s.e.m., standard error of the mean

Item	Processing	Energy concentration – ME (kcal/kg)
Low-fibre diets	Meal	3868d
	Pellet	3949bc
	Ext	3893cd
	EP	3957bc
Medium-fibre diets	Meal	3947cd
	Pellet	4044ab
	Ext	4055a
	EP	3926cd
High-fibre diets	Meal	3583f
	Pellet	3651ef
	Ext	3687e
	EP	3717e
s.e.m.		44
P-value	Fibre	<0.01
	Process	<0.01
	Fibre × process	<0.01

meal diet, whereas ME was not affected by the combination of extrusion and pelleting of the medium-fibre diet compared with the meal diet.

The ME values of the diets were reduced if high-fibre ingredients were included, which was expected because there is a reduction in absorbed energy and nutrients in the small intestine as fibre concentration increases (Noblet and le Goff 2001; Le Gall *et al*. 2009). In contrast, there is an increase in hind-gut fermentation with increased fibre in the diet, which produces VFA that are absorbed by the pig and used for energy, but this will not totally compensate for the reduction of absorption of glucose in the small intestine as the level of fibre increases in the diet (Anguita *et al*. 2006).

The ME values that were obtained for the low-fibre and medium-fibre meal diets were within 25 kcal per kg of the values calculated for these diets from NRC (2012). The observation that there was no difference in the ME between the low-fibre diets and the medium-fibre diets is also in line with expectations because the ME of conventional DDGS is not different from the ME of corn (Pedersen *et al*. 2007). In contrast, the ME of the high-fibre diet was ~160 kcal greater than the value calculated from NRC (2012), which indicates that the soybean hulls used in the present experiment may have contained more ME than predicted from NRC (2012). Nevertheless, the reduction in ME in the high-fibre diets compared with the low- or medium-fibre diets that was observed was expected because of the inclusion of soybean hulls in these diets.

The increase in ME that was observed as a result of pelleting was not influenced by the concentration of fibre in the diet and was calculated as 2.1%, 2.5% and 1.9% increase for the low-fibre, the medium-fibre and the high-fibre diets, respectively, if compared with the meal diets. These values are greater than the improvement of ~1.5% that was reported by Le Gall *et al*. (2009) who also used diets with different fibre concentrations. In agreement with the results of Le Gall *et al*. (2009), the response to pelleting was not influenced by the concentration of fibre in the diets. However, the improvement in ME obtained in the present experiment is less than the improvement in feed conversion rate that has been reported when pigs are offered *ad libitum* access to feed (Wondra *et al*. 1995*a*; Xing *et al*. 2004). However, it is possible that some of the improvement in feed conversion rate observed for pelleted diets offered to pigs on an *ad libitum* basis is a result of reduced feed wastage because if diets are pelleted and then ground into a meal, feed efficiency is not different from that observed for an unpelleted meal diet (Lewis *et al*. 2015). The improved energy values that are observed with extrusion and pelleting may be partly offset by added costs during processing.

Conclusions

Results from these experiments indicated that feed technology may be used to improve energy and nutrient digestibility and enhance absorption of nutrients. This may fully or partly ameliorate the negative effects of fibre on energy and nutrient utilisation in diets fed to pigs and it is possible that effects of feed technology are greater in diets containing high-fibre ingredients than in diets with lower levels of fibre.

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References

Adeola O (2001) Digestion and balance techniques in pigs. In 'Swine nutrition'. (Eds AJ Lewis, LL Southern) pp. 903–916. (CRC Press: Washington, DC)

Anguita M, Canibe N, Pérez JF, Jensen BB (2006) Influence of the amount of dietary fiber on the available energy from hindgut fermentation in growing pigs: use of cannulated pigs and in vitro fermentation. *Journal of Animal Science* **84**, 2766–2778. doi:10.2527/jas.2005-212

Callan JJ, Garry BP, O'Doherty JV (2007) The effect of expander processing and screen size on nutrient digestibility, growth performance, selected faecal microbial populations and faecal volatile fatty acid concentrations in grower-finished pigs. *Animal Feed Science and Technology* **134**, 223–234. doi:10.1016/j.anifeedsci.2006.09.018

de Jong JA, DeRouchey JM, Tokach MD, Goodband RD, Dritz SS, Nelssen JL, McKinney L (2013) Effects of corn particle size, complete diet grinding, and diet form on finishing pig growth performance, caloric efficiency, carcass characteristics. *Journal of Animal Science* **91**, 216. [Abstract]

