Evalutation of feed processing techniques on feed quality and monogastric nutrition

by

Caitlin E. Evans

B.S., North Carolina State University, 2011
M.S., North Carolina State University, 2019

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Grain Science and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2023

Abstract

Four experiments were used to determine the effects of 1) pellet binders and conditioning temperature on pellet quality; 2) conditioning temperature and pellet mill die speed on pellet quality and enzyme stabilities; 3) separation of fine corn particles and cold pelleting on nursery pig performance; and 4) pellet quality on finishing pig performance. Exp. 1 evaluated dry or liquid binders conditioned at 73, 79, and 85°C prior to pelleting. Results indicated that cane molasses and commercial molasses-lactose blends were effective pellet binders regardless of conditioning temperature when included in a high-fiber ration. Exp. 2 investigated the impact of conditioning feed at 74 and 85°C prior to pelleting with 127, 190, and 254 rpm die speed. Decreasing die speed in combination with low conditioning temperature was shown to improve pellet durability index with no impact on enzyme stability. Increasing die speed in combination with high conditioning temperature resulted in reduced phytase stability, but not xylanase stability. Increased conditioning temperature improved pellet durability. In Exp. 3, nursery pigs fed steam or cold pelleted diets had decreased gain and feed intake, resulting in a reduced income over feed cost compared to those fed mash. Pigs fed steam pelleted diets had decreased gain and income over feed cost compared to those fed cold pelleted diets. Cold pelleting was a viable option to steam pelleting in the current experiment. Additionally, removing particles less than 150 μm from ground corn improved the flowability of a mash diet without sacrificing growth performance. Exp. 4 evaluated the impact of increasing pellet fine inclusion in finishing pig diets. The results of this study indicated pelleting feed for finishing pigs does not improve animal performance compared to mash diets. Furthermore, diets containing more than 40% pellet fines were shown to depress G:F compared to mash. Thus, pellet quality should remain an important consideration when pelleting diets for swine.

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Major Professor
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Four experiments were used to determine the effects of 1) pellet binders and conditioning temperature on pellet quality; 2) conditioning temperature and pellet mill die speed on pellet quality and enzyme stabilities; 3) separation of fine corn particles and cold pelleting on nursery pig performance; and 4) pellet quality on finishing pig performance. Exp. 1 evaluated dry or liquid binders conditioned at 73, 79, and 85°C prior to pelleting. Results indicated that cane molasses and commercial molasses-lactose blends were effective pellet binders regardless of conditioning temperature when included in a high-fiber ration. Exp. 2 investigated the impact of conditioning feed at 74 and 85°C prior to pelleting with 127, 190, and 254 rpm die speed. Decreasing die speed in combination with low conditioning temperature was shown to improve pellet durability index with no impact on enzyme stability. Increasing die speed in combination with high conditioning temperature resulted in reduced phytase stability, but not xylanase stability. Increased conditioning temperature improved pellet durability. In Exp. 3, nursery pigs fed steam or cold pelleted diets had decreased gain and feed intake, resulting in a reduced income over feed cost compared to those fed mash. Pigs fed steam pelleted diets had decreased gain and income over feed cost compared to those fed cold pelleted diets. Cold pelleting was a viable option to steam pelleting in the current experiment. Additionally, removing particles less than 150 μm from ground corn improved the flowability of a mash diet without sacrificing growth performance. Exp. 4 evaluated the impact of increasing pellet fine inclusion in finishing pig diets. The results of this study indicated pelleting feed for finishing pigs does not improve animal performance compared to mash diets. Furthermore, diets containing more than 40% pellet fines were shown to depress G:F compared to mash. Thus, pellet quality should remain an important consideration when pelleting diets for swine.

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Chapter 1 – Effects of dry and liquid pellet binder inclusion and conditioning temperature on pellet mill efficiency and pellet quality of a high fiber ration

1.1 ABSTRACT

The objectives of this experiment were: 1) to determine the effects of sucrose and lactose-based liquid ingredient inclusion on the pelleting efficiency and quality of a high-fiber diet; and 2) to evaluate the role of mash conditioning temperature on the binding effectiveness of the tested liquid ingredients. Pellet binders included dry calcium lignosulfonate (DLS), liquid cane molasses (LCM), commercial liquid molasses blend (LMB), and commercial liquid lactose blend (LLB). Treatments were arranged in a 5 × 3 factorial of pellet binder (Control, DLS, LCM, LMB, and LLB) and conditioning temperature (73, 79, and 85°C). Data were analyzed using the GLIMMIX procedure of SAS with linear and quadratic contrasts for increasing conditioning temperature. Treatments were arranged in a completely randomized design and replicated 3 times. Diets were conditioned for approximately 40 sec and pelleted with a 4.8 × 44.0 mm die at a rate of 2.7 MT/hr. There was no evidence of an interaction ($P > 0.209$) between binder type and conditioning temperature when determining PDI according to either the standard or modified tumble box methods. Conditioning temperature alone did not affect PDI ($P > 0.209$); however, differences were observed based on binder inclusion according to either method ($P < 0.046$). Using the standard method of analysis, PDI was improved ($P < 0.046$) by LCM and DLS addition compared to both the control and LMB diets, while LLB was intermediate. According to the modified method with greater agitative stress, PDI was improved ($P < 0.005$) when using LCM and LLB compared to the control diet, with DLS and LCM intermediate. Additionally, LCM inclusion reduced ($P < 0.001$) pellet mill throughput and increased ($P < 0.001$) energy consumption of the pellet mill motor compared to the control and other binders, with no observed differences ($P < 0.268$) resulting from increased conditioning temperature. Under the constraints of this trial, cane molasses and commercial molasses and lactose blends were shown to be effective pellet binders regardless of conditioning temperature when included in a high-fiber ration.

Keywords: pellet binder, conditioning temperature, lignosulfonate, molasses, lactose

1.2 INTRODUCTION

The advantages of pelleted feed compared to mash have long been recognized. Not only is pelleted feed associated with improved handling characteristics, it has also been shown to improve animal performance through various avenues including increased palatability, prevention of selective feeding, enhanced hygienic quality, and greater nutrient availability (Skoch et al., 1983; Thomas and van der Poel, 1996; Behnke, 2001). The multitude of benefits associated with feeding pellets, however, may not be truly realized or the cost of production justified when pellets are of poor quality. Thus, it is important to ensure that pellets maintain a certain level of physical quality to withstand the rigors of handling prior to reaching the animal.

Controlling pellet quality remains no simple task, as numerous contributing factors have been identified including: ingredient characteristics and composition, conditioning parameters, and equipment specifications (Benhke, 2001). While there may be some adjustable margin for improvement of pellet quality, facility or production constraints may limit the magnitude of possibilities, resulting in sub-optimal pelleting conditions. One solution for maintaining quality in marginal conditions is the inclusion of a liquid or granular pellet binder, which can help to enhance inter-particle bridges or bonds (Kaliyan and Morey, 2009).

The selection of pellet binder largely depends on cost and effective inclusion level. Lignosulfonate, a co-product of the pulpwood industry, remains a popular binder option in animal feed due to its effectiveness at relatively low inclusion levels (0.5%). It has been shown to improve surface hydrogen bonding with starch and protein components, leading to increased surface hardness of the pellet, increasing durability (Ouyang et al., 2006 and Wamsley and Moritz, 2013). Still there remains industry reluctance to utilize binders that do not add to the nutritional value of the ration (Leaver, 1988). Molasses and other sugar-based liquids provide an alternative that has been shown not only to improve the physical characteristics of the feed (Thomas et al., 1998), but also to have nutritive benefits (Mukodiningsih et al., 2010; Dunmire et al. 2020). Application of sugar-based liquid ingredients, however, can be cumbersome due to high viscosity and tacky nature (Misljenovic et al., 2016). When applied in the mixer, material build up may occur, which can increase equipment wear, requiring more frequent cleaning and inspection (McCoy, 1992). Commercial liquid blends, however, can ameliorate some of the negative attributes, while maintaining the desirable traits of the original product. This can lead to more favorable handling characteristics, reduced product variability, and enhanced benefits such as increased protein or other desired element (Leaver, 1988).

The use of a binders may be of particular interest when pelleting ruminant rations. These formulations traditionally contain increased levels of fiber, which can be problematic during the conditioning process and detrimental to pellet quality (Thomas and van der Poel, 2020). Thus, a pellet binder may be necessary to ensure pellet durability. Sugar-based liquid binders are an attractive option as they also provide a readily fermentable source of carbohydrates for energy with improved palatability. The established benefits of pelleted feed for ruminants are perhaps less recognized compared to monogastric species. In the modern dairy industry, for instance, the use of robotic feeders has necessitated the need for high quality pellets, which provide a palatable incentive to parlor entry as well as optimized feed intake for increased milk production (Kertz, 1981; Rodenberg et al., 2004). Additionally, it has been reported that pelleting grain and roughage-based starter rations for calves can be advantageous in reducing palatability sensitivity often associated with variable ingredient characteristics or quality (Mukodiningsih et al., 2012).

While the inclusion of sugar-based liquid ingredients such as molasses in animal feed is a known strategy for improving palatability and consequently feed consumption, a detailed study investigating the benefits of inclusion on pellet quality of high fiber rations is lacking. Thus, the present study has 2 objectives: 1) to investigate the effects of sucrose and lactose-based liquid ingredients on the pelleting efficiency and quality of a high-fiber diet; and 2) to evaluate the role of mash conditioning temperature on the binding effectiveness of the tested liquid ingredients.

1.3 MATERIALS AND METHODS

1.3.1 Feed Manufacturing

A starter beef diet (Table 1.1) provided the basis for all 5 experimental treatments. The control diet contained no added pellet binder, while the remaining 4 treatments contained dry granulated or liquid pellet binders at the manufacturer’s recommended inclusion levels. Corn level was adjusted to compensate for differing inclusion levels of the pellet binders when necessary. There were 3 liquid binders each with a 5.0% dietary inclusion: cane molasses (**LCM**), a commercial molasses blend (**LMB**; Westway Products, Tomball, TX), and a commercial lactose blend (**LLB**; SweetLac63, Westway Products, Tomball, TX). Calcium lignosulfonate (**DLS**; Ameribond $_2$X, LignoTech USA Inc., Rothschild, WI) was included in the diet as a dry granule at 0.5% of the formulation. In an effort to evaluate whether or not conditioning temperature affects binder effectiveness, mash feed was conditioned at 73, 79, and 85°C prior to pelleting.

Feed was mixed in 909-kg batches in a 1.63 m^3 twin shaft counterpoise mixer (Hayes and Stolz, model TRDB63-0152, Fort Worth, TX). Dry ingredients were mixed for 180 sec. Liquid binders were added directly into the pellet mill conditioner via a spray pump which was calibrated for each binder to achieve the desired inclusion rate. During testing, viscosity issues with the LCM prevented its uniform application in the pellet mill conditioner. Thus, the addition location was changed to the mixer, where dry ingredients were mixed for 60 sec prior to the inclusion of LCM and followed by 120 sec of additional mix time. There were three 909-kg batches of feed per binder treatment replicate, yielding 2.7 MT of feed per pelleting run.

Experimental mash feed was conditioned for approximately 40 sec at 73, 79, and 85°C in a single pass conditioner with a steam pressure of 2.07 bar. Diets were pelleted on a 100 HP pellet mill (CPM, model 3016-4 Master, Crawfordsville, IN) equipped with a 4.8 × 44.0 mm die with a target production rate of 2.7 MT/hr. The pellet mill was warmed with 909-kg of feed prior to proceeding with experimental batches, which were pelleted in a randomized order within each replication. Upon completion of sample collection at each designated conditioning temperature, the steam was increased until the next greatest conditioner temperature was achieved. Conditioning temperature and production rate were stabilized prior to any sample collection.

1.3.2 Data Collection

1.3.2.1 Pelleting Parameters

Once the conditioning temperature and production rate were stabilized, conditioned mash temperature and pellet die exit temperature (hot pellet) were measured twice during each replicate pellet run. The samples were placed into a pre-warmed double-wall thermos fitted with a digital thermometer. Pellet mill throughput was also measured twice by collecting and weighing the total produced pellets within a 60 sec time period.

1.3.2.2 Energy Consumption

Pellet mill voltage and amperage were recorded every 5 sec during each pelleting run with a data logger (Supco model DVCV, Allenwood, NJ). Motor amperage was averaged across each treatment replicate once conditioning temperature and production rate stabilized. Specific energy consumption (**SEC**) was calculated (Eq. 1) according to Stark (1994):

$$\text{SEC (kWh / MT)} = \frac{\text{I} \times \text{E} \times \text{PF} \times 1.73}{\text{PR} \times 1000}$$

where I is average motor amperage,

E is voltage,

PF is power factor set to 0.85,

PR is production rate expressed in MT/hr.

