EVALUATION OF FEED PROCESSING AND ANALYTICAL METHODS TO IMPROVE NUTRIENT UTILIZATION OF SWINE DIETS

by

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B.S., Kansas State University, 2013

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

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College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2015

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Abstract

A total of 7 experiments were conducted to evaluate the effects of particle size and thermal processing on swine growth performance or to develop improved analytical methods for particle size prediction. First, 5 experiments utilized 596 nursery pigs to assess how corn particle size and pelleting affected nursery pig growth performance and feed preference. The improvements from reducing particle size were mixed among experiments, potentially because pigs preferred to consume more coarsely ground corn in both mash ($P < 0.05$; 79.3 vs. 20.7%) and pelleted diets ($P < 0.05$; 58.2 vs. 31.8%) diets. Pelleting diets led to a reduction in feed disappearance, which tended to improve feed efficiency in nursery pigs ($P < 0.05$; 0.61 vs. 0.64 for pigs fed mash vs. pelleted diets in Exp. 1).

Next, a total of 270 finishing pigs were utilized to determine the effects of long-term conditioning or extrusion of low energy feedstuffs on finishing pig nutrient digestibility, growth performance and carcass characteristics. Treatments included the same basal diet processed as: 1) non-processed mash, 2) pelleted with 45 s conditioner retention time, 3) pelleted with 90 s conditioner retention time, or 4) extruded. Thermal processing, regardless of type, improved daily gain and feed efficiency ($P < 0.05$), but did not affect feed intake ($P > 0.10$). Extruded diets tended to improve feed efficiency compared to pelleted diets ($P < 0.10$). However, pigs fed thermally-processed diets had greater jowl iodine value compared to those fed mash diets ($P < 0.05$).

Finally, 420 samples were used to determine the impact of top sieve size, grain type, technician, and flow agent on the ability of a 3-sieve analytical method to accurately predict the mean particle size determined by a standardized 12-sieve method. The experiment was a 3 × 2 × 2 × 3 factorial with 3 technicians, 2 sieve sizes (U.S. No. 12 vs. 16 sieve as the top sieve), 2 flow

agent levels (0 vs. 0.5 g), and 3 grain types (corn, sorghum, or wheat). Linear regression was used to develop individual equations to predict the mean particle size for each of the 3-sieve methods compared to the standard 12-sieve method recognized as ASAE S319.4, and the GLIMMIX procedure of SAS was used to evaluate the impact of main effects and interactions on predication accuracy. All interactions were removed from the model due to insignificance ($P > 0.10$). Technician, screen size and flow agent did not affect ($P > 0.10$) the accuracy of the prediction equations. Grain was the only main effect of significance ($P < 0.05$), where the prediction equation overestimated the particle size of wheat by approximately 15 µm and underestimated the particle size of corn by approximately 12 µm. While statistically significant, these variations were deemed to be sufficiently accurate for the 3-sieve method, and that separate equations for each grain type were not warranted to retain the simplicity of the method. In summary, technician, sieve size, grain type, and the use of flow agent did not greatly affect the accuracy of the 3-sieve particle size analytical method, so the original method was concluded to be accurate and the preferred method.

Table of Contents

List of Figures

Chapter 4

List of Tables

Chapter 2

Chapter 3

Chapter 4

Acknowledgements

I would like to thank the National Pork Board for their contribution toward this research and express their gratitude toward Wenger Manufacturing for lending their expertise in extrusion. Finally I like to thank all the students, faculty and staff involved for their support and contribution throughout the conduction of this research. I would especially like to thank my family and friends for their love and support during this research program.

Chapter 1 - Literature Review; The Effects of Thermal Processing on Nutrient Utilization of Swine Feeds

Introduction

The addition of thermal processing to improve nutrient utilization of mash diets has been one of the most revolutionary developments in the feed industry. Even today, no discoveries in feed manufacturing have matched the magnitude of improvement in gain and feed efficiency observed when pigs are fed diets that are pelleted, extruded, or expanded. These different forms of thermal processing have similar initial preparation. Dry mash feed is gradually fed into a conditioning chamber where specific processing features, such as heat, steam, moisture and pressure are added while the material is mixed. Then, the conditioned mash is either compressed through a pellet die or extruded or expanded from the die point. Variations in processing features distinguish each method of thermal processing from one another. In pelleting, the optimum moisture of conditioned mash ranges from 16.0 to 17.5%, with 4 to 5% of added moisture coming from conditioning (Behnke and Gilpin, 2014). As a rule of thumb, 1% moisture should be added for each 12.5°C increase in temperature during steam conditioning to reduce die choking or plugging (Schofield, 2005). The feed is pressed through the die to form a shaped pellet that must be cooled. There is limited pressure change in a pelleting system, which is different than both expansion and extrusion.

During the expansion process, steam is added to a chamber until a maximum 22% moisture is reached and conditioning temperatures and pressure build up to 125°C and approximately 8,275 kPa, respectively (Schofield, 2005). The resulting product does not require drying and is not shaped, so it is often used in conjunction with a pellet mill for shaping (Fancher et al., 1993). Similar to expansion, extrusion uses high-energy input processes that utilize steam and mechanical energy to reach acceptable temperatures for expansion cooking. Temperatures during the cooking process of extrusion can reach as high as 200°C, but the retention time is much shorter than in pelleting (Serrano and Agroturia, 1996). Uniform blending of moisture as water, steam, or both, into the cereal-based mixture during extrusion can elevate the moisture content to approximately 25 to 30%, so drying is necessary (Serrano and Agroturia, 1996).

Pelleting is the most common thermal processing method used in swine feeds in the U.S. (Hancock, 2001). In 1971, Vanschoubroek et al. summarized 66 experiments evaluating the effects of pelleting swine diets on production costs, handling characteristics, and pig performance. The advantages of pelleting included increased bulk density, improved transportation characteristics of feeds, reduced ingredient segregation during handling, decreased dust levels, reduced feed intake, increased weight gain, and improved feed utilization (Vanschoubroek et al., 1971). The listed disadvantages included higher manufacturing costs, reduced carcass fat quality, and increased incidences of stomach ulceration. The authors concluded that, at that time, pelleting grow-finish diets was not economically advantageous (Vanschoubroek et al., 1971). However, during times of high feed cost, pelleting may be an economic option for feed manufacturing finishing pig diets (De Jong et al., 2012. In order to maintain this economic advantage, however, pellets must be high quality. Nemechek (2014) indicated that nursery pigs fed diets with poor quality pellets including 30% fines reduced feed efficiency to levels similar to those of the mash control diet.

The growth improvement advantages from feeding pigs diets that have been thermally processed is thought to be a result of the combination of reduced feed wastage, increased starch gelatinization, the rearrangement of protein structures, and nutrients’ increased susceptibility to enzymatic hydrolysis (Chiang and Johnson, 1977). Hancock et al. (1992) outlined that more extreme methods of thermal processing, such as elongated conditioning or extrusion, provides further nutritional advantages, such as feed sterilization, enhanced protein denaturation, increased fat stability, and decreased activity of antinutritional compounds. More extreme processing conditions are timely to evaluate because the United States Food and Drug Administration recently cited a commercial heat step as an effective *Salmonella* mitigation strategy. However, research suggests standard conditioning times are expected to only destroy 93% of pathogenic bacteria (Veldman et al., 1995). Either higher temperatures, longer conditioning times, or extrusion are thought to be necessary to reduce *Salmonella* concentrations to below detectable levels (Jones and Richardson, 2004). In addition, recent data have demonstrated the susceptibility of Porcine Epidemic Diarrhea Virus (PEDV) to be mitigated by pelleting (Jones, 2015). Thus, some facilities are evaluating the practicality of using pellet mills to reduce the risk of biological pathogens by using these harsh processing conditions (Jones and Richardson, 2004; Doyle and Erickson, 2006). As pork producers begin evaluating the potential benefits of reducing pathogen risk by thermally-processing feeds, it is pertinent to include the advantages or disadvantages of thermal processing parameters on nutrient quality.

While harsher thermal processing is beneficial for some nutrients, others may be affected negatively. For example, Maillard reactions that result from heating diminish protein value and may render lysine unreactive and indigestible by monogastric animals (Björk and Asp 1983). Furthermore, thermal processing may have negative implications on carcass fat quality (De Jong, 2013). Many factors affect these nutritional implications, including ingredient particle size, formulation, and processing variables, such as conditioning temperature and duration, screw configuration and speed, and mash moisture (Singh et al., 2007). Furthermore, pelleting is already an energetically expensive process that may reduce feed mill throughput, and harsher processing conditions may exacerbate these disadvantages (Fahrenholz, 2008 and 2012)

Thermal processing has the potential to both improve and detract from nutrient quality. When managed properly, however, it can be one of the primary methods to add value to inbound ingredients during the feed manufacturing process. The purpose of this review is to describe the effects of thermal processing on particular nutrients that are known to be heat-sensitive, including starch, fiber, protein, lipids, and vitamins.

Starch

Starch is the primary carbohydrate source in animal feed, accounting for the majority of its energy availability and lending some structure in pelleted feed (Lewis, 2014). Energy availability from starch is dependent on its digestibility in the diet, and gelatinization of starch increases its susceptibility to enzymatic digestion (Lahaye et al., 2004). Gelatinization is also important because of its role in pellet quality. Starch, in its native form, has less binding potential than gelatinized starch (Kaliyan and Morey, 2009). Wood (1987) found that diets manufactured with pre-gelatinized starch had greater pellet hardness and durability than those manufactured with raw starch. Starch gelatinization during the pelleting process occurs through two mechanisms: 1) hydration and swelling of starch granules, and ultimate disruption of the crystalline structure due to the combined effects of temperature and moisture; and 2) disruption of starch granules by shear friction as the feed mash is pressed through the pellet die (Stevens, 1987; Cavalcanti, 2004). In general, it was originally thought that the greater the percentage of starch gelatinization, the higher the pellet durability (Heffner and Pfost, 1973). However, later research pointed out that other factors, such as changes in protein structure, have a larger impact on pellet integrity.

Starch consists of 2 main structural components: amylose, which is a linear polymer of glucose residues linked by alpha-D-(1-4) bonds, typically constitutes 15% to 20% of starch; and amylopectin, which is a larger branched molecule with both alpha-D-(1-4) and alpha-D-(1-6) bonds, makes up 80 to 85% of the starch granule (British National Foundation, 1990). The combination of heat and moisture during thermal processing causes the starch granule to swell. This may allow starch to become more readily digestible after consumption by an animal, resulting in better nutrient utilization and feed efficiency. When Chaing and Johnson (1997) extruded wheat in a single-screw extruder, they found significant increases in glucose, maltose, maltotriose, and maltotertraose. These results indicate breakdown of alpha (1-4) bonds of malto-oligosaccharides and starch to more basic units during extrusion. According to Lund (1984), starches from different cereals have different gelatinization characteristics. Similarly, the degree of starch gelatinization varies by thermal processing method (Lewis, 2014). Lewis et al. (2015a) discovered that both high conditioning temperatures (77 vs. 88°C) and longer conditioning times (15 vs. 30 vs. 45 s) result in greater gelatinization. However, conditioning only improved starch gelatinization up to 15 s ($P > 0.05$) when compared to the mash treatment. The relationship between starch gelatinization and improved growth performance due to starch digestibility is weak (Lewis et al., 2015b). Certainly, pelleting results in greater starch gelatinization, but this is predominantly due to shear at the frictional heat of the die instead of from steam conditioning (Stevens, 1987; Sievert and Pomeranz, 1989). Using a capillary rheometer, Stark (1994) found that starch particles in corn begin to swell at 16% moisture and 90°C; however, the crystalline region of the starch is not altered by heating. This result leads researchers to believe that the primary source for gelatinization is through mechanical energy exerted at the pellet die. Still, few improvements in pig growth performance have been directly linked to differences in starch gelatinization, and it appears more likely that feed efficiency improvements from pelleting are a result of greater pellet quality instead (Lewis, 2014).

Fiber

In swine nutrition, dietary fiber, is negatively regarded due to its adverse effects on nutrient digestibility and feed intake (Hahn et al., 2006). Nonstructural carbohydrates are predominantly composed of sugars and starches within cell bodies, and are enzymatically digestible in the upper gut (Zijlstra et al., 2012). In contrast, structural carbohydrates are components of cell walls and contain beta linkages that are difficult or impossible for a pig to digest due to limited enzyme capacity (Zijlstra et al., 2012). As a result, high fiber inclusion in a swine diet has been shown repeatedly to decrease nutrient digestibility (Moeser and van Kempen, 2002).

Thermal processing has been proposed as a mechanism to solubilize fiber to a more digestible form (Caprita et al., 2011). Apparent total tract digestibility of fiber in pigs can be increased by an average of 3% by hydrothermal processing of feeds and feed ingredients, although this effect is highly variable (De Vries et al., 2012). The intense mixing and structural disruption exerted during extrusion facilitate these reactions (Asp and Björck, 1989). Wang et al. (1993) evaluated the effects of extrusion on dietary fiber composition in swine diets. Soluble dietary fiber tended to increase in the extruded sample, with the greatest increase observed during extreme conditioning (Wang et al., 1993). Potentially, this effect could be from the disruption of covalent or noncovalent bonds in carbohydrate and proteins leading to smaller, more soluble molecule fractions (Wang et al., 1993). Thus, moderate extrusion conditions improve fiber solubility; however, there is little evidence if traditional or extended conditioning during pelleting has similar results (Siljeström et al., 1986; Wang et al., 1993).