Emiola IA, Opapeju FO, Slominski BA, Nyachoti CM (2009) Growth performance and nutrient digestibility in pigs fed wheat distillers dried grains with solubles-based diets supplemented with a multicarbohydrase enzyme. *Journal of Animal Science* **87**, 2315–2322. doi:10.2527/jas.2008-1195

Hancock JD, Behnke KC (2001) Use of ingredient and diet processing technologies (grinding, mixing, pelleting, and extruding) to produce quality feeds for pigs In 'Swine nutrition'. (Eds AJ Lewis, LL Southern) pp. 474–498. (CRC Press: Washington, DC)

Healy BJ, Hancock JD, Kennedy GA, Bramel-Cox PJ, Behnke KC, Hines RH (1994) Optimum particle size of corn and hard and soft sorghum for nursery pigs. *Journal of Animal Science* **72**, 2227–2236.

Le Gall M, Warpechowski M, Jaguelin-Peyraud Y, Noblet J (2009) Influence of dietary fibre level and pelleting on the digestibility of energy and nutrients in growing pigs and adult sows. *Animal* **3**, 352–359. doi:10.1017/S1751731108003728

Lee JW, McKeith FK, Stein HH (2012) Up to 30% corn germ may be included in diets fed to growing-finishing pigs without affecting pig growth performance, carcass composition, or pork fat quality. *Journal of Animal Science* **90**, 4933–4942. doi:10.2527/jas.2012-5129

Lewis LL, Stark CR, Fahrenholz AC, Goncalves MAD, DeRouchey JM, Jones CK (2015) Effects of pelleting conditioner retention time on nursery pig growth performance. *Journal of Animal Science* **93**, 1098–1102. doi:10.2527/jas.2014-8072

Noblet J, Le Goff G (2001) Effect of dietary fiber on the energy value of feed for swine. *Animal Feed Science and Technology* **90**, 35–52. doi:10.1016/S0377-8401(01)00195-X

NRC (2012) 'Nutrient requirements of swine.' (National Academy Press: Washington, DC)

Pedersen C, Boersma MG, Stein HH (2007) Digestibility of energy and phosphorous in ten samples of distillers dried grains with solubles fed to growing pigs. *Journal of Animal Science* **85**, 1168–1176. doi:10.2527/jas.2006-252

Rojas OJ, Stein HH (2015) Effects of reducing the particle size of corn on the concentration of digestible and metabolizable energy and on the digestibility of energy and nutrients in corn grain fed to growing pigs. *Livestock Science* **181**, 187–193. doi:10.1016/j.livsci.2015.09.013

Rojas OJ, Liu Y, Stein HH (2016) Effects of particle size of yellow dent corn on physical chracteristics of diets and growth performance and carcass characteristics of growing-finishing pigs. *Journal of Animal Science* **94**, 619–628. doi:10.2527/jas2015-9054

Stein HH, Shipley CF, Easter RA (1998) Technical note: a technique for inserting a T-cannula into the distal ileum of pregnant sows. *Journal of Animal Science* **76**, 1433–1436.

Wondra KJ, Hancock JD, Behnke KC, Hines RH, Stark CR (1995*a*) Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *Journal of Animal Science* **73**, 757–763.

Wondra KJ, Hancock JD, Behnke KC, Stark CR (1995*b*) Effects of mill type and particle size uniformity on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *Journal of Animal Science* **73**, 2564–2573.

Wondra KJ, Hancock JD, Kennedy GA, Hines RH, Behnke KC (1995*c*) Reducing particle size of corn in lactation diets from 1200 to 400 micrometers improves sow and litter performance. *Journal of Animal Science* **73**, 421–426.

Xing JJ, van Heugten E, Li DF, Touchette KJ, Coalson JA, Odgaard RL, Odle J (2004) Effects of emulsification, fat encapsulation, and pelleting on weanling pig performance and nutrient digestibility. *Journal of Animal Science* **82**, 2601–2609.