1.3.2.3 Moisture Content

Both mash and pellet samples were collected and analyzed to determine any changes in moisture. Mash samples were taken from a posterior port in the conditioner directly after the liquid spray nozzle (mash) and as mash feed exited the conditioner (conditioned mash). Pellet samples were taken as feed exited the die (hot pellet) and post cooler (cool pellet). Upon collection, sample bags were immediately sealed and placed in a freezer set at -18°C to prevent any potential moisture loss. Samples were analyzed in triplicate according to AOAC 930.15. Briefly, a 100-g sample of mash or pellets was ground to pass through a 1-mm screen. A 2-g subsample of the ground material was then weighed to the nearest 0.1-mg and dried in an air oven at 135°C for 2 hr. Once removed, the sample was placed into a desiccator to cool. The sample was re-weighed and the moisture content calculated based on loss in weight.

1.3.2.4 Pellet Quality

To assess fines level, two samples (approximately 5 kg each) from each treatment replicate were collected at regular intervals at the pellet die and allowed to cool on commercial tri-layer paper feed sacks. The entire sample was weighed and then sifted with a U.S. No. 5 (3.9 mm) sieve to separate fines from pellets. The percentage of pellet fines (**PF)** was then calculated according to Eq. 2:

$$\text{Fines (\%)} = \frac{\text{Sifted Fines Weight}}{\text{Initial Sample Weight}} \times 100 \qquad \text{Eq. 2}$$

The pellet durability index (**PDI**) was assessed using the tumble box and Holmen forced-air methods. Pellet samples were collected directly at the pellet die and placed in a counter-flow laboratory cooler for 10 minutes. Pellets were packaged and stored in commercial tri-layer paper feed sacks and rested for 24 hr prior to analysis. All samples were analyzed in duplicate and results averaged for each method.

In the tumble box method, pellets were initially sifted with a U.S. No. 5 (3.9 mm) sieve for fines removal. A 500-g sample of sifted pellets was then placed in the tumble box and rotated at 50 rpm for 10 min. After tumbling, the sample was collected and sifted again to remove fines. PDI was calculated according to S269.5 (ASAE, 2012):

$$\text{PDI (\%)} = \frac{\text{Recovered Pellet Weight}}{\text{Initial Pellet Weight}} \times 100 \qquad \text{Eq. 3}$$

This standard tumble box PDI procedure was then modified by adding three 19 mm hex-nuts to the tumbling chamber to increase the agitation stress.

For the Holmen methods, samples were analyzed using the NHP 100 (TekPro Ltd, Norfolk, UK) portable forced-air pellet tester and the NHP 200 (TekPro Ltd, Norfolk, UK) automated forced-air pellet tester. For the NHP 100 method, pellets were sifted prior to analysis as outlined above. A 100-g sample of sifted pellets was then placed in the perforated chamber of the Holmen NHP 100. The machine was set to 70 mbar air pressure and outfitted with a tissue filter. Pellets were agitated with forced air for 60, 90, or 120 sec. During agitation fines smaller than the 2.5 mm chamber perforations were constantly removed, eliminating the need for sifting post analysis. Once the recovered pellets were weighed, PDI was calculated in the same manner as the tumble method, according to Eq. 3. For the NHP 200 method, a sample of un-sifted pellets was placed into the machine where it was automatically sieved for removal of fines, pellets weighed, and sample agitated with forced-air in a 2.5 mm perforated chamber. The unit's agitation times were pre-determined based on the selected pellet diameter, which resulted in a 25 sec pre-test at 30 mbar for removal of fines followed by a 100 sec analysis time at 70 mbar. Post-analysis time, the sample was automatically re-weighed and PDI reported.

1.3.3 Statistical Analysis

Data were analyzed using the GLIMMIX procedure of SAS (Cary, NC) with means separated by least squares means procedure. Treatments were arranged in a 5 × 3 factorial of pellet binder (Control, DLS, LCM, LMB, and LLB) and conditioning temperature (73, 79, and 85°C). Linear and quadratic contrasts were used to test the effect of increasing conditioning temperature. Date of manufacture served as a random effect to account for possible environmental differences that may influence the pelleting process. Treatments were replicated 3 times each. Results were considered significant at $P \leq 0.05$.

1.4 RESULTS

1.4.4 Feed Processing

Results of data collected throughout the manufacturing process are reported in Table 1.2. There was no interaction ($P > 0.519$) between binder and conditioning temperature on any of the hot pellet temperature, pellet mill throughput, and pellet mill SEC. Hot pellet temperature at the die was increased by LCM inclusion ($P < 0.001$) compared to the control and other binder treatments and by increasing conditioning temperature (linear, $P < 0.001$). Additionally, LCM inclusion reduced ($P < 0.001$) pellet mill throughput and increased ($P < 0.001$) SEC of the pellet mill motor compared to the control and other binders, with no observed differences ($P < 0.268$) resulting from increased conditioning temperature.

1.4.5 Moisture Content

There was no evidence of an interaction ($P > 0.120$) between binder and conditioning temperature on the moisture content of mash, conditioned mash, hot pellet, or cool pellet samples (Table 1.3). There were main effects of binder ($P < 0.006$) observed for each sample collected, but no main effect of conditioning temperature ($P > 0.187$). Inclusion of LCM, LMB, and LLB liquid binders increased mash ($P < 0.001$) and conditioned mash ($P < 0.001$) moisture compared to the control and DLS binder. Upon exiting the pellet die (hot pellet), moisture was greater ($P < 0.001$) in LMC, LMB, and LLB diets compared to DLS, with the control intermediate to LCM and DLS. Once cooled, pellet moisture was greater ($P < 0.001$) in LLB compared to DLS, with control, LCM, and LMB intermediate.

1.4.6 Pellet Quality

Results on the effect of binder and conditioning temperature on pellet quality are reported in Table 1.4 and include analysis of PF generation and PDI according to multiple methods: tumble box (standard and modified), Holmen NHP 100 (60, 90, and 120 sec analysis times), and Holmen NHP 200.

1.4.6.1 Pellet Fines (PF)

There was evidence of an interaction ($P < 0.001$) between binder and conditioning temperature on the percentage of PF generated at the pellet die. Fines generation in the control diet was decreased when conditioning at 79 and 85°C compared to 73°C. PF level was similar for all tested binders (DLS, LCM, LMB, or LLB) with increasing conditioning temperature. When conditioning diets at 85°C, the control and DLS diets had decreased PF compared to diets containing LMB, with diets containing LCM and LLB being intermediate. Main effects of binder and conditioning temperature were also observed on PF generation. The control diet had increased ($P < 0.001$) PF, with the greatest reduction observed with the addition of DLS and LCM binders, followed by LMB and LLB binders. PF were reduced (quadratic, $P < 0.032$) with increasing conditioning temperature.

1.4.6.2 Tumble Box Methods

There was no evidence of an interaction ($P > 0.209$) between binder type and conditioning temperature when determining PDI according to either the standard or modified tumble box methods. Conditioning temperature alone did not affect PDI ($P > 0.209$); however, differences were observed based on binder inclusion according to either method ($P < 0.046$). Using the standard method of analysis, PDI was improved ($P < 0.046$) by LCM and DLS addition compared to both the control and LMB diets, while LLB was intermediate. According to the modified method with greater agitative stress, PDI was improved ($P < 0.005$) when using LCM and LLB compared to the control diet, with DLS and LMB intermediate.

1.4.6.3 NHP 100 Methods

In the NHP 100 method variation with 60 sec agitation time, analyzed PDI of the control diet was improved (interaction, $P < 0.048$) when conditioning at 85°C compared to 73°C, with 79°C intermediate. PDI remained unaffected by increasing conditioning temperature for all tested binders (DLS, LCM, LMB, or LLB).); though, as with the 90 and 120 sec NHP 100 methods, differences in PDI were observed among binders based on conditioning temperature. PDI was greater for diets containing the LCM binder compared to the control or LMB and LLB diets when conditioning at 73°C. Binder did not affect PDI when conditioning at 79°C; however, LCM had increased PDI compared to LMB when conditioning at 85°C. For main effects, PDI was greatest ($P < 0.001$) for LCM and DLS binders, with DLS intermediate to the control and LLB binder, followed by the LMB binder. Increasing conditioning temperature yielded greater PDI (quadratic, $P < 0.046$).

In the NHP 100 method variation with 90 sec agitation time, greater PDI ($P < 0.028$) was observed in the control and LLB diets when conditioning at 85°C compared to 73°C, with 79°C intermediate. PDI remained unaffected by increasing conditioning temperature for DLS, LCM, and LMB binders; though, as with the 60 and 120 sec NHP 100 methods, differences in PDI were observed among binders based on conditioning temperature. PDI was greatest when using LCM compared to the control, LMB, and LLB binders when conditioning at 73°C; while PDI was unaffected by binder when conditioning at 79 and 85°C. For main effects, PDI was increased ($P < 0.001$) by the addition of LCM and DLS binders, while LMB and LLB binders remained similar to the control diet. Increasing conditioning temperature resulted in increased PDI (linear, $P < 0.001$).

PDI analysis according to the NHP 100 method with a 120 sec agitation time showed evidence of an interaction ($P < 0.001$) between binder and conditioning temperature. Greater PDI was observed in the control diet when conditioning at 79 or 85°C compared to 73°C. PDI was also increased with LLLB binder when conditioning at 85°C compared to 73°C, though 79°C was intermediate. PDI remained unaffected by increasing conditioning temperature for DLS, LCM, and LMB binders; though, as with the 60 and 90 sec NHP 100 methods, differences in PDI were observed among binders based on conditioning temperature. When conditioning at 73°C, LCM and DLS addition improved PDI compared to the control; with LCM also increasing PDI compared to LMB and LLB binders. At 79°C, LCM increased PDI compared to LMB, however, the control, DLS and LLB binders were intermediate to both. This response was echoed when conditioning at 85°C with LCM yielding greater PDI than LMB with remaining treatments intermediate. For main effects, the greatest PDI ($P < 0.001$) was observed with the addition of LCM, followed by the DLS binder, while LMB and LLB binders showed no improve in PDI compared to the control. Increasing conditioning temperature resulted in increased PDI (linear, $P < 0.001$).

1.4.6.4 NHP 200 Method

There was no evidence of an interaction ($P > 0.205$) between binder type and conditioning temperature when determining PDI according to the NHP 200 method. There were main effects observed for both binder inclusion and conditioning temperature. The addition of LMC or DLS was shown to increase ($P < 0.001$) PDI compared to the control and LLB diet. LCM addition also demonstrated improvement in PDI compared to LMB, though DLS remained comparable. Additionally, PDI was improved with increasing conditioning temperature (linear, $P < 0.004$).

1.5 DISCUSSION

1.5.7 Feed Processing

Conditioning temperatures remained comparable to their respective targets of 73, 79, and 85°C as confirmed by measured conditioned mash temperatures (Table 1.3). In general, feed manufacturing was similar for diets containing the DLS, LMB, and LLB binders compared to the control. When including LCM, however, difficulties with uniform application via spray nozzle arose and it became necessary to alter the application site to the mixer. The LCM diet continued to cause issues during the pelleting process where multiple instances of die choking and eventual plugging were observed, with no noticeable changes in frequency due to conditioning temperature. The noted difficulties while pelleting LCM are likely a result of increased resistance at the feed-die interface caused by high sugar content (Thomas et al., 1998). The increased hot pellet temperature and reduced throughput with LCM inclusion provide further indication of increased die friction. The struggle of the pellet mill to overcome these issues and stabilize is further evidenced by the increased electrical demand (SEC) when pelleting LCM. The difficulties of manufacturing with LCM inclusion in this trial are a clear testament to the industry preference for blended molasses products.

1.5.8 Pellet Quality Methods

Evaluating the durability of pellets is the predominant form of measurement and expression of pellet quality in feed manufacturing (Kaliyan and Morey, 2009). Measured at the processing facility, analysis of pellet durability offers an indication of the resistance of pellets to degradation through abrasive or fragmented forces that may occur during handling, transportation, and distribution to the animal (Pfost, 1963; Thomas and Van der Poel, 1996). Durability is often reported as the percentage of recovered pellets post attrition (PDI). Therefore, a high pellet durability, or resistance to fines generation and pellet breakage, is considered to be synonymous with high quality pellets.

Among the most common instruments for durability determination are the tumble box (Pfost, 1963) and the Holmen line of forced-air durability testers (models NHP 100 and NHP 200, TekPro Ltd, Norfolk, UK). The tumble box and NHP 100 empirical methods afford the user the capability of modification to increase attrition stress either through the addition of physical components (ball bearings, hex-nuts, etc.) or increased exposure time to forced air, respectively. The selected durability method and modifications should be chosen to reflect the observed field ratio of pellets to fines presented to the animal at the feeder. Thus, industry practices for determining pellet durability may be variable as a result of system differences and justify the authors' reporting of multiple methods within the present study (Table 1.4).