Protein

As is the case with starch, research has demonstrated a strong influence between protein and pellet quality. Briggs et al. (1999) found that increasing the crude protein content of poultry diets from 16.3 to 21% increased the pellet durability from 76 to 89%. Furthermore, Wood (1987) investigated the impact of raw vs. denatured protein on pellet durability and hardness, and observed that rations containing raw protein produced dramatically stronger pellets than those containing denatured protein (Wood, 1987). Briggs et al. (1999) hypothesized these effects are a result of mash temperature softening the protein polymers. Heat begins to denature hydrogen bonds between polar R-groups, which results in the unfolding of proteins from their quaternary structures to tertiary and secondary shapes (Camire, 1991). As feed moves towards the die, unfolded protein molecules will align with the flow of material and may form disulfide bridges (Harper, 1986 and Buchanan, 2008). During the cooling process, hydrogen bonds are reformed as proteins attempt to refold into their original shapes. However, some denaturation is irreversible, and the refolding and bonding of proteins leads to solid structures and ultimately pellet integrity.

While thermal processing can lead to improved pellet quality, it can also have negative implications on protein availability as both steam and mechanical energy leads to the formation of Maillard reactions. During this chemical reaction, free ε-NH_2 group of amino acids are irreversibly bound to a reducing sugar (Fastinger and Mahan, 2006; Stein et al., 2006). Lysine contains two ε-NH_2 groups in its natural form, making it particularly susceptible to the Maillard reaction (Carpenter and Booth, 1973). Only Lys that retains its reactivity and has not undergone this chemical binding process is bioavailable to the animal, but both forms are observed in nutrient analyses for total Lys (Finot and Magnenat, 1981; Mavromichalis, 2001). Therefore, diets for animals sensitive to Lys availability should either avoid thermal processing or should be evaluated for total Lys reactivity to assess the quantity of the amino acid that is bioavailable.

The quantity of reactive Lys remaining after thermal processing depends upon varying processing characteristics. For example, Noguchi et al. (1982) extruded feed with 20% added sucrose and found reactive Lys retention ranged from 0 to 40%. This difference in Lys loss was due to additional free sugar addition, which caused a greater proportion of the free terminal amines of Lys react with free sugars. This is an important concept, because starch hydrolysis during extrusion can produce these free sugars. Meanwhile, Beaufrand et al. (1978) determined that 32% to 80% of available Lys was lost when feed was extruded at 170°C and 10 to 14% moisture and 60 rpm screw speed. Thus, it is important to maintain mash moisture above 15% when extruding at high temperatures to reduce mechanical friction and preserve Lys availability.

Lipids

Many different added fat sources are used in feed manufacturing, including those of both plant and animal origin. Although fat can play a positive role in increasing dietary energy, it decreases the ability for gelatinization in the starch molecules. Dietary fat inclusion has an inverse relationship with pellet quality (Briggs et al., 1999; McKinney and Teeter, 2004). Fat acts as a lubricant that reduces the friction between the feed and die during pelleting, leading to less mechanical heat production (Behnke, 2001). In addition, the hydrophobic nature of fat inhibits the binding properties of water-soluble components such as starch, protein, and fiber (Thomas et al., 1997). For this reason, fat application through post-pelleting liquid application systems have become a popular method to add caloric density without altering pellet integrity. Still, liquid must be added and pelleted cooled properly to optimize pellet quality.

Because fat serves as lubrication, fat addition in a diet prior to pelleting increases pelleting production rate and reduces the specific energy requirement during pelleting (Richardson and Day, 1976). This result is similar during extrusion, but fat inclusion also impairs the expansion element of extusion. Extrusion of high-fat materials is generally not advisable, because lipid levels over 5 to 6% impair extruder performance (Camire, 2000).

Another negative of thermal processing is that it may potentially oxidize lipids, causing them to have negative sensory and nutritional quality (Singh et al., 2007). The larger surface area created by air cells throughout highly expanded extrudates favors oxidation (Singh et al., 2007). Notably, extrusion may decrease the quantity of extractable fat from a product because of the formation of amylose-lipid complexes (Lai and Kokini, 1991). These complexes are primarily composed of monoglycerides and free fatty acids, which limit their potential for oxidation and rancidity. However, thermally-processed diets may need be subjected to an acid hydrolysis step prior to crude fat determination during wet chemistry nutrient analysis.

De Jong (2013) and Nemechek (2014) reported a previously unknown interaction between thermal processing and lipid utilization. During finishing pig growth experiments, the authors observed that pelleting diets resulted in pigs depositing more unsaturated fat. More specifically, Nemechek (2014) reported that when pigs were fed pelleted diets, their belly fat samples yielded a greater concentration of polyunsaturated fatty acids and higher iodine value, which was driven primarily by an increase in C18:2 concentrations. Potentially, thermal processing increases the digestibility of dietary lipids. In swine diets, the predominant source of dietary lipids are from grain, which is relatively unsaturated in nature. Since more dietary lipids are available for deposition, pigs have reduced de novo fatty acid synthesis, a mechanism that produced fats that are more saturated in nature, thus causing a decline in the polyunsaturated/saturated ratio with increasing fat deposition (De Smet et al., 2004). Therefore, pelleting diets likely shifts fat deposition from saturated de novo products to more unsaturated dietary lipids. This theory needs to be further supported by evaluating the digestibility of various fatty acids subjected to different thermal processing methods.

Vitamins

Vitamin degradation must be considered when thermally processing feeds. In general, fat-soluble vitamins and vitamin-compounds are highly unstable during thermal processing, and retention is often less than 50% during extrusion (Guzman-Tello and Cheftel, 1990; Killeit, 1994). There is conflicting literature to assess B-complex vitamin retention during thermal processing. Within the same reference, thiamine retention values are reported to be between 19 and 90%, while riboflavin retention values are reported to range from 54 to an impossible 125% (Beetner et al., 1974). Generally, vitamin retention is thought to decrease with increasing conditioning temperature and time.

Of the heat sensitive vitamins, thiamine appears to have the most stable denaturation kinetics (Ryley and Kajda, 1994). Ilo and Berghofer (1998) considered thiamine destruction as an indicator of the intensity of the thermal processes. Vitamin stability during pellet processing, tested by Lewis et al. (2015a), indicated that neither conditioning temperature (77 vs. 88°C) nor time (15, 30, and 60 s actual conditioning times) affected riboflavin, niacin, or vitamin D_3 concentrations ($P > 0.50$).

Conclusion

In conclusion, thermal processing of animal feed varies widely based on different parameters used to pellet, extrude, or expand the product. Ultimately, these parameters influence the nutrient quality implications during processing. Thermal processing generally improves starch gelatinization and utilization, as well as pellet quality. While pellet quality also depends on the denaturation of proteins, thermal processing can also negatively impact Lys availability due to the formation of Maillard reactions. The addition of dietary fat tends to decrease pellet quality because it acts as a lubricant at the die, thereby reducing the frictional heat generated during thermal processing. However, increasing temperatures may increase the oxidation rate of lipids. Thermal processing of feed is also hypothesized to increase fatty acid digestibility in pigs, which is the reason that pigs fed pelleted feed deposit more unsaturated fat than pigs fed non-processed mash. Finally, vitamin retention is a concern in thermal processing, but the more extreme temperatures utilized in extrusion and expansion result in greater degradation than in pelleting. Regardless of the parameters used, it is important to recognize that thermal processing can impact nutrient quality in a diet in both a positive and negative manner. One must consider the interaction between processing and animal nutrition prior to creating formal recommendations for processing parameters.

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Chapter 2 - Finely grinding cereal grains in pelleted diets offers little improvement in nursery pig growth performance

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Abstract

Five experiments were conducted to determine the effects of corn particle size and diet form on nursery pig performance and feed preference. In Exp. 1, 192 nursery pigs (PIC 327 × 1050; initially 6.67 kg) were used in a 35-d experiment to determine the effects of corn particle size and diet form on nursery pig growth performance. Pens of pigs were balanced by BW and allotted to 1 of 4 treatments with 6 pigs per pen and 8 pens per treatment. The same corn and soybean meal-based diet formulation was used for all treatments. The 2 × 2 factorial consisted of the main effects of corn particle size (400 vs. 700 µm) and diet form (mash vs. pelleted). Pigs fed mash diets had improved overall ADG and greater ADFI during all periods ($P < 0.05$) and particle size did not impact ($P > 0.10$) performance. In Exp. 2, a preference study utilized 96 pigs to evaluate preference of intake by pigs consuming mash diets with either 400 or 700 µm corn. Pigs overwhelmingly preferred to consume 700 µm corn compared to 400 µm corn (79.3 vs. 20.7% ADFI; $P < 0.05$).

In Exp. 3, 224 nursery pigs (PIC 327 × 1050; initially 10.97 kg) were used in a 10-d experiment to determine the effects of corn particle size in pelleted diets on nursery pig performance. Experimental treatments were formed by grinding corn to 1 of 4 different particle sizes (250, 400, 550, or 700 µm). There was no effect of particle size on ADG ($P > 0.10$), but there were quadratic improvements for ADFI and G:F ($P < 0.0001$). Pigs fed pelleted diets from either 250 or 700 µm corn had poorer G:F than the intermediate treatments. Exp. 4 utilized 91 pigs to evaluate the preference of pigs consuming pelleted diets with either 250 or 700 µm corn from Exp. 3. Even in pelleted form, pigs preferred ($P = 0.01$) to consume diets manufactured with the coarser particle size corn.

In Exp. 5, 180 nursery pigs (PIC 327 × 1050; 36 d of age; initially 16.1 kg) were used in a 35-d experiment to determine the effects of corn particle size and pelleting on nursery pig growth performance. The 2 × 2 factorial consisted of 2 corn particle sizes (500 µm vs. 750 µm) and two diet forms (mash vs. pelleted). Reducing particle size from 750 to 500 µm did not affect growth performance ($P > 0.10$). Pelleting reduced ($P < 0.05$) feed intake, but did not affect ADG or G:F ($P > 0.10$). These studies suggest that there is little value to be gained by fine grinding corn if fed in pelleted form. Furthermore, our data suggests that regardless if fed as mash or pellets, pigs prefer to consume diets manufactured with coarser ground corn if given the choice.

Key words: mash, nursery pig, particle size, performance, pelleting

Introduction

Grinding cereal grains prior to their inclusion in a swine diet is important to maximize nutritive value. Regardless if it is ground by a hammermill or roller mill, reducing particle size is expected to improve feed efficiency of a diet by 1.0 to 1.2% for every 100 micron reduction in corn particle size (Herrman and Harner, 1995; Wondra et al., 1995; Koch, 1996; Kim et al., 2002). However, manufacturing and feeding diets with small particle size can be challenging. Achieving the smaller particle size requires greater electrical energy and may slow mill throughput. In addition, dust, feed bridging, out-of-feed events, and gastric ulcers may all result from feeding diets manufactured from grain with a small particle size (Reese et al., 2000). Pelleting can help overcome some of these disadvantages, but the process requires more even electrical energy and expensive equipment, thus increasing overall feed costs. The return on investment from pelleting comes from improved growth performance, less feed wastage, and greater feed efficiency; however, the magnitude of these improvements depends on other factors, including the particle size of the grain (Skoch et al., 1983).

While pelleting diets manufactured with finely ground grains is common practice in the swine industry, a search of the peer-reviewed data shows surprisingly little research to quantify the effects of varying particle sizes in pelleted diets in nursery pigs of modern genotypes. Therefore, the objectives of these experiments were to: 1) quantify growth performance differences in nursery pigs due to diet form (mash vs. pelleted) and corn particle size, and 2) determine pig consumption preference when given the choice of diets manufactured with corn ground to different particle sizes.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. These studies were conducted at the Kansas State University Swine Teaching and Research Facility in Manhattan, KS.

Experiment 1

In Exp. 1, 192 nursery pigs (PIC 327 × 1050; initially 6.68 kg and 26 days of age) were utilized to evaluate the effects of particle size and diet form on swine growth performance. Pigs were weaned and fed a common diet for 5-d, after which they were balanced by initial BW and randomly allotted to 1 of 4 treatments with 6 pigs per pen and 8 pens per treatment. Each pen contained 1 nipple waterer and 1 self-feeder to allow for *ad libitum* access to water and feed. The 4 experimental treatments were created utilizing the same basal formulation and arranged in a 2 × 2 factorial design with the main effects of feed form (meal vs. pellet) and corn particle size (400 µm vs. 700 µm; Table 2.1). All feed was manufactured at the O.H. Kruse Feed Technology Innovation Center at Kansas State University. Corn was ground using a triple pair roller mill (RMS Roller-Grinder, Harrisburg, SD) and analyzed for particle size according to ASAE Method S319.4 with a 15-min tap time and 1.0 g fumed silica included as a flow agent. Actual corn micron sizes were 387 and 477 vs. 703 and 725 µm for phase 1 and 2 of each treatment, respectively (Table 2.2). Pelleted diets were pelleted at 80°C for 45 s using a CPM pellet mill (California Pellet Mill, Crawfordsville, IN) and analyzed for pellet durability index (PDI) according to ASAE Method S269.4 with a modification to include five 13-mm hexagonal nuts to more closely mimic the pellet quality after handling as described by Fahrenholz (2012). Diets were fed in 2 phases: phase 1 from d 0 to 14, and phase 2 from d 14 to 35. Pigs and feeders were weighed on d 0, 14, and 35 to determine ADG, ADFI, and G:F.