As expected, there were differences in the reported measurements of PDI based on analytical method. When modifying either the tumble box or NHP 100 methods to increase agitative stress, the resulting PDIs were reduced. Fahrenholz (2012) noted a similar response of decreasing PDI with modifications of the tumble box and NHP 100 methods. This clearly aligns with the intended purpose behind method modifications to allow customization to more accurately reflect specific production systems. There was a lack of similarity between the PDI responses observed using the NHP 100 compared to the tumble box (standard and modified) and NHP 200 methods. This is in opposition to previous work (Yoder et al., 2019; Dunmire et al.,2020; Evans et al., 2021) which demonstrated similar treatment responses when analyzing PDI according to the tumble box and NHP 100 methods. It is hypothesized that instrument-specific factors may have unintentionally biased analysis in the current trial when using the NHP 100 and contributed to the changes in response observed between analytical methods.

Previous research has demonstrated the importance of establishing standard operating procedures when using the NHP 100. Fahrenholz (2012) noted changes in PDI results with repeated NHP 100 analysis and attributed the issue to changing operational pressure and temperature with continual use. Wolska et al. (2016) also observed that PDI analyzed using the NHP 100 could be influenced by temperature and pressure changes, with chamber clean-out also affecting variation. Research by Evans et al. (2019) further demonstrated the importance of standardized procedures like instrument warm up times and filter use when operating the NHP 100. While a filter and standard operating pressure were established when analyzing samples in this trial, there was no consistent procedure for instrument clean-out or establishment of a consistent machine temperature prior to sample analysis, which may have influenced results. Additionally, the determination of PDI relies on the separation of pellets from fines. In the tumble box method, fines are defined by the ability to pass through a sieve measuring 80% of the pellet diameter, while fines in the Holmen method are defined by the ability to pass through the test chamber perforations. This can lead to an underestimation of fines generation and an inflated PDI when using the Holmen methods compared to the tumble box. Failure to sift pellet samples post Holmen analysis in this trial also likely contributed to the interpretive changes observed with the tumble box methods. Additional sample biasing may have occurred with NHP 200 method during the pneumatic removal of fines pre-analysis, which pre-exposed pellets to stress. Based on these factors, the authors find the Holmen methods to be more variable without sifting pellets after testing for PDI in the current trial, though results have been included as a discussion point. This study emphasized the need for further work on Holmen method standardization, especially as its popularity within the commercial and scientific community increases.

In comparison to the Holmen methods, the tumble box has no known instrument-specific concerns, making it ideal for use in research. When multiple samples are run consecutively, Temmerman et al. (2006) reported that the tumble box produced more repeatable durability results compared to the Holmen. Thus, the authors believe that the standard and modified tumble box methods may provide the most unbiased and accurate evaluation of binder inclusion and conditioning temperature on PDI for this trial.

1.5.9 Treatment Effects on Pellet Quality

Tumble box PDI results demonstrated that molasses and commercial blends can be an effective binding agent in a high fiber diet. The viscous liquid binders strengthen pellets by adhering to the mash feed particles and facilitating strong surface bonds as sugars solubilize during conditioning and then recrystallize upon cooling (Thomas et al. 1993). Dunmire and others (2020) noted a similar response of increasing PDI when 10% molasses or a commercial liquid lactose blend was added to a corn-soy diet prior to pelleting. Surprisingly conditioning temperature had no effect on pellet durability when analyzed using the tumble box. This contradicts a well-established principle of increased pellet durability with greater conditioning temperatures (Skock et al., 1983; Thomas et al., 1997; Behnke, 2001). The authors can only hypothesize that diet composition may have played a role as fibrous materials are less susceptible to conditioning and thus moisture uptake (Thomas and van der Poel, 2020). This is supported by a lack of observed difference in moisture content in the conditioned mash samples.

1.6 CONCLUSIONS

Under the constraints of this trial, cane molasses and commercial molasses and lactose blends were shown to be effective pellet binders regardless of conditioning temperature when included in a high-fiber ration. Challenges, however, with molasses handling characteristics and increased friction at the die interface may limit its application and encourage instead the utilization of the more manageable blends.

Additionally, reliable methods for measuring pellet durability are important in both commercial production and research, where the accuracy of conclusions provides the foundation for decision making. The results of this study have clearly shown that analytical method can alter the interpretation of results. Additional research is warranted in evaluating factors that may contribute to differences between pellet durability instruments. Once identified, standardized methods can be enacted to reduce variability and improve analytical procedures, which may be especially beneficial in feed processing research.

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Table 1.1. Basal calf starter diet composition

	Inclusion, %
Ingredient,%	
Corn[1]	40.0
Soybean meal	20.0
Alfalfa meal	15.0
Wheat middlings	15.0
DDGS	10.0
Total	100.00
Calculated Analysis	
Crude protein, %	22.2

[1] Experimental pellet binders were included in the diet at the expense of ground corn. Dry calcium lignosulfonate (DLS) was included at 0.5%, while liquid cane molasses (LCM), commercial liquid molasses blend (LMB), and commercial liquid lactose blend (LLB) were included at 5% of the formulation. The control diet remained the same as the basal formulation with no binder addition.

Table 1.2. Effects of pellet binder and conditioning temperature on pellet mill parameters and efficiency[1]

Binder[2]	Cond Temp, °C	Temperature, °C		Throughput, MT/h	SEC,[4] kWh/MT
		Cond Mash[3]	Hot Pellet		
Interaction					
Control	73	74.6	78.1	2.68	13.35
	79	79.4	81.0	2.66	12.79
	85	85.4	86.8	2.67	12.40
DLS	73	74.7	77.7	2.59	13.23
	79	80.1	81.5	2.61	12.67
	85	85.6	85.9	2.61	13.31
LCM	73	75.1	79.3	2.02	17.34
	79	80.1	84.5	2.22	14.84
	85	85.1	88.5	1.76	22.15
LMB	73	75.0	77.8	2.65	12.08
	79	80.7	81.9	2.81	11.65
	85	84.9	86.3	2.71	12.26
LLB	73	73.9	75.2	2.73	11.53
	79	79.7	81.4	2.72	11.74
	85	85.3	83.9	2.76	11.81
SEM		0.54	0.84	0.161	1.803
Main Effects					
Control		79.7	82.0^{B}	2.67^{A}	12.85^{B}
DLS		80.1	81.7^{A}	2.60^{A}	12.73^{B}
LCM		80.1	84.1^{A}	2.00^{B}	18.11^{A}
LMB		80.2	82.0^{B}	2.73^{A}	12.00^{B}
LLB		79.6	80.2^{B}	2.74^{A}	11.69^{B}
SEM		0.34	0.50	0.111	1.056
	73	74.6	77.7	2.53	13.51
	79	80.0	82.1	2.60	12.74

	85	85.3	86.3	2.50	14.19
	SEM	0.28	0.52	0.098	0.829
Source of Variation		------------------------- Probability, *P* < -------------------------			
Binder × Cond Temp		----	0.623	0.801	0.519
Binder		----	<0.001	<0.001	<0.001
Cond Temp[5]					
Linear		----	<0.001	0.737	0.554
Quadratic		----	0.834	0.288	0.268

[AB] Means within the main effect of binder followed by a different letter are significantly different ($P \leq 0.05$).

[1] Diets were conditioned for approximately 40 sec prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) with a 4.8 × 44.5 mm die. Treatments were replicated 3 times.

[2] Experimental binders included dry calcium lignosulfonate (DLS), liquid cane molasses (LCM), a commercial liquid molasses blend (LMB), and a commercial liquid lactose blend (LLB).

[3] Temperature of conditioned mash reported as observational data with no statistical analysis.

[4] Specific energy consumption calculated according to Stark (1994).

[5] Linear and quadratic contrasts testing the response of increasing conditioning temperature with results considered significant at ($P \leq 0.05$).

Table 1.3. Effects of pellet binder and conditioning temperature on moisture content[1]

		Moisture,[3] %			
Binder[2]	Cond Temp, °C	Mash	Cond Mash	Hot Pellet	Cool Pellet
Interaction					
Control	73	13.51	16.61	15.82	15.50
	79	12.77	16.25	16.02	14.07
	85	12.98	16.62	15.52	13.55
DLS	73	12.86	16.28	15.35	12.66
	79	12.87	16.24	15.23	13.21
	85	12.66	16.49	15.90	13.17
LCM	73	13.77	17.89	16.54	12.88
	79	14.19	17.54	16.90	13.10
	85	13.81	17.49	16.64	14.16
LMB	73	13.70	18.39	17.18	13.47
	79	14.40	17.93	17.24	13.93
	85	13.17	18.02	17.16	14.55
LLB	73	13.67	18.18	18.05	15.20
	79	13.66	18.32	17.55	14.67
	85	13.78	17.30	16.93	14.29
SEM		0.259	0.638	0.453	0.575
Main Effects					
Control		13.09^{B}	16.49^{B}	15.79^{BC}	14.37^{AB}
DLS		12.80^{B}	16.34^{B}	15.50^{C}	13.01^{B}
LCM		13.92^{A}	17.64^{A}	16.70^{AB}	13.38^{AB}
LMB		13.76^{A}	18.11^{A}	17.19^{A}	13.99^{AB}
LLB		13.70^{A}	17.93^{A}	17.51^{A}	14.72^{A}
SEM		0.150	0.347	0.297	0.332
	73	13.50	17.47	16.59	13.94
	79	13.58	17.26	15.59	13.80
	85	13.28	17.19	16.43	13.94

SEM	0.116	0.310	0.254	0.257
Source of Variation	---------------------- Probability, *P* < ----------------------			
Binder × Cond Temp	0.120	0.851	0.680	0.182
Binder	<0.001	<0.001	<0.001	0.006
Cond Temp[4]				
Linear	0.187	0.301	0.548	0.996
Quadratic	0.202	0.758	0.730	0.644

[ABC] Means within the main effect of binder followed by a different letter are significantly different ($P \leq 0.05$).

[1] Diets were conditioned for approximately 40 sec prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) with a 4.8 × 44.5 mm die. Treatments were replicated 3 times.

[2] Experimental binders included dry calcium lignosulfonate (DLS), liquid cane molasses (LCM), a commercial liquid molasses blend (LMB), and a commercial liquid lactose blend (LLB).

[3] Moisture content calculated based on AOAC 930.15 using duplicate samples from each replication analyzed in triplicate.

[4] Linear and quadratic contrasts testing the response of increasing conditioning temperature with results considered significant at ($P \leq 0.05$).

Table 1.4. Interaction between pellet binder and conditioning temperature on pellet quality[1]

Binder[2]	Cond Temp, °C	Fines,[3] %	Tumble Box[4]		NHP 100[5]			NHP 200[6]
			Standard	Modified	60 sec	90 sec	120 sec	
Control	73	13.1^{a}	90.3	82.6	86.2^{cd}	76.8^{d}	68.6^{g}	76.6
	79	5.5^{bc}	92.9	87.1	88.1^{abcd}	81.3^{bcd}	76.5^{cdef}	83.7
	85	3.6^{c}	93.6	89.3	90.5^{ab}	85.7^{abc}	82.2^{abc}	87.8
DLS	73	3.9^{bc}	94.1	88.5	88.3^{abcd}	82.8^{abcd}	77.3^{abcdef}	87.9
	79	3.0^{c}	93.4	89.6	88.2^{abcd}	84.0^{abc}	78.0^{abcde}	88.7
	85	3.3^{c}	94.3	89.6	90.8^{ab}	88.1^{a}	82.2^{abc}	89.4
LCM	73	4.8^{bc}	94.1	90.1	91.2^{ab}	87.2^{ab}	84.1^{ab}	89.8
	79	4.6^{bc}	93.6	91.6	89.2^{abc}	85.1^{abc}	80.8^{abcd}	87.9
	85	4.0^{bc}	93.9	90.0	91.4^{a}	88.2^{a}	84.1^{a}	90.8
LMB	73	5.0^{bc}	92.3	87.7	86.7^{cd}	80.5^{cd}	74.1^{defg}	82.7
	79	4.6^{bc}	92.3	88.8	86.2^{cd}	80.8^{cd}	72.3^{efg}	85.3
	85	6.6^{b}	92.3	88.8	87.7^{bcd}	82.6^{abcd}	76.8^{bcdef}	84.2
LLB	73	5.7^{bc}	94.1	91.6	85.5^{d}	76.8^{d}	70.1^{fg}	82.0
	79	5.7^{bc}	93.9	90.0	88.0^{abcd}	82.5^{abcd}	76.6^{cdef}	82.0
	85	4.3^{bc}	93.3	89.8	89.0^{abcd}	84.0^{abc}	79.5^{abcde}	85.1
SEM		0.54	1.02	1.75	0.69	1.22	1.42	2.42
Source of Variation		--------------------	---------- Probability, *P* <	----------				--------------------
Binder × Cond Temp		<0.001	0.449	0.209	0.048	0.028	0.001	0.205
Binder		<0.001	0.046	0.005	<0.001	<0.001	<0.001	<0.001

Cond Temp[7]							
Linear	<0.001	0.364	0.119	<0.001	<0.001	<0.001	0.007
Quadratic	0.032	0.981	0.408	0.046	0.427	0.192	0.909

[a-g] Means within the interaction effect of binder × conditioning temperature followed by a different letter are significantly different ($P \leq 0.05$).

[1] Diets were conditioned for approximately 40 sec prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) with a 4.8 × 44.5 mm die. Treatments were replicated 3 times.

[2] Experimental binders included dry calcium lignosulfonate (DLS), liquid cane molasses (LCM), a commercial liquid molasses blend (LMB), and a commercial liquid lactose blend (LLB).

[3] Fines calculated as the proportion of fines recovered from a complete sample at the die using a U.S. No. 5 (3.9 mm) sieve.

[4] Standard and modified tumble box methods according to ASAE S269.5 with three 19 mm hex nuts used for modification.

[5] Holmen NHP 100 (TekPro Ltd, Norfolk, UK) portable pneumatic pellet tester set at 70 mbar forced air with 60, 90, or 120 sec run time.

[6] Holmen NHP 200 (TekPro Ltd, Norfolk, UK) automated pneumatic pellet tester set at 70 mbar forced air with 100 sec factory-designated run time.

[7] Linear and quadratic contrasts testing the response of increasing conditioning temperature with results considered significant at ($P \leq 0.05$).

Chapter 2 - Effects of conditioning temperature and pellet mill die speed on pellet quality and relative stabilities of phytase and xylanase

2.1 ABSTRACT

The objective of this experiment was to determine the effect of conditioning temperature and die speed on pellet quality and enzyme stability of phytase and xylanase. Treatments were initially arranged as a 2 × 3 factorial of conditioning temperature (74 and 85°C) and die speed (127, 190, and 254 rpm); however, when conditioning at 85°C it was not possible to pellet at 127 rpm. Thus, data were analyzed in 2 different segments using the GLIMMIX procedure of SAS. First, linear and quadratic contrasts were utilized to test the response to increasing die speed at 74°C. Second, the data was analyzed as a 2 × 2 factorial of conditioning temperature (74 and 85°C) and die speed (190 and 254 rpm). Treatments were arranged in a completely randomized design and replicated 3 times. Diets were conditioned for approximately 30 s and pelleted with a 4.8 mm diameter × 44.5 mm effective length die at a rate of 4.5 MT/h. Pellet durability index (PDI) was determined using the tumble box and Holmen NHP 100 methods. Samples of the unconditioned mash (M), conditioned mash (CM) and pellets (P) were collected and analyzed for phytase and xylanase concentration. Relative enzyme stabilities were expressed as CM:M, P:CM and P:M. Stabilities expressed as P:M were used an indication of enzyme stability through the entire pelleting process. Diets conditioned at 74°C showed no evidence of difference in phytase or xylanase P:M stability when decreasing die speed from 254 to 127 rpm. However, when conditioning diets at 74°C, decreasing die speed increased (linear, $P < 0.001$) PDI. There was no conditioning temperature × die speed interaction for overall xylanase P:M stability or PDI.

However, there was a conditioning temperature × die speed interaction ($P < 0.01$) for phytase P:M stability. When conditioning diets at 85°C, increasing die speed decreased phytase P:M stability. However, when conditioning at 74°C, increasing die speed did not influence phytase P:M stability. For main effects of conditioning temperature, increasing temperature improved ($P < 0.001$) PDI with no evidence of difference for xylanase P:M stability. For the main effects of die speed (254 vs 190 rpm), decreasing die speed decreased ($P < 0.001$) the P:M xylanase stability, but there was no evidence of difference for PDI. The results of this trial indicate that die speed should be taken into consideration when evaluating enzyme stability of both phytase and xylanase as pellet mill models may be operating at different speeds. Additionally, increasing conditioning temperature will improve PDI, but may result in decreased phytase stability.

Keywords: die speed, pellet durability, enzyme stability, pellet, pellet mill

2.2 INTRODUCTION

Pelleting properties of mash feed can be influenced by a range of variables, some better understood than others. For decades researchers have explored the relationship of feed conditioning and die specifications on optimized pellet quality (Mohensin and Zaske, 1976; Thomas et al., 1997; Behnke, 2001; Cutlip et al., 2008). In more recent years, greater reliance on exogenous enzymes in animal nutrition has broadened the scope of pelleting research to also include the effects on enzyme stability (Pope, 2019; Saensukjaroenphon, 2019, Truelock, 2020). Little attention, however, has been focused on understanding the influence of equipment parameters such as horsepower, roller assembly (e.g., roll number and size), and die speed on pellet quality or enzyme stability.

Pellet mill die speed is typically measured at the outside diameter of the die. It is a product of the main drive speed, whether gear or belt driven, and any subsequent gear or belt reducers. In general, increased rotational speed not only maximizes throughput, but also reduces the accumulation of conditioned mash in front of the die rolls. Turner (2013) stated that this leads to increased manufacturing stability, as realized through greater possible conditioning temperatures and reduced energy input. Slower speeds, however, may be necessitated by quality concerns with cubes or from high die discharge rates resulting in pellet collision with the interior walls of the pellet mill chamber. Leaver (1988) suggested a peripheral die speed of 610 m per min as the optimum speed for pellets ranging from 3.2 to 6.4 mm in diameter, while reduced speeds between 366 to 396 m per min are preferred for pellet diameters exceeding 16 mm. Similarly, Turner (2013) recommended a die speed of 540 m per min when manufacturing smaller diameter pellets. It remains unclear how these recommendations were derived and validated, whether based on throughput, quality, or a combination of both. Application of Leaver and Turner's guidance is further complicated by the various operating die speeds observed throughout the industry.

There remains no standard operating die speed for pellet mills due to differences in equipment sizing and horsepower requirements. One manufacturer reports what appears to be a decreasing range of recommended die speeds as machine size and horsepower increase. Based on this manufacturer, a 150 hp pellet mill equipped with a 40.6 cm diameter die should operate at a die speed of 254 rpm; while a larger 500 hp pellet mill equipped with a 91.4 cm diameter die should operate at 211 rpm. Taking into account the die circumferences this would correspond to approximately 324 and 606 m per min die peripheral velocities, respectively. These differences in die speed may offer yet another variable to consider when comparing results across various pelleting units.

Furthermore, changes in die speed may be a contributing factor to differences observed between pilot scale research and industry application. Pilot research trials have reported lower enzyme recoveries relative to industry and manufacturer reports (Pope, 2019 and Truelock, 2020). Pope (2019) suggests that these differences may be due to changes in production rate, die working area, and cooling protocols. It is hypothesized that differences in die speed may also be a contributing factor to variations in observed enzyme stability.

Though measurable, die speed remains an inconsistent target across pellet mills with no clear understanding of its role in subsequent pellet quality or enzyme stability. Thus, the objective of this trial was to evaluate the effects of conditioning temperature and die speed on pellet quality and enzyme stability of exogenous enzymes with varying heat tolerances (phytase and xylanase).

2.3 MATERIALS AND METHODS

2.3.10 Feed Manufacturing

A total of 41 MT of a swine finishing diet (Table 2.1) containing commercial phytase (Quantum Blue 5G, AB Vista Inc., Plantation, FL) and xylanase (Econase XT, AB Vista Inc., Plantation, FL) was pelleted to determine the effect of conditioning temperature and die speed on pellet quality and enzyme stability. Mash feed was conditioned at 74 or 85°C and subsequently pelleted at a die speed of 127, 190, or 254 rpm.

Feed was mixed in 909-kg batches in a 1.63 m^3 twin shaft counterpose mixer (Hayes and Stolz, model TRDB63-0152, Fort Worth, TX). Dry ingredients were mixed for 60 s prior to the addition of liquid fat and then mixed for an additional 120 s. There were three 909-kg batches of feed per treatment replicate, yielding 2.7 MT of feed per pelleting run. Upon mixer discharge, mash samples were taken at regular intervals with 5 total samples for each replicate.

The mash batches were conditioned for approximately 30 s at 74 and 85°C in a single pass conditioner with a steam pressure of 1.52 bar. Diets were pelleted on a 100 HP pellet mill (CPM, model 3016-4, Crawfordsville, IN) equipped with a 4.8 mm diameter × 44.5 mm effective length die (Table 2.2) and a target production rate of 4.5 MT/h. There were 3 defined pelleting runs per treatment characterized by allowing the conditioner to empty and the pellet mill to enter automated shut down. Die speed was adjusted via a variable frequency drive located on the main motor. Thus, when operating at 100, 75, and 50% of motor hertz, resulting shaft speeds were 1200, 900, and 600 rpm, respectively (Table 2.3). This yielded peripheral die speeds of 254, 190, and 127 rpm; or, based on die circumference, 324, 243, and 162 m per min. Die rpm was confirmed via precision laser tachometer (Fisher Scientific, Hampton, NH) prior to each pelleting run. The pellet mill die was warmed with 909-kg of feed prior to proceeding with experimental batches. Pelleting order was randomized within conditioning temperature to minimize residual changes in die temperature. Once conditioner temperature and production rate stabilized, conditioned mash and pellets were collected every 4 min for enzyme analysis with a total of 5 samples each. The conditioned mash samples were cooled for 8 min using a laboratory cooler with a 153 mm axial fan, while the pellets were cooled using a laboratory counter-flow cooler for 10 min. Conditioned mash temperature and pellet die exit temperature (hot pellet) were measured twice during each pelleting run. The samples were placed into a pre-warmed double-wall thermos equipped with a digital thermometer. After the end of each pelleting run, the die surface temperature was measured in 2 places along the outside die periphery via infrared digital thermometer (IR002, Ryobi Limited, Anderson, SC). Additional samples of the mash and pellets were taken to determine moisture content and pellet durability as described below.

2.3.11 Data Collection

2.3.11.1 Energy Consumption

Pellet mill voltage and amperage was recorded every 5 s during each pelleting run with a data logger (Supco model DVCV, Allenwood, NJ). Motor amperage was averaged across the individual pelleting run once conditioning temperature and production rate stabilized. Specific energy consumption (SEC) was calculated (Eq. 1) according to Stark (1994):

$$\text{SEC (kWh / MT)} = \frac{\text{I} \times \text{E} \times \text{PF} \times 1.73}{\text{PR} \times 1000} \qquad \text{Eq. 1}$$

where I is average motor amperage,

E is voltage,

PF is power factor set to 0.85,

PR is production rate expressed in MT/h.

2.3.11.2 Moisture Content

Mash samples were taken at the mixer (mash) and conditioner (conditioned mash), while pellet samples were taken at the die (hot pellet) and post cooler (cool pellet) for determination of moisture content. Upon collection, sample bags were immediately sealed and placed in a freezer set at -18°C to prevent any potential moisture loss. Duplicate samples were taken at even intervals and were analyzed in triplicate according to AOAC 930.15. Briefly, a 100-g sample of mash or pellets was ground to pass through a 1-mm screen. A 2-g subsample of the ground material was then weighed to the nearest 0.1-mg and dried in an air oven at 135°C for 2 h. Once removed, the sample was placed into a desiccator to cool. The sample was re-weighed and the moisture content calculated based on loss in weight:

2.3.11.3 Pellet Durability

Pellet samples were collected directly off of the pellet die and placed in a counter-flow laboratory cooler for 10 minutes. There were 2 pellet samples taken per treatment replicate. Pellets were packaged and stored in commercial tri-layer paper feed sacks and rested for 24 h prior to analysis. The pellet durability index (**PDI**) was assessed using the tumble box and Holmen forced-air methods. In the tumble box method, pellets were initially sifted with a U.S. No. 5 (3.9 mm) sieve for fines removal. A 500-g sample of sifted pellets was then placed in the tumble box and rotated at 50 rpm for 10 min. After tumbling, the sample was collected and sifted again to remove fines. PDI was calculated according to S269.5 (ASAE, 2012):

$$\text{PDI (\%)} = \frac{\text{Recovered Pellet Weight}}{\text{Initial Pellet Weight}} \times 100 \qquad \text{Eq. 2}$$

This standard tumble box PDI procedure was then modified by adding three 19 mm hex-nuts to the tumbling chamber to increase the agitation stress. For the Holmen method, pellets were sifted prior to analysis as outlined above. A 100-g sample of sifted pellets was then placed in the chamber of the Holmen NHP100 (TekPro Ltd, Norfolk, UK). The machine was set to 70 mbar air pressure and outfitted with a tissue filter. Pellets were agitated with forced air for 30 or 60 s, after which the sample was collected and sifted for removal of fines. PDI was calculated according to Eq. 2, the same manner as the tumble box method. All samples were analyzed in duplicate and results averaged.