Experiment 2

A separate 10-d study utilized 96 pigs (PIC 327 × 1050; initially 6.30 kg and 26 days of age) to evaluate the preference of pigs consuming mash diets manufactured with either the 400 or 700 µm corn from Exp. 1. There were 12 pens utilized and 8 pigs per pen. Each pen was equipped with two identical 4-hole dry self-feeders and a nipple waterer to allow for *ad libitum* access to consume feed from either treatment. Feeder location was changed daily to prevent a location bias of the feeder within the pen. Preference was measured by feed disappearance from an individual feeder. Feeders were weighed on d 0 and 10 to determine feed disappearance and ADFI per feeder.

Experiment 3

In Exp. 3, a total of 224 nursery pigs (PIC 327 × 1050; initially 10.74 kg and 40 d of age) were utilized in a 10-d experiment to determine the effects of corn particle size in pelleted diets on late nursery pig growth performance. Pigs were weaned and placed on a common phase 1 and phase 2 diets. On d 19 post-weaning, pigs were balanced by initial BW and randomly allotted to 1 of 4 treatments with 7 pigs per pen and 8 pens per treatment. Each pen contained 1 nipple waterer and 1 self-feeder to allow for *ad libitum* access to water and feed. The same basal diet formulation was utilized for all diets, with experimental treatments created by including corn ground to four different mean particle sizes (approximately 250, 400, 550, or 700 µm; Table 2.3). All feed was manufactured at the O.H. Kruse Feed Technology Innovation Center at Kansas State University. Corn was ground using a hammermill (Bliss Industries, LLC, Ponca City, OK) and analyzed for particle size as described in Exp. 1. To achieve the intended corn micron size in a consistent manner, corn was blended to achieve similar particle size separation between treatments. Treatment 1 contained only corn ground through a #4 screen. Treatment 4 contained only corn ground through a #24 screen. Treatment 2 contained 66% corn from #4 screen and 33% corn from #24 screen. Treatment 3 contained 66% corn from #24 screen and 33% corn from #4 screen. Actual corn micron sizes were 212, 422, 509, and 739 µm (Table 2.4). Diets were pelleted as described in Exp. 1and PDI was determined using a Holmen NHP100 (Tekpro Limited, Norfolk, United Kingdom, Table 2.4) for 60 seconds. Percentage fines were also determined on each sample. Fines were characterized as material that would pass through a #6

Tyler Sieve (3,360-µm opening) after 15 sec of manual shaking. Diets were fed for 10 d, and pigs and feeders were weighed on d 0 and 10 determine ADG, ADFI, and G:F.

Experiment 4

A separate 10-d study utilized 91 pigs (PIC 327 × 1050; initially 10.75 kg and 40 d of age) to evaluate the preference of pigs consuming pelleted diets manufactured with either 250 or 700 µm corn from Exp. 3. There were 12 pens utilized and 7 or 8 pigs per pen. Each pen was equipped with two identical 4-hole dry self-feeders and a nipple waterer to allow for *ad libitum* access to consume feed from either treatment. Feeder location was changed daily to prevent a location bias of the feeder within the pen. Preference was measured by feed disappearance from an individual feeder. Feeders were weighed on d 0 and 10 to determine feed disappearance and ADFI per feeder.

Experiment 5

A total of 180 (PIC 327 × 1050; 36 d of age; initially 7.15 kg) pigs were used in a 35 d growth trial to evaluate the effects of particle size and diet form on swine growth performance. Pigs were weaned on d 26 of age, blocked by initial BW, and fed a pelleted acclimation phase 1 diet for 10 days. On d 0 of the experiment, pigs were randomly assigned to pens in a randomized complete block design with 5 pigs per pen and 9 replications per treatment. Each pen contained 1 nipple waterer and 1 self-feeder to allow for *ad libitum* access to water and feed. The 4 experimental treatments were created utilizing the same basal formulation and arranged in a 2 × 2 factorial design with the main effects of feed form (meal vs. pellet) and corn particle size (500 µm vs. 750 µm; Table 2.5). All feed was manufactured at the O.H. Kruse Feed Technology Innovation Center at Kansas State University. Again, the same basal diet formulation was used for all diets. Corn was ground using a hammermill (Bliss Industries, LLC, Ponca City, OK) and analyzed for particle size as described in Exp. 1 (Table 2.6). Diets were pelleted and analyzed for PDI as described in Exp. 1. Experimental diets were fed in two phases: d 0 to 14 and d 14 to 35.

Statistical Analysis

Data were analyzed using PROC GLIMMIX in SAS (SAS Institute, Inc., Cary, NC). Growth performance data were analyzed with pen as the experimental unit. In Exp. 1 and 5, particle size and feed form, as well as their interaction, were considered main effects. In Exp. 2, 3, and 4 treatment served as a fixed effect. Linear and quadratic effects of particle size were determined utilizing orthogonal contrasts. Results were considered significant if $P < 0.05$ and trends if $P < 0.10$.

Result and Discussion

Experiment 1

In Exp. 1, there were no effects of corn particle size ($P > 0.10$) on any measured response criteria, nor were there particle size × feed form interactions for ADG or ADFI ($P > 0.10$; Table 2.7). The lack of feed efficiency response from the decrease in particle size was surprising considering that previous research had reported a near linear improvement of feed efficiency with decreasing particle size (Paulk et al., 2011; De Jong et al., 2012).

While we were surprised to find no overall improvement from the main effect of particle size, the negative effect of pelleting on ADG was even more unexpected. Pigs fed pelleted diets had poorer ($P < 0.05$) ADG than those fed mash diets from d 14 to 35 and d 0 to 35. These differences were largely driven by ADFI, which was greater in mash diets across all phases ($P < 0.05$). Therefore, G:F was improved by 11% from pelleting from d 0 to 14, but there were no differences from d 14 to 35. This resulted in a tendency ($P < 0.10$) for improved G:F from pelleting overall. Still, this improvement in feed efficiency did not overcome the improvements in ADG observed in pigs fed mash diets, so those fed mash diets tended ($P < 0.10$) to be heavier by the end of the 35-d experiment. . These findings are in contrast to those reported by De Jong et al. (2013), who found that pelleting diets improved both ($P < 0.05$) ADG and G:F.

There was a particle size × feed form interaction for G:F from d 14 to 35 and d 0 to 35 ($P < 0.05$; Table 2.8). Pigs fed pelleted diets manufactured from 700 µm ground corn had greater ($P < 0.05$) G:F from d 14 to 35 and d 0 to 35 than pigs fed pelleted diets manufactured from 400 µm ground corn, with mash treatments being intermediate.

Experiment 2

When pigs were allowed to choose to consume either the mash diet manufactured from 400 µm or 700 µm corn, they clearly preferred diets manufactured from corn with the coarser particle size ($P < 0.05$; Table 2.9) with nearly 80% of the feed consumed being from the coarser particle size diet (0.14 vs. 0.54 kg/d for 400 vs. 700µm, respectively). Fine grinding corn in mash diets is known to create feed flowability issues, but feeders were managed closely during the course of this experiment to prevent differences in quantity of feed in the pan. This preference data suggests that fine grinding corn in nursery pig diets may also have negative implications on feed intake. We can assume that different particle sizes can influence sensory characteristics, such as texture. Solá-Oriol et al. (2009) found feed preference in pigs was correlated with the feed texture due to palatability. Follow up research is needed to confirm this hypothesis by tracking number of feeder visits, total meal time, and average feed consumed per meal.

Experiment 3

Because of the interesting findings from Exp. 1, we wanted to further evaluate the effect of reducing particle size in pelleted diets, particularly when evaluating even lower particle sizes of grain. Again, reducing particle size in pelleted diets did not affect ADG or ADFI ($P > 0.10$). These findings confirm our initial results and suggest the reduction in particle size does not always linearly influence ADG. For example, Healy et al. (1994) fed starter diets to 21 day old weaned pigs with sorghum ground to 900, 700, 500, or 300 µm. Reducing grain particle size to 500 or 300 microns had little effect on ADG, but reduced ADFI, which then improved G:F. Numerically, the results of our experiment were variable, but there was a tendency for decreased particle size in pelleted diets to improve ($P < 0.10$) feed efficiency in a quadratic manner (Table 2.10). These diets were fed as a phase 3 nursery diet, when pigs were 40 days of age. Bramelcox et al., (1994) suggested that the response to reducing particle size is greatest during the first 2 weeks post-weaning, and that optimal particle size for corn and sorghum increases with age of nursery pigs. Notably, there were marked differences in PDI across different treatments in our experiment, with the PDI from diets manufactured from 250 or 700 µm corn being greater than those manufactured with corn from the intermediate particle sizes (PDI = 68.3, 50.8, 43.2 and 68.9, respectively). It is important to understand that these PDI values are all strikingly low, especially compared to the range from 84.9 to 89.0 observed in Exp. 1.These PDI values were obtained from analysis using the Holmen NHP 100 method compared to the modified tumbling box method utilized in Exp. 1. Thus, a slight change in PDI due to different analytical methods may explain some of these differences across the trials, but not to the extent observed. Boac et al. (2008) demonstrated that differences exist between the Holmen tester and tumbling box methods, but only 3 to 5%. Still, one would expect that poor pellet quality would be associated with poor feed efficiency as described by Harper (1998), but this did not occur as the treatment responsible for the greatest feed efficiency had one of the lowest PDI's. For these reasons, PDI was not utilized as a covariate in statistical analysis.

Experiment 4

We can evaluate effects between particle sizes in pelleted diets further through the preference experiment between diets manufactured with 250 or 700 µm ground corn because those treatments had similar PDI. In agreement with Exp. 2, pigs preferred to consume diets manufactured with the coarser particle size corn ($P < 0.05$; Table 2.11). However, the percentage of preference of the pelleted diets was not as extreme as was observed when the diets were in mash form (31.8 vs. 58.2% ADFI for 250 vs. 700 µm corn, respectively; $P < 0.05$). While the first experiment alluded to small particle size playing a role in feeding behavior, it was interesting to see this effect still existed, although in a diluted manner, when the diets were pelleted. This shows that pigs can still detect a particle size difference, even when diet form is altered. Additional research is needed to more clearly evaluate these findings at a larger scale and extended period of time.

Experiment 5

To further evaluate the variability in results from Exp. 1 and 3, as well as address potential differences in particle size and feed form using a hammermill, a 35 d-growth experiment was conducted as Exp. 5. While a roller mill was used to grind grain by shear for Exp. 1, this experiment utilized a hammermill to reach target particle sizes in ground corn. Reducing particle size from 750 to 500 µm again did not affect growth performance ($P > 0.10$; Table 2.12). Similar to Exp. 1, pelleting reduced ($P < 0.05$) feed intake during each phase, potentially due to less feed wastage than in the mash diet. Contrary to Exp. 1, there was no effect of pelleting on overall ADG or G:F ($P > 0.10$). This is interesting because past research (Hansen et al., 1992; Wondra et al., 1992; Traylor et al., 1996) overwhelmingly suggests that pelleting improves growth rate and feed efficiency in nursery pigs.

The interaction between particle size and diet form affected G:F from d 0 to 14 (Table 2.13), where again coarsely ground pelleted diets had greater feed efficiency than finely ground pelleted diets or coarsely ground mash diets ($P < 0.05$; 0.72, 0.68, 0.68, and 0.74 for 500 µm mash, 500 µm pelleted, 750 µm mash, and 750 µm pelleted diets, respectively). This was not due to PDI, because pellet quality was consistent across treatments within phases. Additionally, the interaction tended to affect ADG from d 0 to 14 and overall, where pigs fed finely ground mash diets had greater ADG than those fed finely ground pelleted diets ($P < 0.10$; 0.46 vs. 0.40 kg/d for d 0 to 14 and $P = 0.103$; 0.53 vs. 0.48 kg/d for d 0 to 35, respectively). However, this was offset by a tendency for the interaction to affect ADFI from d 14 to 35 as pigs fed finely ground mash diets had greater feed disappearance than those fed finely ground pelleted diets ($P < 0.10$). While our findings are unexpected, the lack of feed efficiency is similar to recently published research in both nursery (De Jong et al., 2012) and finishing pigs (De Jong et al., 2013), yet confounding to others (Ball et al., 2015) that suggest there is little advantage of pelleting diets with a fine particle size. Potentially, the digestibility of the diet is already maximized by pelleting, so further reducing particle size does not result in greater digestibility. However, more research is needed to evaluate the physiological causes of this effect.

In general, this series of 5 experiments suggests pigs fed pelleted diets had reduced ADFI and improved feed efficiency than those fed mash diets. We observed mixed effects regarding the effect of particle size, with no effect in mash diets and a quadratic effect in pelleted diets. The best feed efficiency was achieved when pigs were fed pelleted diets manufactured from 700 µm corn. Finally, pigs preferred to consume a coarser corn particle size, particularly when the diet was fed in mash form.