2.3.11.4 Enzyme Activity

Mash (**M**), conditioned mash (**CM**), and pellet (**P**) samples were analyzed for phytase and xylanase content by the manufacturer according to the methods described by Pope and Fahrenholz (2020). Phytase content was determined using the QuantiPlate ELISA kit specific for Quantum Blue in accordance with ESC Standard Analytical Method SAM099 of AB Vista. Xylanase content was determined using the QuantiPlate ELISA kit specific for Econase in accordance with ESC Standard Analytical Method SAM115 of AB Vista. The percent phytase and xylanase stability of the conditioned mash samples (n=5) were then expressed relative to the average mash recovery for each treatment replicate (CM:M) according to Eq. 4. The percent phytase and xylanase stability of the pellet samples (n=5) were expressed relative to both the average recoveries of mash (P:M) and conditioned mash (P:CM) according to Eq. 4.

$$\text{Stability (\%)} = \frac{R_S}{R_{Avg}} \times 100 \qquad \text{Eq. 3}$$

where R_S is the enzyme recovery of the individual sample,

R_{Avg} is the average enzyme recovery of the desired reference sample group.

2.3.12 Statistical Analysis

Treatments were initially arranged as a 2 × 3 factorial of conditioning temperature (74 and 85°C) and die speed (127, 190, and 254 rpm); however, during testing, conditioning at 85°C and pelleting at 127 rpm was infeasible. Thus, data were analyzed in 2 different segments using the GLIMMIX procedure of SAS. First, linear and quadratic contrasts were utilized to test the response to increasing die speed at 74°C. Second, the data was analyzed as a 2 × 2 factorial of conditioning temperature (74 and 85°C) and die speed (190 and 254 rpm). Treatments were arranged in a completely randomized design and replicated 3 times each with date of manufacture serving as a random effect. Results were considered significant at $P \leq 0.05$.

2.4 RESULTS AND DISCUSSION

2.4.13 Feed Manufacturing

The effect of conditioning temperature and die speed on pelleting parameters are shown in Table 2.4. Conditioning temperatures remained comparable to their respective targets of 74 and 85°C as indicated by conditioned mash temperatures. Measured peripheral die speeds were also closely aligned with their targets of 127, 190, and 254 rpm. Production rates remained consistent across treatments, though, when conditioning at 85°C it was impossible to produce pellets at 127 rpm due to instances of die choking and eventual plugging.

It is hypothesized that a combination of increased feed accumulation in front of the die rolls and moisture content were responsible for this failure. As conditioned mash is fed to the die rolls, it undergoes compaction to form a layer of feed commonly referred to as the feed pad. If the conditioned mash begins to accumulate too quickly in the die, the fixed die rolls may struggle to extrude feed through the die at the appropriate rate to sustain production. Thus, slowing die speeds, as Turner (2013) suggests, will result in increased accumulation of conditioned mash in front of the die rolls and a thicker feed pad. Once the feed pad becomes too thick for the die roll to overcome, roll slip force will increase allowing further accumulation of conditioned mash in the pelleting chamber until the die becomes choked and unable to rotate. While equipment failure is the greatest indicator of roll slip, increased pellet mill energy consumption (**SEC**) is also indicative of the roll's struggle to compensate for conditioned mash accumulation at the feed pad. This was evident in the current trial where there was a quadratic increase (quadratic, $P < 0.001$) in SEC as die speed decreased from 254 to 127 rpm when conditioning at 74°C. There was no evidence of interaction ($P = 0.074$) between conditioning temperature and die speed (190 and 254 rpm only) for SEC. Additionally there was no evidence of difference in SEC for increasing conditioning temperature ($P = 0.578$) or die speed ($P = 0.106$).

The theorized roll slip issues observed is this trial may have been amplified by increasing the conditioning temperature and would provide rationale for the ability to pellet at 127 rpm when conditioning at 74 as opposed to 85°C. Based on previous research conducted using this pellet mill, increasing conditioning temperature from 74 to 85°C increased the mash moisture content by 0.8% (Kort et al., 2020). Under the constraints of the current trial; however, only a 0.5% increase in moisture was observed when conditioning at 85°C with no evidence of differences (*P* > 0.495) in conditioned mash moisture between treatments. The authors can only postulate what level of moisture is needed to induce roll slip and result in equipment failure; however, changes in the observed hot pellet exit temperatures (Table 2.4) appear to further support the theory that increased moisture content may have been a contributing factor when conditioning at 85°C. The lower ΔT between conditioned mash and hot pellet exit temperature when conditioning at 85°C compared to 74°C indicates that the difference in moisture content was great enough to increase lubrication and reduce die friction. The responses observed in this trial may have further been exacerbated by the pellet mill model and die size. Larger dies and rolls may be less sensitive to changes in feed pad thickness and moisture content, creating an advantage in overcoming increased nip angles at the roll-die interface.

Moisture results indicated a change in moisture between feed entering the die chamber and exiting the die. When feed was conditioned at 74°C, decreasing die speed quadratically decreased (quadratic, *P* = 0.017) hot pellet moisture after the die. Additionally, there was an interaction (*P* < 0.001) between conditioning temperature and die speed (190 and 254 rpm) that demonstrated decreasing die speed lowered hot pellet moisture when conditioning at 85 compared to 74°C. The authors can only speculate on the cause of this response, but perhaps differences in residence time in the feed pad was a factor. The slower die speeds potentially have thicker feed pads with lower instances of roll contact (Table 2.4) and thus longer residence time in the feed pad. This could lead to greater loss in moisture in the die chamber as feed dwell time increased in the feed pad, which would explain the increased moisture loss with the slower die speeds. The loss of moisture may further be increased at higher conditioning temperatures where the die and chamber temperature may influence evaporative moisture loss. This may explain the lack of change when conditioning at 74°C and pelleting at 190 rpm compared to conditioning at 85°C.

2.4.14 Pellet Durability

Pellet durability index was assessed using both mechanical (tumble box) and pneumatic (NHP 100) agitation (Table 2.6). Agitation stress was increased in the tumble box by adding hex-nuts and in the NHP 100 by increasing pellet exposure time to the forced air stream. Though raw values differed numerically between the durability methods utilized in this trial, the interpretation of the effect between treatments remained the same. When conditioning diets at 74°C, decreasing die speed from 254 to 127 rpm increased (linear, $P < 0.001$) PDI. There was no interaction ($P > 0.103$) between conditioning temperature and die speed (190 and 254 rpm) for PDI. For main effects, increasing conditioning temperature improved ($P < 0.001$) PDI, while there was no evidence of difference ($P > 0.198$) in PDI based on die speed.

The increased PDI resulting from conditioning at a higher temperature has been well-documented by other researchers (Cutlip et al., 2008; Stark and Ferket, 2011). Generally, this response to the addition of heat and moisture has been attributed to altered physico-chemical properties of the feed, typically leading to improved binding properties between particles (Thomas and van der Poel, 1996). Previous work examining the effects of die speed on pellet durability is more poorly documented. Stevens (1987) examined the effect of die speed on the pellet durability of a corn-based swine formulation after conditioning at 75°C. The corn diet was pelleted at die speeds from 150-268 rpm, or 143-256 m per min velocity based on die circumference. Results demonstrated improved pellet durability when utilizing the lowest die speed setting of 150 rpm, with no evidence of a difference between the other die speeds. This is similar to the findings of this trial where pelleting at 127 rpm or 162 m per min yielded the greatest PDI for feed conditioned at 74°C.

2.4.15 Phytase Stability

One of the primary concerns for exogenous enzyme use in pelleted livestock feed is their ability to withstand the rigors of pelleting (Pope, 2019). Factors like temperature and moisture have been shown to influence enzyme inactivation (Bychkov et al., 2011 and Perdana et al., 2012). Two commercial exogenous enzymes were chosen for testing in this experiment: a phytase produced by a strain of *Trichoderma reesi* reported to tolerate conditioning temperatures up to 90°C and a xylanase reported to be intrinsically thermostable and tolerant of conditioning temperatures up to 95°C. In an effort to understand how the processes of conditioning and pressing the pellets at different die speeds effect the enzyme stability, samples were taken directly after conditioning (CM) and as feed exited the pellet die (P).

Enzyme stability results are shown in Table 2.7. When diets were conditioned at 74°C, there was no evidence of a difference ($P > 0.198$) in the phytase recovery in pellets relative to the initial mash (P:M). There was a conditioning temperature × die speed (254 and 190 rpm only) interaction ($P = 0.004$) for phytase stability of pellets relative to the initial mash. When conditioning diets at 85°C, increasing die speed from 190 to 254 rpm decreased phytase stability, while increasing die speed did not influence phytase stability when conditioning at 74°C. Focusing on the phytase activity in the conditioned mash relative to mash (CM:M) provides insight into losses in activity occurring due to conditioning temperature alone. In this study, there was no evidence of differences ($P > 0.086$) in phytase stability among any treatment, indicating that the conditioning temperature (up to 85°C) alone was least likely to influence the change in phytase stability in the experiment conducted herein. Comparing the phytase activity in the pellets relative to conditioned mash (P:CM) represents changes in stability due to the pressing process. Under the constraints of this trial, there was no evidence of a difference ($P > 0.123$) in phytase stability with decreasing die speed when the feed was conditioned at 74°C. There was a conditioning temperature × die speed (254 and 190 rpm only) interaction ($P = 0.004$) for phytase stability of pellets relative to the conditioned mash, which was similar to that observed in pellets relative to initial mash. When conditioning diets at 85°C, increasing die speed from 190 to 254 rpm decreased phytase stability, while increasing die speed did not influence phytase stability when conditioning at 74°C. These results would indicate that the greatest contributors to phytase degradation occur during the extrusion of the material through the die. These authors recognize that conditioning temperature and moisture may also interact at the die interface causing degradation; however, these changes would again influence forces during the pressing process and not strictly conditioning. Pope (2012) had a similar conclusion based on his works where phytase denaturation was not simply a result of exposure to steam within the conditioner, but was rather a complex response to the accumulation of forces necessary to bind particles within the pellet mill die such as moisture, heat, and pressure.

The authors can only hypothesize that the reduced phytase stability at greater die speed when conditioning at a higher temperature is a result of a combination of several factors. Hot pellet temperatures (Table 2.4) would indicate that the exit temperature of pellets exceeded the recommended temperature for phytase preservation. This is a theory supported by Truelock (2020) who found hot pellet temperature was a better indicator for phytase degradation than conditioning temperature alone. Perhaps die temperature or the amount of die to roll contact played some role in the observed results. Ultimately the complexities among factors and forces occurring during the pressing process make it difficult to come to a definitive conclusion in this regard and need further research.

2.4.16 Xylanase Stability

Comparatively, conditioning temperature and die speed seem to have had a reduced effect on the stability of the more thermal tolerant xylanase in this trial. There was no evidence of differences ($P > 0.103$) in xylanase stability in pellets relative to the initial mash (P:M) when conditioning at 74°C with increasing die speed. There was no interaction ($P = 0.283$) between conditioning temperature and die speed (190 and 254 only), however, there was a main effect of die speed in which increased die speed resulted in greater xylanase stability. This is in direct opposition to the response of phytase to increased die speed. When comparing the xylanase recovery in the conditioned mash relative to the mash (CM:M), there was no evidence of a difference ($P > 0.077$) in xylanase stability when conditioning at 74°C with increasing die speed. There was, however, an interaction ($P = 0.026$) between conditioning temperature and die speed (190 and 254 only) where xylanase stability was poorer at the slower die speed when conditioning at 85°C compared to 74°C. Similar to P:M, pellets relative to the conditioned mash (P:CM) had no evidence of differences ($P > 0.122$) in xylanase stability with increasing die speed when conditioning at 74°C. There was no interaction ($P = 0.283$) between conditioning temperature and die speed (190 and 254 only), however, there was a main effect of die speed in which increased die speed resulted in greater xylanase stability.

2.5 CONCLUSIONS

The results of this trial indicate that conditioning temperature and die speed can influence pellet quality. When conditioning at lower temperatures (74°C) decreasing die speed will improve pellet durability, while high conditioning temperatures (85°C) will yield greater durability regardless of die speed. However, reducing die speed resulted in increased specific energy consumption. Regarding enzyme stability, die speed should be considered when conditioning feed at 85°C due to increased phytase degradation. It is unclear the mode of action behind this response, which warrants further exploration into the role of temperature, moisture, and friction at the mash-die interface. Additionally, when pelleting more heat tolerant enzymes like the xylanase used in this trial, conditioning temperature and die speed may be of less concern in preserving activity.

Most importantly, because pellet mill models may be operating at different die speeds, care should be taken when interpreting or applying pelleting research. This may be especially true when comparing small pellet mills with lower die peripheral speeds and velocities to larger industry sized equipment.

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Table 2.1. Diet composition for finishing swine

Ingredient	Inclusion, %
Corn[1]	76.05
Soybean meal	20.05
Soy oil	1.50
Limestone	1.10
Sodium chloride	0.35
Mono-calcium phosphate, 21% P	0.33
L-lysine HCl	0.26
Trace mineral premix[2]	0.13
Vitamin premix[3]	0.13
L-threonine	0.05
DL-methionine	0.02
Phytase[4]	0.02
Xylanase[5]	0.01
Total	100.00

[1] Ground corn was analyzed according to ASAE S319.2 for geometric mean diameter (568μm) and standard deviation (2.83).
[2] Composition per kg of premix: 73 g iron, 73 g zinc, 22 g manganese, 11 g copper, 0.2 g iodine and 0.2 g selenium.
[3] Composition per kg of premix: 1,653,439 IU vitamin A, 661,376 IU vitamin D_3, 17,637 IU vitamin E, 13.3 mg vitamin B_{12}, 1,323 mg menadione, 3,307 mg riboflavin, 11,023 mg d-pantothenic acid and 19,841 mg niacin.
[4] Quantum Blue 5G (AB Vista Inc., Plantation, FL) provided 1000 FTU/kg feed.
[5] Econase XT (AB Vista Inc., Plantation, FL) provided 16,000 BXU/kg of feed.

Table 2.2. Die specifications

Die hole diameter, mm [D]	4.8
Die Diameter, mm [L]	44.5
Internal die surface area, cm^2 [a]	1477.5
Holes per cm^2 [h_d]	2.3
Effective volume per hole,[1] cm^3 [v]	0.8
Feed per die in effective length,[2] kg [f]	1.7

[1] The effective volume per hole equals $\pi D^2 L/4$.
[2] The amount of material in the effective length of the die equals total number holes [ah_d] × volume per hole [v] × material density [0.609 g/cm^3].

Table 2.3. Pellet mill speed definitions

Shaft speed[1], rpm	Die speed, rpm	Peripheral die speed, m/min
1200[*]	254	324
900	190	243
600	127	162

[1] Main drive shaft speed set via a variable frequency drive to 100, 75, and 50%, respectively.
[*] Standard main drive shaft speed for 100 HP pellet mill model 3016-4 (CPM Co., Crawfordsville, IN).

Table 2.4. The effect of conditioning temperature and die speed on pelleting paramaters[1]

	Conditioning Temperature, °				
	74°C			85°C	
Die Speed, rpm	127	190	254	190	254
Actual die peripheral speed[2]	130	195	261	194	260
Die roll contact[2], hits/min	260	390	522	388	520
Prod. rate, MT/h	4.5	4.6	4.4	4.2	4.3
Die retention[3], sec	1.4	1.3	1.4	1.4	1.3
Temperature, °C					
Cond. Mash	73.8	73.9	73.8	83.2	85.2
Hot Pellet	76.2	77.1	77.6	84.6	86.4
ΔT across die	2.4	3.2	3.8	1.4	1.2
Die	67.5	69.1	67.7	78.3	81.7

[1] Diets were conditioned for approximately 30 s prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) on a 4.8 × 44.5 mm die with 3 replications per treatment.
[2] Peripheral die speed (rpm) measured via laser tachometer prior to each pelleting run.
[3] Calculated based on Saensukjaroenphon (2019) using die specifications (Table 2.2) and production rate.

Table 2.5. The effect of conditioning temperature and die speed on moisture content[1]

	Conditioning Temperature, °						Probability, $P <$				
	74°C			85°C			74°C, die speed[2]		2 × 2 factorial[3]		
Die speed, rpm	127	190	254	190	254	SEM	Linear	Quad	Temp	RPM	Temp × RPM
Moisture,[4] %											
Mash	13.3	13.6	13.7	13.3	13.4	0.32	0.024	0.436	0.502	0.463	0.994
Condition Mash	17.1	16.8	16.9	17.2	17.3	0.42	0.495	0.493	0.519	0.674	0.949
Hot Pellet	16.2	16.8	16.6	16.3	17.1	0.26	0.057	0.017	0.969	0.037	<0.001
Cool Pellet	13.6	13.7	13.9	13.6	13.5	0.27	0.045	0.908	0.532	0.932	0.216

[1] Diets were conditioned for approximately 30 s prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) on a 4.8 × 44.5 mm die. Treatments were replicated 3 times.

[2] Linear and quadratic contrasts testing the effect of increasing die speed when conditioning at 74°C.

[3] Factorial analysis consisted of two conditioning temperatures (74 and 85°C) and two die speeds (190 and 254 rpm).

[4] Moisture content calculated based on AOAC 930.15 using duplicate samples from each replication analyzed in triplicate.

Table 2.6. The effect of conditioning temperature and die speed on specific energy consumption (SEC) of the pellet mill and pellet quality[1]

	Conditioning Temperature, °						Probability, *P* <				
	74°C			85°C			74°C, die speed[2]		2 × 2 factorial[3]		
Die speed, rpm	127	190	254	190	254	SEM	Linear	Quad	Temp	RPM	Temp × RPM
SEC,[4] kWh/MT	10.9	8.9	9.0	9.6	9.1	0.41	0.001	0.001	0.578	0.106	0.074
PDI, %											
Std Tumble[5]	85.8	83.9	83.3	91.2	91.2	0.58	0.001	0.082	0.001	0.245	0.313
Mod Tumble[5]	68.6	64.1	61.7	80.3	80.6	1.84	0.001	0.262	0.001	0.198	0.103
NHP 30s[6]	78.1	73.1	70.8	87.7	87.8	1.51	0.001	0.207	0.001	0.214	0.175
NHP 60s[6]	56.6	46.3	43.3	78.7	78.2	2.46	0.001	0.063	0.001	0.257	0.433

[1] Diets were conditioned for approximately 30 s prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) on a 4.8 × 44.5 mm die. Treatments were replicated 3 times. Date of production served as a random effect to account for any environmental changes that may have influenced pelleting parameters.
[2] Linear and quadratic contrasts testing the effect of increasing die speed when conditioning at 74°C.
[3] Factorial analysis consisted of two conditioning temperatures (74 and 85°C) and two die speeds (190 and 254 rpm).
[4] Specific energy consumption was calculated according to Stark (1994) based on production rate and average pellet mill motor amperage over the run.
[5] Standard and modified tumble box methods according to ASAE S269.4 with three 19 mm hex nuts used for modification.
[6] Holmen NHP100 (TekPro Ltd, Norfolk, UK) pneumatic pellet tester set at 70 mbar forced air with 30 or 60 s run time.

Table 2.7. The effect of conditioning temperature and die speed on relative stabilities of phytase and xylanase[1]

	Conditioning Temperature, °						Probability, $P <$				
	74°C			85°C			74°C, die speed[2]		2 × 2 factorial[3]		
Die speed, rpm	127	190	254	190	254	SEM	Linear	Quad	Temp	RPM	Temp × RPM
Phytase Stability[4]											
CM:M	84.1	87.7	85.0	84.8	85.8	3.74	0.086	0.663	0.769	0.810	0.612
P:CM	103.6	99.5	97.7	87.9	70.8	3.01	0.123	0.699	0.019	0.001	0.004
P:M	90.9	88.0	86.6	75.8	61.1	3.09	0.198	0.799	0.035	0.001	0.004
Xylanase Stability[5]											
CM:M	102.9	101.4	95.1	88.0	94.9	5.49	0.077	0.504	0.430	0.906	0.026
P:CM	92.8	89.0	94.1	89.8	96.1	5.30	0.692	0.122	0.861	0.020	0.806
P:M	93.2	89.6	94.9	81.6	87.3	7.79	0.611	0.103	0.542	0.019	0.283

[1] Diets were conditioned for approximately 30 s prior to pelleting (Model 3016-4 CPM Co., Crawfordsville, IN) on a 4.8 × 44.5 mm die. Treatments were replicated 3 times. Date of production served as a random effect to account for any environmental changes that may have influenced pelleting parameters.

[2] Linear and quadratic contrasts testing the effect of increasing die speed when conditioning at 74°C.

[3] Factorial analysis consisted of two conditioning temperatures (74 and 85°C) and two die speeds (190 and 254 rpm).

[4] Relative phytase stability calculated as the percent FTUs remaining in conditioned mash (CM) or pellet (P) samples compared to the initial mash (M) or CM.

[5] Relative xylanase stability calculated as the percent BXUs remaining in conditioned mash (CM) or pellet (P) samples compared to the initial mash (M) or CM.

Chapter 3 - Effects of separation of fine corn particles and cold pelleting on growth performance and economic return in nursery pigs

3.1 ABSTRACT

A total of 320 pigs (DNA 241×600; initially 10.2 kg BW) were used in a 21-d experiment to determine the effects of removing fine corn particles (< 150 microns) and pelleting technique on nursery pig growth performance. There were 5 pigs per pen and 8 pens per treatment and diets were all manufactured using corn initially ground to 400 microns. Diets were fed as a mash or pelleted using a traditional vertical die pellet mill equipped with a steam conditioner (steam pellet) or a horizontal pellet die with hot water conditioning prior to pelleting (cold pellet). Therefore, the 8 treatments were: 1) ground corn diet fed as mash, 2) ground corn diet steam pelleted, 3) ground corn diet cold pelleted, 4) ground corn with fines less than 150 microns removed from the diet and the diet fed as mash, 5) ground corn with fines less than 150 microns removed from the diet and the diet without fines was steam pelleted, 6) ground corn with fines less than 150 microns removed from the diet and the diet without fines was cold pelleted, 7) fines less than 150 microns were steam pelleted then proportionally added back to ground corn and fed as a mixture of pellets and mash, and 8) fines less than 150 microns were cold pelleted then proportionally added back to ground corn and fed as a mixture of pellets and mash. Removal of fines less than 150 microns from the corn improved the flowability characteristics of the diets as indicated by improved composite flow index values. The best flowability was achieved when fines were pelleted and added back to the mash diets. Pigs fed steam or cold pelleted diets had

decreased ($P < 0.02$) ADG, ADFI, and d-21 BW, total feed cost, revenue, and income over feed cost (IOFC) compared to those fed mash diets. Pigs fed steam pelleted diets had decreased ($P < 0.006$) ADG, d-21 BW, revenue, and IOFC compared to those fed cold pelleted diets. There were no growth performance differences between pigs fed ground corn diets or ground corn diets with fines removed. Pigs fed diets with fines removed, pelleted, and subsequently added back had increased ($P < 0.05$) ADFI and feed cost with poorer G:F compared to all other treatments. It is assumed that this response resulted from increased feed wastage resulting from pigs sorting pellets mixed with mash diets. The results of this study indicate that removing particles less than 150 microns improved the flowability of a mash diet without sacrificing growth performance. Additionally, cold pelleting was a viable option to steam pelleting in the current experiment. However, pelleting diets reduced pig performance compared to pigs fed mash diets. Further research is needed to validate the response to cold pelleting when the expected response to pelleting using steam conditioning is achieved.

3.2 INTRODUCTION

Reducing the particle size of cereal grains is well understood to be a means to improve the efficiency of gain in swine (Goodband and Hines, 1988; Giesmann et al., 1990; Wondra et al., 1995). Opinions vary somewhat among swine producers regarding the optimum particle size of cereal grains for animal production and feed manufacturing economics. None the less, a shift has occurred over the past several years resulting in mills routinely grinding cereal grains as fine as possible for swine diets. Fine grinding grains, however, can result in ‘flouring’ where a large portion of the material is ground to a fine powder. These ‘grinding fines’ are traditionally less than 150 μm and are believed to have an adverse effect on feed flowability, making grain handling and feeder management more challenging when fed in meal form. This poses a problem for swine producers because when feed bridges in the feeding system, out of feed events occur which result in decreased performance and increased potential of ulceration, increased stress, and potentially mortality. Thus, a means to remove the smallest particles and create a free-flowing product would be highly beneficial to feed manufacturers, owners, and swine producers.

Pelleting is a feed processing method shown to improve handling and transportation characteristics of feeds, while reducing ingredient segregation during handling, decreasing dust levels, and improving feed utilization in swine (Vanschoubroek et al., 1971). There are multiple facrors (moisture, heat, frictional die characteristics, and the inherent variability of diets) involved in producing high quality pellets which requires a fundamental understanding of the process. The perceived challenges and anticipated capital cost often deter many swine producers from utilizing pelleting technology and capitalizing on the associated benefits.

The flat-die or flat-bed pellet mill (**PM**) may offer some producers a more cost-effective alternative to the vertical ring die PM traditionally used to produce pelleted commercial animal feed. While both PM designs are centered around the same die and roller principle, the flat-bed PM has the die and rolls positioned in the horizontal plane, where the die remains stationary as the roller assembly rotates and pushes feed through the die (Sears, et al., 2001). This relatively simple design yields lower maintenance cost and energy consumption when compared to the vertical ring PM. Furthermore, while the rotational speed of the roll assembly may be limited, contributing to reduced throughput compared to the vertical ring PM, it also serves to increase compression through the die and enhances particle binding (Thomas et al., 1996). The potential for improved particle binding with the flat-bed PM may reduce or eliminate the need to thermally condition feed prior to pelleting, a process known as “cold pelleting”. This may be particularly attractive to producers wanting to avoid the added cost of purchasing and maintaining a boiler, which is required for steam conditioning of feed prior to pelleting with a vertical ring PM.