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Figures and Tables

Table 2.1 Composition of experimental diets (Exp. 1 and 2; as-fed basis)

	Phase[1]:	
Item	2	3
Ingredient, %		
Corn	55.57	64.23
Soybean meal, 46.5%	27.15	30.40
Select menhaden fish meal	3.00	---
Spray dried whey	10.00	---
Soy oil	2.00	2.00
Monocalcium P, 21% P	0.65	1.05
Limestone	0.39	1.00
Salt	0.35	0.35
L-lysine HCl	0.24	0.31
DL-methionine	0.12	0.12
L-threonine	0.11	0.12
Trace mineral premix	0.15	0.15
Vitamin premix	0.25	0.25
Phytase[2]	0.02	0.02
Total	100.00	100.00
Calculated analysis		
Standard ileal digestible (SID) amino acids, %		
Lysine	1.25	1.20
Isoleucine:lysine	62	62
Leucine:lysine	129	131
Methionine:lysine	34	33
Met & Cys:lysine	58	58
Threonine:lysine	64	63
Tryptophan:lysine	17.5	17.5
Valine:lysine	69	69
SID Lysine:ME, g/Mcal	3.67	3.51
ME, kcal/kg	1,545	1,550
Total lysine, %	1.38	1.33
CP, %	20.8	20
Ca, %	0.8	0.7
P, %	0.64	0.61
Available P, %	0.50	0.43

[1] Phase 2 diets were fed from approximately 6.7 to 9.7 kg (day 0 to 14); Phase 3 diets were fed from approximately 9.7 to 20.7 kg (d 14 to 35).

[2] Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided a release of 0.11% available P.

Table 2.2 Physical analysis of corn and diets (Exp. 1 and 2)[1]

	Phase	
Item	2	3
Particle size[2]		
400 µm corn		
Geometric mean, µm	387	477
Standard deviation	2.46	2.40
700 µm corn		
Geometric mean, µm	703	825
Standard deviation	2.48	2.09
Pelleted diet durability index[3]		
400 µm corn diets	89.0	88.8
700 µm corn diets	84.9	85.2

[1] A composite sample of 2 subsample was utilized for analysis

[2] Determined according to ASAE S319.3, 2003 using 0.5 g of flow agent and sifted for 10 minutes.

[3] Determined according to ASAE S269.4, 2003 with a modification to include five 1.27 cm hex nuts in the tumbling chamber.

Table 2.3 Composition of experimental diets (Exp. 3 and 4; as-fed basis)[1]

Item	
Ingredient, %	
Corn	64.23
Soybean meal, 46.5%	30.40
Soybean oil	2.00
Monocalcium P, 21% P	1.05
Limestone	1.00
Salt	0.35
L-lysine HCl	0.31
DL-methionine	0.12
L-threonine	0.12
Trace mineral premix	0.15
Vitamin premix	0.25
Phytase[2]	0.02
Total	100.00
Calculated analysis	
Standard ileal digestible (SID) amino acids, %	
Lysine	1.20
Isoleucine:lysine	62
Leucine:lysine	131
Methionine:lysine	33
Met & Cys:lysine	58
Threonine:lysine	63
Tryptophan:lysine	17.5
Valine:lysine	69
SID Lysine:ME, g/Mcal	3.51
ME, kcal/kg	1,545
Total lysine, %	1.33
CP, %	20
Ca, %	0.70
P, %	0.61
Available P, %	0.43

[1] Diets were fed from approximately 10.9 to 15.2 kg

[2] Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided a release of 0.11% available P.

Table 2.4 Physical analysis of corn and diets (Exp. 3 and 4)[1]

	Particle size[1]		
Item	Geometric mean, µm	Geometric standard	Pelleted durability index[2]
250 µm	212	2.52	68.3
400 µm	422	2.55	50.8
550 µm	509	2.80	43.2
700 µm	739	2.48	68.9

[1] Determined according to ASAE S319.3, 2003 using 0.5 g of flow agent and sifted for 10 minutes.

[2] Determined using a Holmen NHP 100 (TekPro; Norfolk, GBR) with 100 g of sample for 60 seconds.

Table 2.5 Composition of experimental diets (Exp. 5; as-fed basis)[1]

Item	Phase[1]: 2	3
Ingredient, %		
Corn	55.57	64.23
Soybean meal, 46.5%	27.15	30.40
Select menhaden fish meal	3.00	---
Spray dried whey	10.00	---
Soy oil	2.00	2.00
Monocalcium P, 21% P	0.65	1.05
Limestone	0.39	1.00
Salt	0.35	0.35
L-lysine HCl	0.24	0.31
DL-methionine	0.12	0.12
L-threonine	0.11	0.12
Trace mineral premix	0.15	0.15
Vitamin premix	0.25	0.25
Phytase[2]	0.02	0.02
Total	100.00	100.00
Calculated analysis		
Standard ileal digestible (SID) amino acids, %		
Lysine	1.25	1.20
Isoleucine:lysine	62	62
Leucine:lysine	129	131
Methionine:lysine	34	33
Met & Cys:lysine	58	58
Threonine:lysine	64	63
Tryptophan:lysine	17.5	17.5
Valine:lysine	69	69
SID Lysine:ME, g/Mcal	3.67	3.51
ME, kcal/kg	1,548	1,550
Total lysine, %	1.38	1.33
CP, %	20.8	20
Ca, %	0.8	0.7
P, %	0.64	0.61
Available P, %	0.50	0.43

[1] Phase 2 diets were fed from approximately 6.7 to 9.7 kg (day 0 to 14); Phase 3 diets were fed from approximately 9.7 to 20.7 kg (d 14 to 35).

[2] Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided a release of 0.11% available P.

Table 2.6 Physical analysis of corn and diets (Exp. 5)[1]

Item	Particle size[1]		Pelleted durability index[2]
	Geometric mean, µm	Standard	
500 µm			
Phase 2	512	2.41	85.3
Phase 3	469	2.33	66.2
750 µm			
Phase 2	764	2.49	90.7
Phase 3	770	2.51	78.9

[1] Determined according to ASAE S319.3, 2003 using 0.5 g of flow agent and sifted for 10 minutes.

[2] Determined according to ASAE S269.4, 2003 with a modification to include five ½” hex nuts in the tumbling chamber.

Table 2.7 Main effects of corn particle size and diet form on nursery pig growth performance (Exp. 1)[1]

	Particle size, µm			Diet form			*P* =	
Item	400	700	SEM	Mash	Pellet	SEM	Particle size	Diet form
d 0 to 14								
ADG, kg	0.24	0.23	0.008	0.23	0.24	0.008	0.421	0.410
ADFI, kg	0.38	0.36	0.012	0.40	0.35	0.012	0.253	0.009
G:F	0.62	0.63	0.015	0.57	0.67	0.015	0.548	< 0.001
d 14 to 35								
ADG, kg	0.52	0.52	0.012	0.55	0.48	0.012	0.873	< 0.001
ADFI, kg	0.84	0.82	0.017	0.89	0.77	0.017	0.441	< 0.001
G:F	0.62	0.63	0.011	0.63	0.63	0.011	0.437	0.806
d 0 to 35								
ADG, kg	0.41	0.40	0.010	0.43	0.39	0.010	0.650	0.006
ADFI, kg	0.66	0.64	0.013	0.70	0.61	0.013	0.252	< 0.001
G:F	0.62	0.63	0.010	0.61	0.64	0.010	0.334	0.062
BW, kg								
d 0	6.68	6.70	0.198	6.70	6.68	0.198	0.948	0.948
d 14	9.75	9.65	0.266	21.27	21.51	0.266	0.793	0.775
d 35	20.66	20.76	0.429	21.28	20.14	0.429	0.867	0.071

[1] A total of 192 pigs (PIC 327 × 1050) were used in a 35 d trial with 8 pens per treatment and 6 pigs per pen.

Table 2.8 Interactive means of feed efficiency for particle size and diet form (Exp. 1)[1]

Particle size:	400 µm		700 µm		P =
Diet form:	Mash	Pellet	Mash	Pelleted	Particle size × Diet form
d 0 to 14					
ADG, kg	0.23	0.24	0.22	0.23	0.883
ADFI, kg	0.40	0.37	0.40	0.33	0.364
G:F	0.58	0.66	0.57	0.70	0.244
d 14 to 35					
ADG, kg	0.56	0.48	0.55	0.49	0.603
ADFI, kg	0.88	0.79	0.89	0.75	0.242
G:F	0.64^{ab}	0.61^{b}	0.62^{ab}	0.65^{a}	0.048
d 0 to 35					
ADG, kg	0.43	0.39	0.42	0.39	0.803
ADFI, kg	0.70	0.63	0.70	0.58	0.167
G:F	0.62^{b}	0.62^{b}	0.60^{b}	0.66^{a}	0.031
BW, kg					
d 0	6.65	6.70	6.74	6.65	0.790
d 14	9.65	9.86	9.65	9.66	0.804
d 35	21.41	19.92	21.16	20.36	0.574

[1] A total of 192 pigs (PIC 327 × 1050) were used with 8 pens per treatment and 6 pigs per pen.

[ab] Letters within a row that do not share a common superscript differ $P < 0.05$.

Table 2.9 Preference of meal diets based on corn ground to two particle sizes (Exp. 2)[1,2]

Item	400 µm	700 µm	SEM	*P* =
ADFI, kg	0.14	0.54	0.072	0.001
ADFI, %	20.7	79.3	---	---

[1] A total of 96 pigs were used with 12 pens per treatment and 8 pigs per pen.

[2] Two feeders each containing the same formulated diet but manufactured with either 400 µm or 700 µm corn were provided per pen. Intake was determined by feed disappearance from each feeder.

Table 2.10 Effects of corn particle size in pelleted diets on nursery pig growth performance (Exp. 3)[1]

	Corn particle size, µm					*P* =		
Item	250	400	550	700	SEM	Treatment	Linear	Quadratic
d 0 to 10								
ADG, kg	0.46	0.49	0.48	0.46	0.031	0.302	0.589	0.084
ADFI, kg	0.73	0.71	0.74	0.72	0.016	0.594	0.956	0.733
G:F	0.63	0.69	0.64	0.64	0.018	0.145	0.662	0.101
BW, kg								
d 0	11.10	10.74	11.16	10.85	0.406	0.856	0.859	0.956
d 10	15.26	15.14	15.47	14.96	0.428	0.864	0.762	0.650

[1] A total of 224 pigs (PIC 327 × 1050) were used with 8 pens per treatment and 7 pigs per pen.

Table 2.11 Preference of pelleted diets based on corn ground to two particle sizes (Exp. 4)[1,2]

Item	250 µm	700 µm	SEM	*P* =
ADFI, kg/d	0.20	0.28	0.053	0.011
ADFI, %	41.8	58.2	---	---

[1] A total of 91 pigs were used with 12 pens per treatment and 7 or 8 pigs per pen.

[2] Two feeders each containing the same formulated diet but manufactured with either 250 µm or 700 µm corn were provided per pen. Intake was determined by feed disappearance from each feeder.

Table 2.12 Main effects of corn particle size and diet form on nursery pig growth performance (Exp. 5)[1]

	Particle size, µm			Diet form			*P* =	
Item	500	750	SEM	Mash	Pellet	SEM	Particle size	Diet form
d 0 to 13								
ADG, kg	0.43	0.43	0.012	0.44	0.42	0.012	0.892	0.110
ADFI, kg	0.61	0.61	0.016	0.63	0.59	0.016	0.940	0.045
G:F	0.70	0.71	0.016	0.70	0.71	0.016	0.644	0.645
d 13 to 35								
ADG, kg	0.67	0.65	0.037	0.66	0.66	0.037	0.983	0.578
ADFI, kg	1.13	1.12	0.028	1.16	1.10	0.027	0.78	0.042
G:F	0.60	0.59	0.025	0.58	0.61	0.025	0.556	0.140
d 0 to 35								
ADG, kg	0.50	0.50	0.021	0.51	0.49	0.021	0.827	0.337
ADFI, kg	0.78	0.78	0.020	0.80	0.75	0.020	0.982	0.020
G:F	0.66	0.65	0.018	0.64	0.66	0.018	0.878	0.224
BW, kg								
d 0	7.23	7.15	0.156	7.20	7.18	0.156	0.525	0.860
d 14	13.22	13.10	0.308	13.28	13.04	0.308	0.660	0.365
d 35	27.18	26.83	0.487	27.16	26.85	0.487	0.440	0.478

[1] A total of 180 pigs (PIC 327 × 1050 at 36 d of age) were used with 9 pens per treatment and 5 pigs per pen.

Table 2.13 Interactive means of feed efficiency for particle size and diet form (Exp. 5)[1]

Particle size:	500 µm		750 µm		*P* =
Diet form:	Mash	Pelleted	Mash	Pelleted	Particle size × Diet form
d 0 to 14					
ADG, kg	0.46^{x}	0.40^{y}	0.43^{xy}	0.43^{xy}	0.064
ADFI, kg	0.64	0.58	0.63	0.60	0.650
G:F	0.72^{ab}	0.68^{b}	0.68^{b}	0.74^{a}	0.044
d 14 to 35					
ADG, kg	0.68	0.66	0.64	0.67	0.378
ADFI, kg	1.18^{x}	1.08^{y}	1.13^{xy}	1.12^{xy}	0.082
G:F	0.58	0.62	0.58	0.61	0.803
d 0 to 35					
ADG, kg	0.53^{x}	0.48^{y}	0.49^{xy}	0.51^{xy}	0.103
ADFI, kg	0.82	0.74	0.79	0.76	0.245
G:F	0.66	0.65	0.63	0.67	0.206
BW, kg					
d 0	7.25	7.22	7.16	7.14	0.988
d 14	13.49	12.94	13.07	13.13	0.262
d 35	27.58	26.77	26.74	26.92	0.256

[1] A total of 180 pigs (PIC 327 × 1050) were used with 9 pens per treatment and 5 pigs per pen.