Cold pelleting with a flat-bed PM is typically utilized for products that are highly fibrous or bulky, such as straw, wood, or biomass, but has been used in Europe for pelleting broiler diets with whole wheat instead of ground wheat (Svihus et al., 2004). However, to our knowledge, no peer-reviewed literature exists to compare the flat die technology to standard pelleting with steam conditioning and a ring die for animal diets. Though the technology has never been evaluated before, it has the potential to be an alternative method of pelleting animal feed. Therefore, the objective of this study was to determine the effects of pelleting diets using standard steam conditioning or flat die technology without steam, and the removal of fines from the diet on feed handling characteristics and growth performance of nursery pigs.

3.3 MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used for this experiment. All dietary treatments were manufactured in accordance with CGMP's (Current Good Manufacturing Practices) at Kansas State University O.H. Kruse Feed Technology Innovation Center in Manhattan, KS.

A total of 320 nursery pigs (241 × 600, DNA Genetics, Columbus, NE) were used in a 21-d experiment at Kansas State University Swine Teaching and Research Center in Manhattan, KS. There were 5 pigs per pen and 8 pens per dietary treatment. Pigs were provided *ad libitum* access to feed and water for the duration of the trial. Each pen was equipped with one nipple waterer and dry self-feeder. On d 0 of the trial, pens were weighed and randomly assigned to 1 of the 8 dietary treatments. Pen weights and feed intake, determined by feed disappearance, were collected on d 0, 7, 14, and 21 to calculate average daily gain (**ADG**), average daily feed intake (**ADFI**), and gain to feed ratio (**G:F**).

The diets were based on the same corn-soybean meal formulation and the treatments were created by changing the corn processing and the final form of the feed (Table 3.1). The 8 treatments were: 1) ground corn diet fed as mash, 2) ground corn diet steam pelleted, 3) ground corn diet cold pelleted, 4) ground corn with fines less than 150 microns removed from the diet and the diet fed as mash, 5) ground corn with fines less than 150 microns removed from the diet and then the diet without fines was steam pelleted, 6) ground corn with fines less than 150 microns removed from the diet and then the diet without fines was cold pelleted, 7) fines less than 150 microns were steam pelleted, then proportionally added back to ground corn and fed as a mixture of mash with pel- lets, and 8) fines less than 150 microns were cold pelleted then proportionally added back to ground corn and fed as a mixture of pellets and mash.

Corn was initially ground to approximately 400 microns with a roller mill (RMS Model 924, Harrisburg, SD). A portion of this ground corn was used to manufacture dietary treatments 1, 2, and 3, while the remainder of the ground corn was sifted using a rotary horizontal sifter to remove any particles less than 150 microns. The resulting ground corn with the fines removed was approximately 622 microns and was included in dietary treatments 4, 5, and 6. The sifted fines were retained and pelleted prior to proportionally adding them back to the ground corn from which they were previously removed. The sifted fines that were pelleted were included in treatments 7 and 8.

Diets were fed either as a mash, a steam conditioned pellet, or a cold pellet. Steam conditioned pellets were manufactured on a pellet mill (California Pellet Mill, model 1112-2, Crawfordsville, IN) equipped with a 6.4 × 63.5 mm vertical ring die. Mash was conditioned at

80°C for approximately 30 seconds prior to pelleting. Cold pellets were manufactured on a flat-bed pellet mill (Amandus Kahl Model # 33-390, Reinbek, GER) equipped with a 6.4 × 30.2 mm horizontal die. Prior to pelleting with the flat bed pellet mill, mash feed passed through a blending screw where warm water (54°C) was added at a rate of 4%. Moisture and heat were removed with ambient air in a counter-flow cooler prior to bagging. Conditioned mash temperature and pellet die exit temperature (hot pellet) were measured twice during each pelleting run with a pre-warmed double-wall thermos equipped with a digital thermometer. Production rates and electrical energy use on the main PM motor were recorded during the steam and cold pellet runs with specific energy consumption (SEC) calculated according to Stark (1994).

Representative feed samples were obtained for each dietary treatment and analyzed by Ward Laboratories (Kearney, NE) for dry matter (AOAC Official Method 934.01, 2012), crude protein (AOAC Official Method 990.03, 2012), acid detergent fiber (ADF, AOAC Official Method 973.18, 2012), calcium (AOAC Official Method 985.01, 2012), and phosphorous (AOAC Official Method 985.01, 2012).

Samples of the ground corn fractions were analyzed by Ward Laboratories (Kearney, NE) for dry matter (AOAC Official Method 934.01, 2012), crude protein (AOAC Official Method 990.03, 2012), and acid detergent fiber (ADF, AOAC Official Method 973.18, 2012). Corn fraction samples were also analyzed for particle size according to dry sieving method ASAE S319.2 (ASAE, 1995). Analysis included 13 sieves, the addition of sieve agitators and 0.5 g of dispersing agent (silicon dioxide, model SSA-58, Gilson, Lewis Center, OH) per 100 g of sample with a 15 min analysis time.

The flowability characteristics of mash diets and hybrid mash/pellet diets were evaluated using results for angle of repose (**AOR**), critical orifice diameter (**COD**), and compressibility index, which were then used to calculate the composite flow index (**CFI**) as described by Taylor et al. (2000). AOR was determined by allowing material to flow from a vibratory conveyor above a free-standing platform until it reached maximum piling height. The angle that the side of the conical sample pile makes with the horizontal plane was defines as the AOR, calculated as the inverse tangent of the height of the pile divided by the platform radius. COD was determined using a powder flowability test instrument (Flodex Model WG-0110, Paul N. Gardner Company, Inc., Pompano Beach, FL) equipped with discs of varying interior hole diameters ranging from 4 to 34 mm for analysis. Compressibility index (**CI**) was calculated based on bulk density and tapped density, where the consolidated volume was measured after 7 min of agitation at a rate of 900 vibrations per minute (Fischer-Wheeler sieve shaker, model 5, Fisher Scientific Co., Pittsburg, PA).

Pellet durability index (**PDI**) was determined for pellets using the standard and modified tumble box methods according to S269.5 (ASAE, 2012). Pellets were sifted pre and post analysis with a U.S. No. 3.5 (5.6 mm) sieve for fines removal. The modified tumble box method included the addition of three 19-mm hex-nuts to the tumbling chamber to increase the agitation stress on the pellets.

At the conclusion of the trial an economic analysis was performed to determine the financial impact of the treatments. Ingredient prices from April 2016 were used for all economic calculations with corn valued at $141 per MT and soybean meal at $377 per MT. The cost of feed ($/MT) included ingredients, kwh, and boiler fuel usage when applicable. A standard price of $0.12 per kilowatt hour was used to calculate electrical energy costs for thermal processing and added to overall feed cost. The total feed cost per pig was calculated by multiplying the ADFI by the number of days on trial and the diet cost. The cost per kg of gain was calculated by dividing the total feed cost per pig by the ADG. Total revenue per pig was calculated by multiplying the ADG by the number of days on trial and the assumed live price of $1.14 per kg. Finally, the total feed cost per pig was subtracted from the total revenue per pig to calculate the income over feed cost (**IOFC**).

Data were analyzed using the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC) with pen as the experimental unit as a completely randomized design. Results were considered significant if $P \leq 0.05$, and a trend if $0.05 < P \leq 0.10$. Orthogonal contrasts were used to evaluate interactions between steam vs. cold pelleted diets, and steam or cold pellet vs. mash diets.

3.4 RESULTS AND DISCUSSION

3.4.1 Diet

The flowability characteristics of mash diets and combination mash/pellet diets were evaluated based on the CFI, which characterizes flow property by integrating the results of several different flow tests, including AOR, COD, and CI (Table 3.4). In general, a greater CFI value is indicative of a better flowing product (Horn, 2008). Applying this methodology and scale to the data, removal of fine particles less than 150 µm from the ground corn had minimal improvement on the overall flowability of the mash diet when compared to using the entire ground corn fraction with the fines included (CFI, 66.0 vs. 64.4, respectively). However, the CFI was improved by steam or cold pelleting the fine corn particles (CFI, 71.7 and 72.3, respectively). In this study, the improvement in CFI as a result of fines removal was less than the improvement observed by Kalivoda (2016), in which CFI was improved when corn was fractioned to particles greater than 630 µm (CFI, 80) compared to the composite of ground corn of 400 µm (CFI, 71). While increased fines resulting from current fine grinding practices may result in poor flowability of feed both in the manufacturing process and on the farm, improvement of flowability can be achieved through removal or pelleting of the fines and returning them to the mash diets. Ultimately, pelleting the fines and including them in the diet would be ideal for feed manufacturers, as it results in no grain waste and an overall improvement in flowability when compared to both mash diets.

The electrical consumption per MT was different for steam and cold conditioned pelleting. SEC was reduced for cold conditioned pellets regardless of the corn fraction (15.3, 17.5, and 38.8 kWh/MT) when compared to steam pelleting (16.7, 13.2, and 40.4 kWh/MT). This was likely due to the thinner die (lower L:D) and increased production rate observed on the flat-bed PM. SEC was considerably increased when pelleting the fine corn particles with either PM compared to complete diets. The fines were difficult to pellet, and throughput was decreased in an effort to improve pellet quality. Increased hot pellet temperatures measured after the die and before cooling indicated increased friction between the material and surface of the die hole. This slowed throughput and in extreme cases, over- loaded the pellet mill motor. Differences in PDI were also observed based on conditioning and pelleting technique. Cold condition pelleting resulted in a lower standard and modified-PDIs compared to steam pelleting. The lower PDI values could be a result of a lower effective thickness to pellet die hole diameter ratio (L:D) of the die, which would have resulted in less compression. Additionally, the lack of steam likely reduced the binding potential of the protein and starch fractions in the diet leading to weaker pellets (Thomas, et al., 1996). Subsequent studies are needed to further examine die specifications and conditioning parameters on pellet quality. The PDI of the pelleted fines was low for both the steam and cold conditioned pellet methods (62.2 and 25.6%, respectively). The low L:D ratio (4.8) of the die used to pellet the cold conditioned fines resulted in weak pellets, but another die was not available at the time of manufacturing and this lack of available equipment created a significant difference in feed quality, and ultimately feed wastage. Subsequent studies are needed to determine the optimal die specifications when pelleting fine corn particles with the flat-bed PM.

All diets were analyzed post processing (Table 3.3). Analyses were consistent with formulated values and were similar across treatments. Overall, removal of the corn fines fraction did not alter the nutrient composition of the diets; however, ADF values were the most variable in diets where the fine corn particles were removed. This may be explained by increased levels of ADF in the analyzed upper fraction of the ground corn (Table 3.2) used to manufacture these diets. There is no clear explanation for why these values were increased with steam pelleting when compared to the meal and cold pelleted diets.

3.4.2 Growth Performance

Overall, there were no growth performance differences between pigs fed mash with ground corn or ground corn with fines removed. This was consistent with diet analysis and suggests that the fine corn particles can be removed with no impact on performance.

Pigs fed steam or cold pelleted diets had decreased ($P < 0.001$) ADG, ADFI, and d-21 BW compared to pigs fed mash diets. This is similar to observations of Lewis et al. (2013), in which authors could only postulate on the reason behind the reported decreases in ADG and ADFI along with static G:F between pigs fed pelleted and mash diets. Based on the majority of research comparing pelleted and mash diets in nursery pigs, one would expect G:F to be improved with pellets in response to reduced ADFI, measured as lower feed disappearance or wastage (Stark, 1994; Groesbeck et al., 2009; Nemechek et al., 2015; Harrison et al., 2019). In this trial, however, both ADFI and ADG were negatively impacted by pelleting, with no measured improvement in G:F. It remains unclear why pigs fed mash diets had greater ADG and ADFI. The authors can only speculate that there was a negative impact on palatability of the pellets. Perhaps the 6 mm diameter pellets produced by steam and cold pelleting impeded feed intake, though Clark et al. (2016) fed larger, 12 mm diameter pellets at a similar age and reported no issue in comparison to a smaller 3 mm diameter pellet. As expected, pigs fed steam or cold pellet diets had decreased ($P < 0.016$) feed cost per pig, total revenue, and IOFC as a result of depressed ADFI and ADG, respectively compared to pigs fed mash diets.