[ab] Letters within a row that do not share a common superscript differ $P < 0.05$.

[xy] Letters within a row that do not share a common superscript differ $0.05 < P < 0.05$.

Chapter 3 - Evaluation of extreme thermal processing methods to improve nutrient utilization of low energy diets for finishing pigs[1,2]

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Abstract

A total of 270 pigs (PIC 337 × 1050; initially 52.2 kg BW) were utilized in a 79-d experiment to determine the effects of long-term conditioning or extrusion on finishing pig nutrient digestibility, growth performance and carcass characteristics. There were 7 or 8 pigs per pen and 9 pens per treatment. Treatments included the same basal diet processed as: 1) non-processed mash, 2) pelleted with 45 s conditioner retention time, 3) pelleted with 90 s conditioner retention time, or 4) extruded. Diets were fed in 3 phases with the same low energy diet formulation fed across treatments, containing 30% corn dried distillers grains with solubles and 19% wheat middlings. Pigs fed thermally-processed feed, regardless of method, had improved ADG, G:F, and EE and CF apparent total tract digestibility (*P* < 0.05) compared to those fed the mash diet, but thermal processing did not affect ADFI (*P* > 0.10). Extruded diets tended to improve G:F compared to pelleted diets (*P* = 0.087). Interestingly, HCW was greater when pigs were fed pelleted diets compared to extruded diets, regardless of conditioning time ($P < 0.05$). However, pigs fed any thermally-processed treatment had greater HCW compared to those fed mash ($P < 0.05$). Alterations in nutrient digestibility led to improved caloric efficiency in pigs fed thermally-processed diets which lead to greater HCW ($P < 0.05$). Thermal processing did not influence percentage yield, backfat, or loin depth when HCW was used as a covariate ($P > 0.10$). However, pigs fed thermally-processed diets had greater jowl iodine values compared to those fed mash diets ($P < 0.05$). Electrical energy usage during thermal processing was recorded. Pigs fed mash diets had greater cost per kg of gain, as well as reduced gain value and income over feed costs compared to those fed thermally-processed diets. This experiment again confirms the benefits of thermally processing feeds to improve ADG and G:F, but compromises carcass fat firmness. Additionally, this research suggests that more extreme thermal processing conditions may be used without hindering nutrient utilization.

Key words: extrude, pellet, performance, pig

Introduction

High fiber byproduct ingredients often price into least-cost formulas (Cromwell et al., 2000). However, their inclusion in a swine diet may have negative consequences, including increased nutrient variability, decreased growth performance, and reduced carcass yield and fat quality (Stein and Shurson, 2009; Coble et al., 2015). Furthermore, the physical characteristics of these ingredients often create handling challenges because they have decreased bulk density compared to their origin grain or oilseed (Asmus et al., 2014). In addition, it is often difficult to produce a high quality pellet due to the increased fracture points and poor starch gelatinization potential from their high fiber content (Fahrenholz, 2008 and 2012).

Still, if one manipulates thermal processing parameters so a high quality pellet is produced, advantages in diet quality may be captured. Increasing conditioning time during the pelleting process improves pellet quality and increases the diet's propensity for starch gelatinization and susceptibility to enzymatic hydrolysis (Chiang and Johnson, 1977; Cramer et al., 2003; and Lundblad et al., 2009). While extended processing is beneficial for some nutrients, others may be affected negatively. For example, De Jong (2013) summarized the negative influence pelleting had on carcass fat quality. Furthermore, pelleting is already an energetically expensive process that reduces feed mill throughput, and harsher processing conditions exacerbate these disadvantages (Fahrenholz, 2012). Still, it is important to evaluate the effects pelleting diets that include low energy byproducts in order to calculate the cost:benefit of these harsh thermal processing methods in pork production. Therefore, the objective of this experiment was to assess how long-term conditioning or extrusion of low energy diets impact nutrient digestibility, growth performance, and carcass characteristics in finishing pigs.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used for this experiment. This experiment was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan.

Diet Manufacturing

Four treatments were manufactured for this experiment by varying the same diet with different thermal processing methods: 1) non-processed mash, 2) positive control: pelleted with 45 s conditioner retention time, 3) pelleted with 90 s conditioner retention time, and 4) extruded. Diets were fed in 3 phases with the same low energy diet formulation fed across treatments with 30% corn dried distillers grains with solubles and 19% wheat middlings (Tables 3.1). The basal diets, as well as treatments 1, 2, and 3, were manufactured at the Kansas State University O. H. Kruse Feed Technology Innovation Center in Manhattan. Treatments 2 and 3 were conditioned at 82°C and pelleted using a pellet mill (California Pellet Mill Model #3016-4, Crawfordsville, IN) fit with a 4.4 mm × 28.6 mm die. The conditioner motor speed was decreased to manufacture Treatment 3 with a longer conditioning time to mimic the time of a double-pass conditioner. Meanwhile, the basal diet was transported to Wenger Manufacturing, Inc. in Sabetha, KS, where Treatment 4 was manufactured using a Universal Pellet Cooker (Model UP/C, Wenger Manufacturing, Sabetha, KS) with 170°C preconditioning temperature. Because other processing and steam costs are extremely variable from one location and system to another, our efforts focused on the evaluating the differences in electrical energy requirements for additional thermal processing requirements, regardless of steam. For this reason, mash diets were assigned $0 of added electrical costs for thermal processing. Electrical energy use and production rate (tonne/hour) were recorded during thermal processing. Measurements were taken every 30 seconds for a 3-minute period twice during the production of each of the three phases and averaged to determine the overall production rate per phase. A standard price of $0.12 per kilowatt hour was utilized to calculate electrical energy costs for thermal processing and added to overall feed cost per pig (Table 3.2). Pellet durability was determined according to the standard and modified ASAE Standard S269.4 as described by Farhenholz (2012) where five 13-mm hex nuts were added to the each tumbling compartment (Table 3.2).

Growth Experiment

A total of 270 finisher pigs (PIC 337 × 1050; initially 52.2 kg) were utilized in this 79-d experiment. There were 7 to 8 pigs per pen and 9 pens per treatment. All pens contained one waterer and self-feeder allowing *ad libitum* access to feed and water. On d 0, pens were weighed and randomly assigned one of the four dietary treatments. Pen weights and feed disappearance were collected on d 0, 25, 46, 60, and 79 to calculate the ADG, ADFI, and G:F. Phase 3 diets (60 to 79 d) included 0.4% titanium dioxide, and fecal samples were collected between 66 and 68 d. from three pigs or more and combine to make one cohesive sample per pen Prior to slaughter, pigs were individually tattooed for identification purposes at the packing plant. Individual pig weights were collected at the farm before slaughter on d 79. Pigs were slaughtered and carcass data collected in a single run at Triumph Foods in St. Joseph, Missouri. Hot carcass weights were measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and jowl iodine value. Carcass yield was calculated by dividing the HCW at the packing plant by the live weight at the farm. Fat depth and loin depth were measured by optical probe insertion between the third and fourth rib from the proximal end. Jowl fat samples were analyzed by near infrared spectroscopy (Bruker MPA, Breman, Germany) for iodine value using the equation by Cocciardi et al. (2009). Economic value was calculated with market values at the time of pig slaughter in September 2014; specifically, corn $253/tonne, soybean meal $467/tonne, DDGS $227/tonne, wheat midds $218/tonne, and lean hog price $107.97/cwt.

Nutrient Digestibility Analysis

Fecal samples were dried according to AOAC Official Method 934.01. All feed and fecal samples were analyzed for proximate analysis (AOAC Official Methods 990.03, 942.05, 920.39, 978.10, and 934.01), NDF (Van Soest et al., 1991), ADF (AOAC Official Method 973.18), cellulose (AOAC Official Method 973.18), beta-glucan (AOAC Official Method 995.16), fatty acid profile (AOAC Official Methods 996.06, Ce 2-66), amino acid composition (AOAC Official Method 982.30), and available Lys (AOAC Official Method 975.44). Digestibility coefficients were calculated according to Stein et al. (2006).

Statistical Analysis

Data were analyzed as a completely randomized design using the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC) with pen as the experimental unit. Hot carcass weight was used as a covariate for backfat and loin depth. Results were considered significant if $P < 0.05$, and a trend if $0.05 < P < 0.10$. Orthogonal contrasts were used to evaluate differences between pelleted vs. extruded diets, pelleted vs. control diets, 45 s pellet vs. 90 s pellet, and thermally-processed vs. control diets.

Results and Discussion

Diet Manufacturing

Post-mixing production rate varied widely among treatments due to differences in equipment (Table 3.2). Both pelleted diets were manufactured using the same model pellet mill with a variable frequency drive to control conditioner speed, so the pelleted diet with a 45 s conditioning time was manufactured at 66.2, 84.8, and 80.8% of the production rate of the pelleted diet with a 90 s conditioning time in phase 1, 2, and 3, respectively. The extruded diet was manufactured at a lower production rate, but was more stable throughout the phases and was held at a constant 1,200 kg/hr. The electrical energy consumption of the thermal processing equipment was as predicted, with the pelleted diets having lower energy usage than extruded diets, and 45 s conditioning time have less energy usage than the 90 s conditioning time for pelleted diets. The differences in equipment also influenced pellet durability index. The longer conditioning time in the pelleted diets improved standard and modified PDI, by 1.6 and 5.2%, respectively. Gilpin et al. (2002) found that increased retention time by using the same method of altering the variable frequency drive significantly improved pellet durability. However, the extruded treatment had substantially higher PDI than either pelleted treatment. This is likely due to greater starch gelatinization in the extruded diet due to the higher moisture and heat (Kaliyan and Morey, 2009).

Table 3.3 displays the analyzed diet composition after processing. While many nutrients are consistent with formulated values, differences exist between treatments. Notably, the pelleted diets conditioned for 90 s had the greatest DM. It is likely that the reduction in production rate for the 90 s pellets resulted in longer time spent in the cooler where more water was pulled off the pellets. In addition, mash diets had greater ADF concentrations and much greater NDF concentrations than the thermally processed diets. Potentially, more of the fibrous particles from wheat middlings or distillers dried grains with solubles were part of the fines separated from the complete pelleted diet because they have a low propensity for starch gelatinization and pelleting, and were therefore not utilized in the analysis of the pelleted diets. Adding increasing concentrations of distillers dried grains with solubles to diets have been demonstrated to cause a linear increase in pellet fines production (Min et al., 2008). There are conflicting reports regarding the effect of extrusion on dietary fiber solubility, but it appears that moderate extrusion conditions improve fiber solubility, while extreme temperatures (150 to 200°C) actually increased the percentage of fiber due to an alteration of starch chemistry (Siljeström et al., 1986, Wang & Klopfenstein, 1993). The extruded diet had the lowest CF concentration in phase 1 and 2, but was intermediate in phase 3. Both cellulose and beta-glucan concentrations were greatest in the extruded diet in phase 3, but were intermediate in phase 1 and 2. Future research should include evaluating the nutritional composition of fines compared to pelleted diets, which may explain some of the differences in nutrient concentration between the mash and thermally-processed feeds.

In addition to crude nutrients, we evaluated the role of feed processing on both fatty acid and amino acid composition (Table 3.4). Previous research has suggested that pelleting elicited softer carcass fat, potentially due to greater digestibility of dietary lipids that are more unsaturated in nature (De Jong et al., 2013). Unsurprisingly, the majority of fatty acids in the diet were linoleic, oleic, palmitic, and linolenic acids. Based on our findings, feed processing method did not appear to alter fatty acid concentrations within the diet. Amino acids also did not seem altered by dietary treatment, but lysine availability slightly decreased with increasingly harsh thermal processing conditions compared to mash. Thermal processing is known to alter protein availability, and particularly Lys reactivity. Reactive lysine values were highest in mash diets and lowest in extruded diets in all but the last phase. This is different from research that has previously reported less reactive Lys in pelleted diets than extruded diets (Tran and Hendriks, 2007). However, it is logical that extruded diets would have the least reactive Lys due to the formation of Maillard reactions. Maillard reactions brought on during conditioning or preconditioning irreversibly bind the free ε-NH_2 group of Lys and other amino acids to a reducing sugar (Fastinger and Mahan, 2006; Stein et al., 2006). Only Lys that retains its reactivity and thus has not undergone this binding chemical process is bioavailable to the animal, but is still present in nutrient analyses for total Lys (Finot and Magnenat, 1981). Ohh et al. (2002) measured digestibility of Lys and Thr and found a reduction in digestibility in diets containing whey protein concentrate when extruded at 100°C and at 120°C respectively, as compared to other protein sources. Opposite to this, Peisker (1992) reported no change in the total lysine and reactive lysine when the feed was subjected to 120°C during an expander treatment.

Growth Performance

Feed processing method had a large impact on finishing pig growth performance overall, but particularly during the early stages of growth (Table 3.5). There were no difference between pelleted diets, but diet form affected ADG and G:F from d 0 to 25, 25 to 46, and overall, where thermally processed diets were improved compared to mash diets ($P < 0.05$). Interestingly, ADFI was impaired when pigs were fed extruded diets from d 0 to 25 ($P < 0.05$), but was not affected after the initial phase ($P > 0.10$). As described above, the PDI of the extruded diets was substantially greater than the pelleted diets in all phases. This feed hardness may have contributed to the poor ADFI of pigs during the first phase, but then they became acclimated to the physical characteristics of the diet and intake was no longer affected. Mercier (1980) and Bjorck et al. (1985) found that extruded ground corn had increased starch gelatinization, which improved the palatability and feed intake of corn-based products. Solà-Oriol et al. (2009) studied the effect of extrusion on the texture characteristics of different cereals and found both affected pellet integrity. Extrusion increased the hardness, fragility, and chewing work required in diets manufactured with barley, rice, and wheat compared to corn. Williams (2010) also found that pigs fed extruded diets manufactured with 30% DDGS had poorer ADFI than those fed mash or pelleted diets that was overcome with time.

Overall, thermal processing improved pig ADG by 3.1 to 5.9% and G:F by 5.6 to 8.1% without affecting overall ADFI. Ultimately, these growth performance improvements resulted in a pig that was to 3.1 to 5.2 kg heavier at market compared to those fed mash diets, with the greatest weight increase coming from those fed pelleted diets that had been conditioned for 90 s. While these results in ADG and G:F from thermal processing are similar to those previously reported (Lundblad et al, 2011; De Jong, 2013), there is still disagreement as to the reasoning for this improvement. Pelleting is known to increase hydrogen bonding of starch molecules and starch gelatinization, which then improves starch and subsequent energy digestibility (Fahrenholz, 2012). Hancock (1992) outlined that thermal processing methods provide both nutritional and non-nutritional advantages, including feed sterilization, increased fat stability, decreased activity of antinutritional compounds, decreased feed wastage, and increased bulk density decreasing feed wastage. Amornthewaphat et al. (2008) suggested that greater bulk density of extruded maize had reduced water solubility of the diet and increased viscosity and transit time in the digestive tract. Nevertheless, thermal processing had a substantial impact on pig growth performance, but there was little differentiation among the thermal processing methods themselves.

Nutrient Digestibility and Carcass Quality

While some of the differences in growth performance may be attributed to changing physical diet form, broad differences in nutrient digestibility due to differences in feed manufacturing method suggest the bulk of differences are due to nutrient extraction (Table 3.6). Pigs fed pelleted diets conditioned for 90 s had the greatest ATTD CP, NDF, and ADF concentration ($P < 0.05$) compared to all other treatments. Also extruded diets tested the lowest CP, Ash, and NDF values. Additionally, pigs fed thermally-processed diets had EE and CF digestibility improvements compared to those fed mash diets ($P < 0.05$). Past research suggests that harsh thermal processing of swine diets, such as extrusion, improves ileal DM digestibility (Muley et al., 2007), NFE in nursery pigs (Van der Poel et al., 1989). Alterations in nutrient digestibility led to improved caloric efficiency in pigs fed thermally-processed diets compared to those fed mash diets and, ultimately, greater HCW ($P < 0.05$).

Feed processing method did not affect ($P > 0.10$) carcass yield or backfat depth, but had a tendency ($P = 0.08$) to increase the measurement of loin depth in treatments with thermal processing. In agreement with our results, Johnston et al., (1999) evaluated standard long-term and expander conditioner effects on carcass quality and found no significant difference in backfat thickness.

While the quantity of fat did not change significantly, the composition of fat was altered in a dramatic manner. Jowl iodine value was increased ($P < 0.05$) when pigs were fed diets that were thermally processed. This finding confirms that reported previously by De Jong (2013) and Nemechek (2014), who described a previously unknown interaction between thermal processing and the quality of fat deposition. During finishing pig growth experiments, they observed that pelleting diets resulted in pigs depositing more unsaturated fat. Potentially, thermal processing increases the digestibility of dietary lipids, which are predominantly from grain and therefore relatively unsaturated in nature. We can therefore link the effects of thermal processing on carcass iodine value with dietary fatty acid concentrations stemming from predominantly grain sources. Averette Gatlin et al. (2002) reported that an increase in dietary beef tallow decreased IV and PUFA concentrations in pork fat compared with pigs fed an animal-vegetable fat blend. The iodine value regression equation is built upon the proportion of fatty acids present in a fat sample (Benz et al., 2010). The fatty acids included in the equation include C16:1, C18:1, C18:2, C18:3, C20:1, and C22:1, with C18:3 having the greatest influence on the equation (AOCS, 1998). Since more dietary lipids are available for deposition, pigs potentially have reduced de novo fatty acid synthesis. The fatty acids created during de novo fatty acid synthesis are highly saturated in order to maximize energetic efficiency. Thus, thermally processing diets likely shifts fat deposition from saturated de novo products to more unsaturated dietary lipids. This makes the ingredient inclusion an important factor in carcass fat quality. Whitney et al. (2006) reported that, while feeding 10 to 30% distillers dried grains with solubles does affect carcass lean characteristics, the ingredient addition in a diet results in an increase in unsaturated carcass fat and the likelihood of soft bellies. The tested diets were high fiber diets that were somewhat limited in dietary fat compared to diets with lower by-product inclusion levels. Still, the relationship between thermal processing, fatty acid digestibility, and the degree of unsaturation in carcass fat deposition is important to continue to evaluate.

Economic Analysis

Finally, the ultimate measure of the value of thermal processing is if the potential income it generates by improving growth performance and feed efficiency is greater than the extra feed costs due to processing (Table 3.7). Feed costs per pig versus feed cost per ton of feed must be considered in the economic analysis, since higher quantities of fibrous feed per day is needed to meet nutritional needs (Crenshaw, 2005). Notably, feed costs included the electricity utilized by various thermal processing equipment, but not the cost of steam or changes in production capacity. Thus, the feed cost for pelleted diets with a 90 s conditioning time were greatest, but all four diets were relatively similar in diet price overall. Previously, Stark (2009) reported that an increase in pellet mill throughput led to a linear increase in pellet mill efficiency and linear reduction in pellet durability. While feed costs did not vary greatly on a per pig basis across treatments ($P > 0.10$), we can observe differences when the values are placed on a basis of cost of gain. Pigs fed mash diets had greater cost per kg of gain, as well as reduced gain value and income over feed costs, which was driven by a poorer overall ADG ($P < 0.05$). Ultimately, thermal processing improved income over feed costs by $8.82 to $10.03 compared to feeding pigs mash diets. Fahrenholz (2012) has explained that it is possible to manipulate energy efficiency in such a way as to preserve pellet durability while maintaining the lowest possible energy consumption. Fahrenholz (2012) predicted that lowest overall feed cost had both a mid-range energy consumption (9.1 kWh/tonne) and pelleting cost ($8.21/tonne). As ingredient prices continue to fluctuate, it is important for individual production systems to evaluate their costs of pelleting relative to their value of nutrient extraction.

In summary, thermal processing, regardless of type, improved overall ADG and G:F, but not ADFI in finishing pigs. Pigs fed any thermally-processed treatment had greater HCW and jowl iodine value compared to those fed the negative control mash. This experiment again confirms the benefits of thermally processing feeds to improve ADG and G:F, but neither extended conditioning nor extrusion extracted additional nutrients from low energy feedstuffs compared to traditional pelleting.

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Figures and Tables

Table 3.1 Calculated diet composition (as-fed basis)[1]

Ingredient, %	Phase 1	Phase 2	Phase 3
Corn	37.14	40.35	42.59
Soybean meal, 48%	11.60	8.55	6.05
Corn distillers dried grains with solubles	30.00	30.00	30.00
Wheat middlings	19.00	19.00	19.00
Monocalcium phosphate	0.00	0.00	0.00
Limestone	1.30	1.20	1.20
Salt	0.35	0.35	0.35
L-Lys-HCL	0.29	0.27	0.23
Trace mineral premix[2]	0.15	0.13	0.08
Vitamin premix[3]	0.15	0.13	0.08
Phytase[4]	0.02	0.02	0.02
Titanium Dioxide[5]	0.00	0.00	0.40
Total	100.00	100.00	100.00
Calculated analysis			
Standardized ileal digestible (SID) amino acids, %			
Lysine	0.86	0.77	0.68
Isoleucine:lysine	73	75	78
Leucine:lysine	192	206	224
Methionine:lysine	35	38	41
Methionine & cysteine:lysine	67	71	77
Threonine:lysine	64	66	69
Tryptophan:lysine	18.5	18.5	18.9
Valine:lysine	89	93	99
Total lysine, %	1.05	0.96	0.86
ME, kcal/kg	1,468	1,473	1,466
SID lysine:ME, g/Mcal	2.66	2.37	2.10
CP, %	20.1	18.9	17.8
Ca, %	0.58	0.53	0.52
P, %	0.55	0.53	0.52
Available P, %	0.35	0.34	0.34

[1] A single diet formulation for each of three phases of a 79-d finishing pig experiment was manufactured and then processed according to different parameters to create 4 dietary treatments.

[2] Provided per kg 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}.

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

[4] Provided .181 kg of phytase per ton.

[5] Titaium dioxide was used as in indigestible marker for calculating digestibility of nutrients.

Table 3.2 Physical analysis of diets, (as-fed basis)[1]

Phase:	1				2				3			
Treatment:	Mash	45 s	90 s	Extrude	Mash	45 s	90 s	Extrude	Mash	45 s	90 s	Extrude
Production rate, kg/h	---	1,995	1,336	1,200	---	2,170	1,355	1,200	---	6,466	3,402	1,200
Electrical, kilowatt/h	---	14.13	18.9	26.5	---	9.78	17.3	26.0	---	9.2	16.8	24.5
Pellet durability index[2]												
Standard	---	91.9	93.6	99.8	---	87.7	92.9	99.1	---	91.0	92.6	99.0
Modified	---	84.6	87.3	99.3	---	80.9	85.6	98.0	---	82.2	86.2	97.8

[1] A single diet formulation for each of three phases of a 79-d finishing pig experiment was manufactured and then processed according to different parameters to create 4 dietary treatments.

[2] Determined according to ASAE S269.4, 2003 with a modification to include five hex nuts in the tumbling chamber.

Table 3.3 Analyzed diet composition (as-fed basis)[1]

	Phase 1				Phase 2				Phase 3			
Item;	Mash	45 s	90 s	Extrude	Mash	45 s	90 s	Extrude	Mash	45 s	90 s	Extrude
DM, %	87.5	87.6	89.0	86.5	89.6	89.8	91.5	89.2	88.6	88.4	88.7	90.3
GE, kcal/kg	3,500	3,510	3,530	3,400	3,580	3,600	3,630	3,520	3,480	3,580	3,540	3,650
CP, %	17.62	17.48	18.97	17.48	18.3	18.11	19.3	17.8	17.91	16.88	18.11	17.92
EE, %	3.28	3.44	3.30	2.51	3.42	3.58	3.43	2.83	2.89	4.29	3.64	4.06
CF, %	4.80	3.97	3.97	3.80	5.11	3.99	3.73	3.74	4.09	3.85	3.81	4.01
Ash, %	4.17	4.22	4.65	4.43	4.46	4.31	4.93	4.48	5.13	4.46	4.78	4.34
ADF, %	6.88	6.13	5.62	5.04	7.22	6.02	5.41	5.56	6.58	5.67	6.30	6.21
NDF, %	17.78	13.86	13.91	14.71	19.29	15.2	14.44	14.62	17.5	15.54	15.27	16.23
Cellulose, %	4.49	4.45	2.29	2.40	4.90	4.31	3.74	3.95	3.47	3.86	3.32	4.37
Beta-glucan, %	0.29	0.63	0.56	0.47	1.01	0.95	0.99	1.27	0.70	0.94	0.72	1.42

[1] A single diet formulation for each of three phases of a 79-d finishing pig experiment was manufactured and then processed according to different parameters to create 4 dietary treatments.

Table 3.4 Analyzed fatty acid and amino acid composition of the diet (as-fed basis)[1]

	Phase 1				Phase 2				Phase 3			
Item:	Mash	45 s pellet	90 s pellet	Extrude	Mash	45 s pellet	90 s pellet	Extrude	Mash	45 s pellet	90 s pellet	Extrude
Fatty acid, %												
Myristic (14:0)	0.09	0.12	0.12	0.10	0.12	0.07	0.08	0.09	0.12	0.10	0.12	0.10
Palmitic (16:0)	14.9	15.0	14.9	14.8	14.7	14.8	15.0	14.9	15.1	14.8	14.9	14.6
Palmitoleic (9c-16:1)	0.20	0.24	0.20	0.20	0.21	0.21	0.23	0.22	0.24	0.22	0.22	0.22
Margaric (17:0)	0.14	0.12	0.12	0.18	0.12	0.11	0.11	0.11	0.09	0.10	0.12	0.11
Stearic (18:0)	2.20	2.09	2.14	2.15	2.20	2.13	2.21	2.12	2.17	2.09	2.14	2.04
Oleic (9c-18:1)	22.7	22.7	22.7	23.0	23.4	23.3	23.0	23.9	23.0	22.9	22.6	23.5
Vaccenic (11c-18:1)	0.81	0.79	0.81	0.82	0.80	0.79	0.79	0.80	0.80	0.77	0.80	0.77
Linoleic (18:2n6)	54.9	55.1	55.2	54.9	54.8	55.0	54.8	54.4	54.7	55.3	55.0	55.1
Linolenic (18:3n3)	2.21	2.29	2.35	2.27	2.07	2.10	2.16	2.02	2.21	2.18	2.29	2.03
Gonodic (20:1n9)	0.36	0.36	0.37	0.32	0.31	0.37	0.38	0.37	0.38	0.40	0.38	0.31
Behenoic (22:0)	0.21	0.20	0.17	0.17	0.22	0.19	0.21	0.18	0.18	0.20	0.22	0.21
Lignoceric (24:0)	0.39	0.18	0.17	0.15	0.18	0.18	0.25	0.17	0.17	0.13	0.18	0.15
Amino Acid, %												
Threonine	0.77	0.73	0.80	0.73	0.74	0.72	0.74	0.67	0.69	0.66	0.71	0.70
Valine	0.99	0.94	1.03	0.90	0.94	0.92	1.01	0.91	0.93	0.88	0.94	0.92
Methionine	0.37	0.38	0.40	0.35	0.38	0.36	0.37	0.35	0.37	0.34	0.37	0.37
Isoleucine	0.81	0.78	0.87	0.72	0.77	0.74	0.76	0.72	0.73	0.71	0.76	0.73
Leucine	2.01	1.99	2.18	1.97	1.95	1.97	2.13	1.86	1.99	1.87	1.97	1.97
Phenylalanine	0.99	0.95	1.06	0.92	0.95	0.94	0.98	0.88	0.92	0.87	0.93	0.92
Lysine	1.12	1.05	1.17	1.03	1.08	1.03	1.05	0.99	0.92	0.88	1.00	0.88
Lysine availability[2]	1.10	1.04	1.15	1.01	1.06	1.01	1.03	0.98	0.91	0.86	0.99	0.87
Histidine	0.54	0.52	0.56	0.52	0.51	0.51	0.54	0.49	0.50	0.48	0.51	0.50
Arginine	1.14	1.05	1.16	1.07	1.07	1.04	1.06	0.99	0.99	0.95	1.03	0.99
Tryptophan	0.21	0.20	0.22	0.22	0.19	0.20	0.20	0.19	0.18	0.19	0.20	0.19
Total amino acid	19.88	18.92	20.75	18.70	18.86	18.73	19.53	17.69	18.25	17.39	18.58	18.16

[1] A single diet formulation for each of three phases of a 79-d finishing pig experiment was manufactured and then processed according to different parameters to create 4 dietary treatments.

[2] Indicates the percentage of reactive lysine available in the diet post-processing.

Table 3.5 .Effects of feed processing method on finishing pig growth performance[1]

	Diet form					*P* =			
Item;	Mash control	45 s pellet	90 s pellet	Extrude	SEM	Processing method	Pelleted vs. extruded	Pelleted vs. control	Mash vs. thermally processed
d 0 to 25									
ADG, kg	0.93^{b}	0.99^{a}	1.00^{a}	0.96^{b}	0.008	< 0.001	< 0.001	< 0.001	< 0.001
ADFI, kg	2.57^{ab}	2.54^{b}	2.58^{a}	2.44^{c}	0.035	0.013	0.003	0.841	0.208
G:F	0.40	0.42	0.42	0.42	0.005	0.002	0.575	< 0.001	< 0.001
d 25 to 46									
ADG, kg	0.95^{b}	1.04^{a}	1.02^{a}	1.06^{a}	0.019	< 0.001	0.134	< 0.001	< 0.001
ADFI, kg	2.81	2.76	2.80	2.77	0.041	0.759	0.904	0.570	0.520
G:F	0.34^{b}	0.38^{a}	0.36^{a}	0.38^{a}	0.006	< 0.001	0.104	< 0.001	< 0.001
d 46 to 60									
ADG, kg	0.93	0.93	0.99	0.97	0.029	0.309	0.812	0.399	0.329
ADFI, kg	2.96	2.91	2.94	2.92	0.048	0.885	0.911	0.592	0.544
G:F	0.32	0.32	0.34	0.33	0.008	0.245	0.760	0.213	0.156
d 60 to 79									
ADG, kg	0.99^{b}	0.99^{b}	1.04^{a}	1.02^{a}	0.023	0.325	0.883	0.377	0.324
ADFI, kg	3.20	3.10	3.20	3.12	0.061	0.391	0.583	0.460	0.330
G:F	0.31	0.32	0.33	0.33	0.006	0.089	0.406	0.063	0.026
d 0 to 79									
ADG, kg	0.95^{b}	0.99^{a}	1.01^{a}	0.98^{a}	0.012	< 0.001	0.330	0.001	0.001
ADFI, kg	2.78	2.73	2.78	2.68	0.038	0.140	0.084	0.585	0.233
G:F	0.34^{b}	0.36^{a}	0.36^{a}	0.37^{a}	0.003	< 0.001	0.087	< 0.001	< 0.001
BW, kg									
d 0	52.5	52.6	52.6	52.6	0.415	0.997	0.949	0.871	0.845
d 25	75.6^{b}	77.0^{a}	77.23^{a}	75.2^{b}	0.583	< 0.001	< 0.001	0.001	0.034
d 46	95.3^{b}	98.6^{a}	98.6^{a}	97.4^{a}	0.847	0.001	0.121	<0.001	< 0.001
d 60	108.3^{b}	111.6^{a}	112.5^{a}	111.0^{a}	0.869	< 0.001	0.197	<0.001	< 0.001
d 79	127.1^{c}	130.2^{b}	132.3^{a}	130.3^{b}	1.143	0.008	0.444	0.002	0.002

[1] A total of 270 (PIC 327 × 1050) were used in a 79-d experiment to evaluate the effects of feed processing method on finishing pig performance. A single diet formulation was manufactured into 4 different dietary treatments. There were 7 to 8 pigs per pen with 9 replications per treatment.

$^{.abc}$Means within a row that do not share a common superscript differ $P < 0.05$

Table 3.6 Effects of feed processing method on finishing pig nutrient digestibility, caloric efficiency, and carcass charactersitcs[1]

	Diet form					P =			
Item;	Mash control	45 s pellet	90 s pellet	Extrude	SEM	Processing method	Pelleted vs. extruded	Pelleted vs. control	Mash vs. thermally processed
ATTD, %									
DM	82.7	81.3	84.8	82.6	0.83	0.379	0.820	0.837	0.891
GE	81.2	82.4	82.7	82.1	0.42	0.318	0.449	0.524	0.683
CP	80.1^{b}	79.7^{c}	83.4^{a}	79.3^{c}	0.78	0.003	0.027	0.141	0.442
EE	36.3^{c}	66.7^{a}	65.4^{a}	60.4^{b}	2.36	< 0.001	0.063	< 0.001	< 0.001
Ash	53.7^{a}	41.0^{b}	52.7^{a}	38.9^{c}	1.78	< 0.001	0.0006	0.002	< 0.001
CF	38.8^{c}	70.5^{a}	63.0^{b}	69.5^{a}	3.26	< 0.001	0.484	< 0.001	< 0.001
NDF	40.5^{b}	35.9^{c}	45.1^{a}	34.1^{c}	2.33	0.010	0.031	0.997	0.422
ADF	44.8^{a}	33.4^{b}	46.5^{a}	36.3^{b}	3.26	0.023	0.368	0.232	0.115
Cellulose	30.5	40.0	36.3	39.1	3.12	0.157	0.801	0.056	0.036
Caloric efficiency[2]									
ME, kcal/kg	9,509^{a}	8,940^{b}	8,925^{b}	8,813^{b}	64.3	< 0.001	0.102	< 0.001	< 0.001
NE, kcal/kg	6,947^{a}	6,530^{b}	6,519^{b}	6,439^{b}	47.0	< 0.001	0.105	< 0.001	< 0.001
Carcass characteristics									
HCW, kg	91.5	95.1^{a}	95.5^{a}	94.9^{a}	1.20	1.000	0.772	0.007	0.006
Carcass yield[2], %	72.2	72.6	72.3	72.6	0.12	0.205	0.564	0.222	0.136
Backfat depth[3], mm	20.5	19.7	20.9	20.6	0.56	0.524	0.700	0.730	0.817
Loin depth[3], mm	60.9	62.7	62.5	62.7	0.84	0.353	0.875	0.106	0.077
Jowl iodine value[4]	75.4^{b}	77.1^{a}	77.3^{a}	77.6^{a}	0.37	< 0.001	0.370	< 0.001	< 0.001

[1] A total of 270 (PIC 327 × 1050) were used in a 79-d experiment to evaluate the effects of feed processing method on finishing pig performance. A single diet formulation was manufactured into 4 different dietary treatments. There were 7 to 8 pigs per pen with 9 replications per treatment.

[2] Carcass yield calculated by dividing HCW by live weight obtained at the farm prior to transportation to the packing plant.

[3] Adjusted by using HCW as a covariate

[4] Jowl iodine value (g/100 g) was measured at the packing plant by near-infrared spectroscopy.

[abc] Means within a row that do not share a common superscript differ $P < 0.05$

Table 3.7 Effects of feed processing method on overall (d 0 to 79) pig and carcass value[1,2]

	Diet form				*P* =			
Item;	Mash	45 s pellet	90 s pellet	Extrude	Processing method	Pelleted vs. extruded	Pelleted vs. control	Mash vs. thermally processed
Cost analysis								
Feed cost[2], $/pig	68.56^{a}	68.09^{b}	69.09^{b}	66.86^{b}	0.299	0.104	0.977	0.577
Cost, $/kg of gain[2]	0.92	0.87	0.87	0.86	< 0.001	0.185	< 0.001	< 0.001
Gain value[2], $/kg gain	122.12^{b}	130.47^{a}	132.12^{a}	130.44^{a}	0.003	0.701	< 0.001	< 0.001
Income over feed cost, $	53.56^{b}	62.38^{a}	63.04^{a}	63.59^{a}	< 0.001	0.606	< 0.001	< 0.001

[1] A single diet formulation for each of three phases of a 79-d finishing pig experiment was manufactured and then processed according to different parameters to create 4 dietary treatments.

[2] Used standardized costs for time when pigs were marketed (September 2014): corn $253/tonne, soybean meal $467/tonne, DDGS $227/tonne, wheat midds $218/tonne, electricity $0.12/kilowatt hour, pig live weight $107.97/cwt

^{ab}Means within a row that do not share a common superscript differ $P < 0.05$

Chapter 4 - Evaluating the accuracy of the 3-sieve particle size analysis method compared to the 12-sieve method[1]

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Abstract

The 3-sieve particle size analysis method was developed to estimate the particle size of ground grain within feed mills without the time and expense required for a 12-sieve analysis. The 3-sieve method is more simplistic because it is hand-shaken with fewer sieves, but has drawbacks because it is not as precise as the 12-sieve method. Because shaking is not automated, technician may impact results. Furthermore, the accuracy of the original 3-sieve method has been questioned because the method was developed for corn between 400 to 1,200 µm, and the industry now grinds various grains more finely. Some variations, such as changing the top sieve to a smaller diameter hole or using flow agent may help improve its accuracy. Therefore, 420 samples were used to determine the impact of top sieve size, grain type, technician, and flow agent on the ability of a 3-sieve analytical method to accurately predict the mean particle size determined by a standardized 12-sieve method. The experiment was a 3 × 2 × 2 × 3 factorial with 3 technicians, 2 sieve sizes (U.S. No. 12 vs. 16 sieve as the top sieve), 2 flow agent levels (0 vs. 0.5 g), and 3 grain types (corn, sorghum, or wheat). Prior to the experiment, all samples were analyzed according to the standard ASAE S319.4 method using a 12-sieve stack with a 15-minute tap time and 1 g of flow agent. Linear regression was used to develop individual equations to predict the mean particle size for each of the 3-sieve methods compared to the standard 12-sieve method, and the GLIMMIX procedure of SAS was used to evaluate the impact main effects and interactions on predication accuracy. All interactions were removed from the model due to insignificance ($P > 0.10$). Technician, screen size and flow agent did not affect ($P > 0.10$) the accuracy of the prediction equations. Grain was the only main effect of significance ($P < 0.05$), where the prediction equation overestimated the particle size of wheat by approximately 15 µm and underestimated the particle size of corn by approximately 12 µm. While statistically significant, these variations were deemed to be sufficiently accurate for the 3-sieve method, and that separate equations for each grain type were not warranted to retain the simplicity of the method. In summary, technician, sieve size, grain type, and the use of flow agent did not greatly affect the accuracy of the 3-sieve particle size analytical method, so the original method was concluded to be accurate and the preferred method.

Key words: 3-sieve, analysis, grain, method, particle size

Introduction

Reducing the particle size of cereal grains is understood to improve feed efficiency in swine and poultry (Goodband and Hines, 1988; Giesemann et al., 1990; Wondra et al., 1995).

Therefore, the accurate determination of particle size, or mean diameter, of cereal grains is important to feed manufacturers and producers. A standardized method for determining the geometric mean and standard deviation of particle size has been determined and was first reported in 1968, and was most recently updated in 2012 (ASAE, 1968 and 2012). The standard method uses 12- or 13-sieves, an automated machine to tap and rotate the sieve stack for 10 or 15 minutes, and sometimes uses a flow agent to facilitate particle dispersal during the shaking process. This standard method is expensive to purchase and maintain, and can be time consuming. For that reason, feed manufacturers may use a 3-sieve method to predict approximate mean particle size during each shift in the mill, and validate their findings with the standard method at an outside laboratory weekly or monthly.

The 3-sieve method was originally developed by Baldridge et al. (2001) to quickly predict the particle size of corn between 400 and 1,200 µm. As the industry evolves to further reduce particle size of grain, it is necessary to validate if the existing 3-sieve method remains accurate for particle sizes of various grains ground smaller than 400 µm. Furthermore, it is important to evaluate if different interventions, such as the use of different sieve sizes, flow agent, or a single technician, can further improve the ability of the 3-sieve method to predict the mean particle size according to the standard method. Therefore, the objective of this experiment was to determine the impact of top sieve size, grain type, technician, and agent on the ability of a 3-sieve analytical method originally developed by Baldridge et al. (2001) to accurately predict the mean particle size determined by a standardized 12-sieve method.

Materials and Methods

The original 3-sieve method developed by Baldridge et al. (2001) utilizes a U.S. No. 12, 30, and 50 screen plus a lid and receiving pan with a caruncle brush and rubber ball placed on the

U.S. No. 30 screen and two brushes and one ball placed on the U.S. No. 50 screen to facilitate particle movement through the sieve. The weights of empty sieves and the pan are recorded, the sieves stacked in order by descending screen size and placed on top of the receiving pan. Fifty grams of ground corn is weighed, placed on the top sieve, a lid is placed on top of the sieve stack, and the stack is shaken from side-to-side by hand for 90 s. The weight of each sieve and receiving pan is then recorded, and the percentage of material caught in each sieve is utilized to calculate the predicted particle size using the equation: Particle Size, $\mu m = (18.832 \times A) + (10.870 \times B) + (1.1827 \times C) - 149.978$ with A, B, and C representing the percentage of sample on the #12, 30, and 50 screen, respectively.

Field reports and personal observations noted the potential areas of highest variability affecting the accuracy of the 3-sieve method were person-to-person variability in shaking, grain type, and grinding fineness. In fact, it was noticed that nearly all the material sifted through the U.S. No. 12 screen when grain was ground below 600 µm, which presumably would impact the accuracy of the 3-sieve method for smaller particle sizes. Therefore, we deemed it important to evaluate a 3-sieve stack with a different top sieve to catch a greater proportion of material. Finally, it was challenging for some of the very finely ground material to sift through the smallest sieve when shaking by hand. A flow agent, such as fumed silica, helps prevent this occurrence in the standardized method, and may be applicable to the 3-sieve method. Thus, a 3 × 2 × 2 × 3 factorial arrangement of treatments was designed with 3 technicians, 2 sieve sizes (U.S. No. 12 vs. U.S. No. 16 sieve as the top sieve), 2 flow agent levels (0 vs. 0.5 g), and 3 grain types (corn, sorghum, or wheat).

Technicians were instructed to shake the 3-sieve stack by hand from side-to-side for 90 s according to Baldridge et al. (2001). The U.S. No. 16 (1.19 mm) sieve was chosen as a replacement for the U.S. No. 12 sieve (1.68 mm) by evaluating the screens that caught the greatest proportion of grain on the 12-sieve stack. Finally, 0.5 g of fumed silica was chosen as a flow agent based on the proportion of flow agent used in the standard method, which is 1 g of flow agent per 100 g of ground grain. Prior to the experiment, all samples were analyzed according to the standard ANSI/ASAE S319.4 (ASAE, 2009) method using a 12-sieve stack with a 15-minute tap time (W. S. Tyler RX-30 Ro-Tap Shaker, Mentor, OH) and 1 g of flow agent. A total of 420 samples of ground grain were used in these analyses. This included 140 samples each of ground corn, sorghum and wheat that were ground by either hammermill or roller mill, with 70 samples per mill per grain type.

Statistical analysis

Linear regression by the REG procedure of SAS was used to develop individual equations to predict the mean particle size for each of the 3-sieve methods compared to the standard 12-sieve method, and the GLIMMIX procedure of SAS was used to evaluate the impact main effects and interactions on predication accuracy with mill type serving as a random effect. All interactions were removed from the model due to insignificance (*P* > 0.10).

Results and Discussion

Results are depicted as residuals between the predicted particle size according to the 3-sieve method and the standard 12-sieve method. Technician, top screen size, and flow agent did not impact the accuracy of the 3-sieve method (*P* > 0.10, Table 4.1). The variability within technician was greater than that among technicians, with a maximum mean deviation of 5.1 µm from the 12-sieve method. Thus, there appears to be little technician-to-technician variability when personnel are instructed to shake sieves for 90 s. Baldridge et al. (2001) indicated that a 90 s shake time optimized the relationship between efficiency and accuracy, with 1.0 g less sample passing through the screens when shaken for 60 s and only 0.3 g more material passing through the screens when shaken for 120 s.

Likewise, there was little variability when evaluating the 3-sieve method with either the U.S. No. 12 or U.S. No. 16 sieve as the top screen. Even though it did not catch much material, the U.S. No. 12 sieve was within an average of 0.15 µm of accurately predicting the particle size according to the standard method. Notably, the variability of the 3-sieve method was greater when the U.S. No. 12 sieve was used compared to the U.S. No. 16 sieve, which is particularly true for small particle sizes as depicted in Figure 4.1. Because of the accuracy of the original 3-sieve method, there was no additional improvement observed when 0.5 g of fumed silica was included as a flow agent. The flow agent resulted in the 3-sieve method underpredicting the mean particle size by an average of 2.4 µm compared to overpredicting the particle size by 4.1 µm without the flow agent. This lack of effect is not surprising given that the original 3-sieve method was accurate. However, Stark and Chewning (2012) demonstrated that analyzing samples without a flow agent could overestimate the particle size and underestimate the distribution of the particles of a sample (Stark and Chewning, 2012).

In contrast, the type of grain used in the 3-sieve method impacted its accuracy. The original 3-sieve method routinely underpredicted the particle size of corn by an average of 12.3 µm and overpredicted the particle size of wheat by an average of 14.7 µm, while sorghum was, on average, within 0.1 µm of the 12-sieve standard method ($P < 0.05$). Several studies have shown that grinding different grains under similar conditions may result in varying particle sizes (Douglas et al., 1990; Nir et al., 2001). The hardness of a grain sample is related to the percentage of fine particles obtained after grinding, with a higher percentage of fine particles from lower hardness grains (Carré et al., 2005). A harder endosperm is expected to give larger particles with more irregular shapes, while a soft endosperm was expected to produce smaller size particles (Rose et al., 2001). While the 3-sieve method should be able to accurately predict the mean particle size, it is possible that the change of particle shape alters its flow through the 3-sieve stack during shaking. This effect can be observed in Figure 4.2, where grains are grouped by mean particle size, even though they were ground to the same parameters. We recognize that, due to its significance, it is statistically appropriate to have a separate regression equation for each grain type. However, the true intent of the 3-sieve method is to accurately and easily predict the mean particle size of a ground grain compared to a 12-sieve standardized method. It is our conclusion that the robustness of a single 3-sieve equation to predict the particle size of three types of grains to within 15 µm of a standard 12-sieve stack is a more valuable industry tool than three separate regression equations for each grain. However, we recognize that this conclusion limits the average accuracy of the equation.

Conclusion

In summary, the original 3-sieve particle size analysis method developed by Baldridge et al. (2001) using U.S. No. 12, 30, and 50 sieves accurately predicts the particle size of ground corn, sorghum, and wheat to within 15 µm of the 12-sieve standard method without the use of flow agent and amongst the tested technicians. It remains a recognized, useful, and accurate way to predict the particle size of ground grain in a feed mill without the expense and time required for the standard method, and this experiment proves its robustness for three grain types and from 200 to 900 µm. Still, the 3-sieve method should be validated at least monthly by an equally representative sample analyzed according to the 12-sieve standard to verify procedures and accuracy.

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Figures and Tables

Table 4.1 Residual particle size fixed effects[1]

Item;	Residual between the 3- and 12-sieve standard, µm	SEM	$P =$
Technician			
1	5.08	6.035	0.401
2	-0.97	6.055	0.872
3	-1.62	5.990	0.787
Top sieve hole diameter			
U.S. No. 12 (1.68 mm)	-0.14	7.432	0.978
U.S. No. 16 (1.19 mm)	1.8	4.919	0.716
Flow agent, 0.5 g fumed silica			
Yes	-2.43	4.956	0.625
No	4.08	4.884	0.404
Grain type			
Corn	-12.27	6.011	0.041
Sorghum	0.06	6.032	0.992
Wheat	14.70	6.035	0.015

[1] A total of 420 samples were analyzed in a 3 × 2 × 2 × 3 factorial with 3 technicians, 2 sieve sizes, 2 flow agent levels, and 3 grain types. Prior to the experiment, all samples were analyzed according to the standard ANSI/ASAE S319.4 method using a 12-sieve stack with a 15-minute tap time and 1 g of flow agent. Linear regression was used to develop individual equations to predict the mean particle size for each of the 3-sieve methods compared to the standard 12-sieve method.

Figure 4.1 Residual particle size value for 3-sieve methods

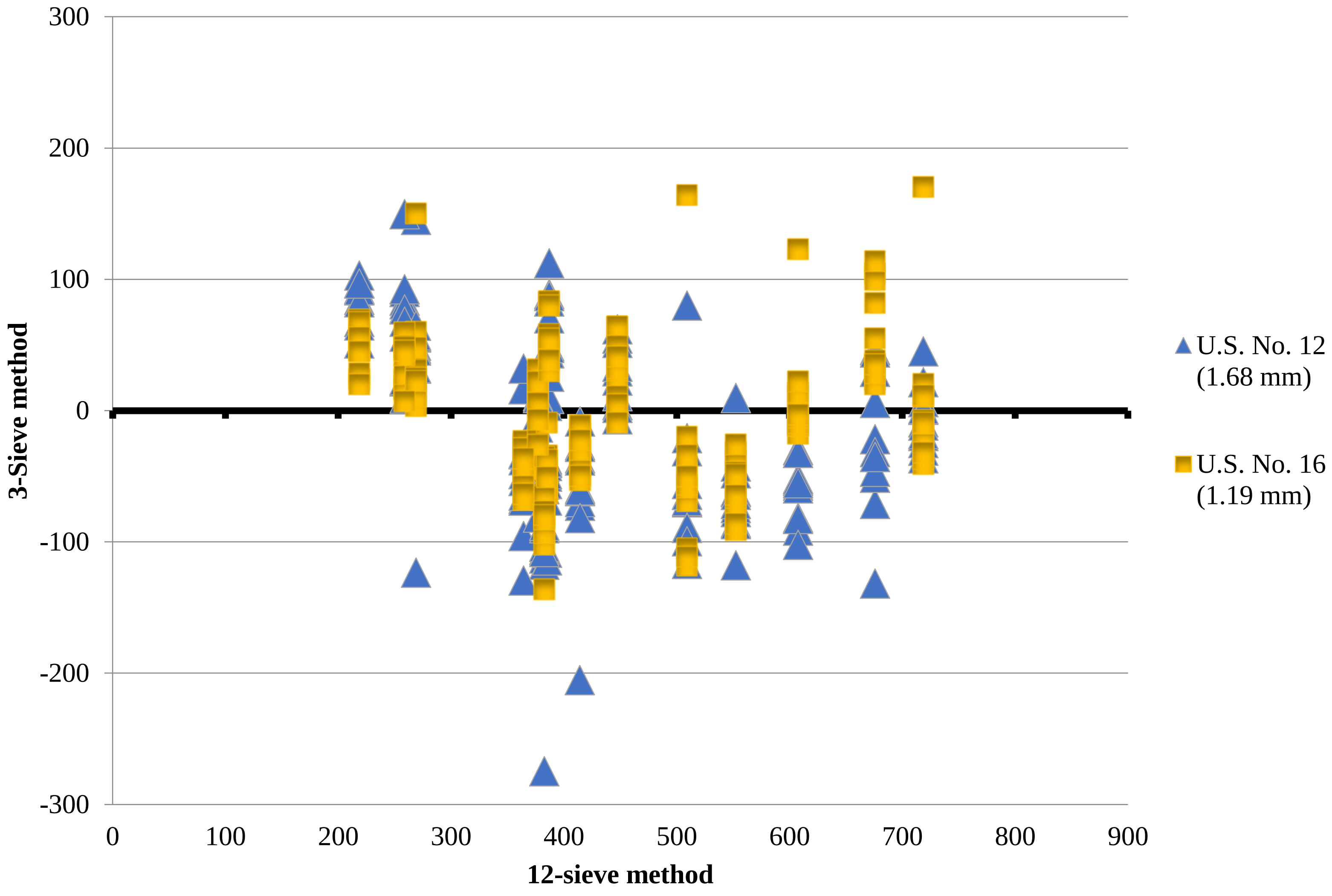

Figure 4.2. Grain sample particle size for 3-sieve method