When comparing pelleting techniques, pigs fed steam pelleted diets had decreased ($P < 0.006$) ADG, d-21 BW, revenue and IOFC, with a tendency ($P < 0.089$) for decreased ADFI and total feed cost compared to cold pelleted diets. These findings disagree with Lundblad et al. (2011) who observed no difference in ADG, ADFI, or G:F when feed was conditioned at 47°C versus 90°C. These conditioning temperatures were similar to parameters used in this trial where 54°C water was added prior to cold pelleting and 80°C steam was used prior to steam pelleting. In addition to changes in conditioning, the vertical ring die used for steam pelleting had a greater effective thickness when compared to the horizontal die used for cold pelleting (63.5. mm and 35.1 mm, respectively). Greater effective thickness is associated with an increased amount of shear on the material during compaction or pressing (Thomas et al., 1996). While it is possible that increased frictional heat with the thicker die may have negatively impacted nutrient quality, available feed analysis does not support this theory. There was a small numerical increase in PDI with steam pelleted diets that may have contributed to reduced palatability, though this seems unlikely due to the relatively small PDI difference between diets.

Pigs fed diets with steam and cold pelleted fine corn particles added back to the formulation had increased ($P < 0.020$) ADFI and poorer G:F; culminating in increased total feed cost and lower IOFC when compared to all other treatments. It is likely that the observed increase in ADFI is a consequence of increased feed wastage caused by pigs sorting pellets from the pellet and mash diets. Preferential selection of pellets by the pig is well documented and is often discussed in reference to low-quality pelleted feeds (Myers et al., 2013). In the current trial, disproportionate intake of the pelleted corn fines versus the complete mash diet would theoretically result in underconsumption of essential nutrients for growth like protein. The authors also speculate that the intake level of the corn pellets may differ between diets with steam pelleted fines and cold pelleted fines based on pellet quality. Steam pelleted corn fines had greater PDI than cold pelleted corn fines (62 vs 26%), indicating a higher probability that steam pellets would remain intact until reaching the pig where they would be preferentially selected. This theory may explain why pigs fed steam pelleted fine corn in combination with the mash diet had increased ADFI, lower ADG and poorer G:F compared to pigs fed cold pelleted fine corn in combination with the mash diet. It is also important to note that feeder management was also a challenge with pigs fed diets with fines pelleted and added back to the mash. It was necessary to set feeder gaps that allowed passage of the 6 mm diameter pellet, which, in turn, increased the mash flow and likely encouraged sorting behavior and feed wastage.

3.5 CONCLUSIONS

The results of this study indicate that removing particles less than 150 microns had minimal improvement on the flowability of a mash diet with no difference in growth performance. Additionally, cold pelleting was a viable option to steam pelleting in the current experiment. However, pelleting diets with either pelleting process reduced pig performance compared to pigs fed mash diets. This poorer performance from pelleted diets is unexpected and further research is needed to validate the response to cold pelleting when the expected response to pelleting using steam conditioning is achieved.

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Table 3.1. Basal diet composition (as-fed basis) for phase 3 nursery pigs[1]

Ingredient, %	Basal diet
Corn[2]	62.61
Soybean meal	33.98
Monocalcium phosphate, 21% P	1.15
Limestone	0.95
Sodium chloride	0.35
L-Lysine HCl	0.30
DL-Methionine	0.12
L-Threonine	0.12
Trace mineral premix[3]	0.15
Vitamin premix[4]	0.25
Phytase[5]	0.02
Total	100.00
Calculated analysis	
Crude protein, %	21.7
ME, kcal/kg	1483
SID Lysine,%	1.24
Total Lysine, %	1.39
SID Lysine: ME g/Mcal	3.79
Calcium, %	0.70
Phosphorous, %	0.65
Available P, %	0.43

[1] A single diet formulation was manufactured using specified ground corn fractions and then processed using different pelleting techniques to create 8 dietary treatments.

[2] Dependent on treatment, the entire composite corn fraction, the upper corn fraction with fines removed, or the entire corn fraction with fines pelleted was used.

[3] 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}.

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

[5] Provided 780 phytase units (FTU)/kg, with a release of 0.11% available P.

Table 3.2. Analyzed nutrient content (as-fed basis) and particle size of ground corn fractions[1]

	Ground Corn Composite	Ground Corn Upper Fraction	Ground Corn Fines Fraction
Analyzed Nutrient			
Dry matter, %	87.1	87.5	87.3
Crude protein, %	7.7	8.4	5.5
Crude fat, %	2.6	2.7	1.4
Acid detergent fiber, %	1.8	2.5	0.7
Particle Size[2]			
d_{gw}, µm	400	622	126
S_{gw}	2.49	2.12	1.85

[1] A single diet formulation was manufactured using specified ground corn fractions and then processed using different pelleting techniques to create 8 dietary treatments.

[2] Geometric mean diameter (d_{gw}) and standard deviation (S_{gw}) calculated according ASAE standard S319.2 with agitators and dispersing agent.

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

	Ground Corn[2]			Ground Corn with Fines Removed[3]			Ground Corn with Fines Pelleted[4]	
	Mash	Steam Pellet[5]	Cold Pellet[6]	Mash	Steam Pellet	Cold Pellet	Mash with Fines Steam Pelleted	Mash with Fines Cold Pelleted
Dry matter, %	88.57	88.58	88.92	88.07	88.91	88.77	89.14	89.18
Crude protein, %	23.00	22.30	22.80	22.00	22.30	22.40	23.00	23.00
Acid detergent fiber, %	3.00	3.30	2.50	2.60	4.10	3.40	2.90	2.80
Calcium, %	0.83	0.85	0.85	0.97	0.85	0.90	0.92	0.86
Phosphorous, %	0.60	0.69	0.69	0.67	0.72	0.70	0.65	0.72

[1] A single diet formulation was manufactured using specified ground corn fractions and then processed using different pelleting techniques to create 8 dietary treatments.
[2] Ground corn particle size of 400 microns.
[3] Ground with fines removed via sifting, remaining fraction particle size of 622 microns.
[4] Ground with fines removed via sifting, followed by. Pelleting prior to being proportionally being added back.
[5] Steam conditioned for approximately 30 s at 80°C and pelleted (California Pellet Mill Model #1112-2, Crawfordsville, IN) with a 6.4 mm × 63.5 mm vertical die.
[6] Blended with 4% water (54°C) and pelleted (Amandus Kahl Model 33-390, Reinbek, GER) with a 6.4 mm × 35.1 mm horizontal die.

Table 3.4. The effect of corn fraction and pelleting technique on flowability characteristics, pelleting parameters, and pellet quality[1]

	Ground Corn[2]			Ground Corn with Fines Removed[3]			Ground Corn with Fines Pelleted[4]	
	Mash	Steam Pellet[5]	Cold Pellet[6]	Mash	Steam Pellet	Cold Pellet	Mash with Fines Steam Pelleted	Mash with Fines Cold Pelleted
Flowability[7]								
AOR, °	32.1	----	----	32.3	----	----	30.6	29.0
COD, mm	32.0	----	----	30.0	----	----	28.0	26.0
CI, %	4.6	----	----	5.4	----	----	1.9	5.9
CFI	64.4	----	----	66.0	----	----	71.7	72.3
Prod. Rate, MT/h	----	0.71	1.09	----	0.87	0.99	0.41	0.49
SEC,[8] kWh/MT	----	16.7	15.3	----	17.5	13.2	40.4	38.8
Temperature, °C								
Cond. Mash	----	82.5	46.2	----	82.4	45.2	60.5	44.4
Hot Pellet		89.0	51.6	----	88.9	50.9	86.9	57.2
PDI,[9] %								
Std. Tumble	----	90.1	86.6	----	89.7	84.9	74.0	34.8
Mod. Tumble	----	84.6	78.3	----	80.9	79.4	62.2	25.6

[1] A single diet formulation was manufactured using specified ground corn fractions and then processed using different pelleting techniques to create 8 dietary treatments.
[2] Ground corn particle size of 400 microns
[3] Ground with fines removed via sifting, remaining fraction particle size of 622 microns.
[4] Ground with fines removed via sifting, followed by. Pelleting prior to being proportionally being added back.
[5] Steam conditioned for approximately 30 s at 80°C and pelleted (California Pellet Mill Model #1112-2, Crawfordsville, IN) with a 6.4 mm × 63.5 mm vertical die.

[6] Blended with 4% water (54°C) and pelleted (Amandus Kahl Model 33-390, Reinbek, GER) with a 6.4 mm × 35.1 mm horizontal die.

[7] Individual test results from angle of repose (AOR), critical orifice diameter (COD), and compressibility index (CI) were weighted and transformed according to Taylor et al. (2000) to characterize product flowability.

[8] Specific energy consumption (SEC) calculated according to Stark (1994) based on production rate and average pellet mill motor amperage.

[9] Pellet durability index (PDI) determined using the standard and modified tumble box methods according to ASAE S269.4 with three 19 mm hex nuts included for modification.

Table 3.5. Effects of corn fraction and pelleting technique on nursery pig growth performance and economic value[1]

	Ground Corn			Ground Corn with Fines Removed			Ground Corn with Fines Pelleted			Probability, *P* <			
	Mash	Steam Pellet	Cold Pellet	Mash	Steam Pellet	Cold Pellet	Mash with Fines Steam Pelleted	Mash with Fines Cold Pelleted	SEM	Trt	Steam Pellet vs. Cold Pellet	Steam Pellet vs. Mash	Cold Pellet vs. Mash
BW, kg													
d 0	10.2	10.2	10.2	10.2	10.2	10.3	10.3	10.2	0.40	1.000	0.935	1.000	0.842
d 21	22.2[a]	19.5[c]	20.8[abc]	22.1[a]	19.6[c]	21.2[ab]	19.4[c]	20.5[bc]	0.63	0.001	0.006	0.002	0.009
d 0 to 21													
ADG, g	557[a]	440[c]	501[b]	568[a]	444[c]	523[ab]	436[c]	489[bc]	19.3	0.001	0.001	0.001	0.001
ADFI, g	814[c]	673[d]	709[d]	831[c]	677[d]	761[cd]	1051[a]	947[b]	33.6	0.001	0.073	0.004	0.008
G:F	0.69[a]	0.65[a]	0.71[a]	0.68[a]	0.66[a]	0.69[a]	0.43[c]	0.53[b]	0.02	0.020	0.078	0.818	0.676
Cost analysis													
Feed cost[2]	222.83	226.46	225.38	222.83	226.41	225.50	227.18	225.73	---	---	---	---	---
Total feed cost[3]	4.20[c]	3.53[d]	3.70[d]	4.29[c]	3.55[d]	3.97[dc]	5.53[a]	4.95[b]	0.176	0.001	0.089	0.008	0.016
Cost[4]	0.36[c]	0.38[c]	0.35[c]	0.36[c]	0.38[c]	0.36[c]	0.61[a]	0.49[b]	0.023	0.001	0.311	0.726	0.682
Total revenue[5]	13.35[a]	10.54[c]	11.98[b]	13.60[a]	10.62[c]	12.51[ab]	10.45[c]	11.70[bc]	0.463	0.001	0.001	0.001	0.001
IOFC[6]	9.16[a]	7.01[bc]	8.29[ab]	9.31[a]	7.07[bc]	8.54[a]	4.92[d]	6.75[c]	0.451	0.001	0.004	0.008	0.009

[1] A total of 320 pigs (DNA 241 x 600) were used in a 21-d experiment to evaluate the effects of corn fraction and pelleting technique on nursery pig performance. Dietary treatments (8) were manufactured using either the entire composite corn fraction, the upper corn fraction with fines removed, or the entire corn fraction created by pelleting the fines and then proportionally adding them back to the upper corn fraction from which they were previously removed. Diets were fed as mash, steam or cold pellet, or a hybrid mash/pellet combination.

[2] Standardized cost, $/ton, for time of feed manufacture: corn $141 per MT, soybean meal $377 per MT, electricity $0.12 per kwh.

[3] Total feed cost per pig calculated as feed cost times feed consumed per pig.

[4] Cost per kg of gain calculated as total feed cost divided by total gain per pig.

[5] Total revenue per, $/pig, where 1 kg of live weight gain was estimated to be worth $1.14.

[6] Income over feed cost, $, (IOFC) calculated as total revenue per pig minus feed cost per pig.

[a-e] Means with different superscripts are significantly different ($P \leq 0.05$).

Chapter 4 - Effect of pellet fines level on the growth performance of finishing pigs

4.1 ABSTRACT

A total of 200 finishing pigs (241 × 600, DNA Genetics, Columbus, NE), initially 64 kg BW, were used in a 56 -d experiment to determine the effects of increasing pellet fines on finishing pig growth performance. Pens of pigs were allotted to 1 of 5 dietary treatments, with 3 gilts and 2 barrows per pen and 8 pens per treatment. Dietary formula was constant across all treatments with feed form altered. Treatments consisted of mash control diet, pelleted diet with 20% fines, pelleted diet with 40% fines, pelleted diet with 60% fines, and pelleted diet with alternating fines levels between 20, 40 and 60%. Overall, there were no observed differences ($P > 0.131$) in ADG, ADFI or d-56 BW between pigs fed mash or pelleted diets, regardless of the percent fines or feeding duration. However, pigs continuously fed the same pellet quality throughout the trial tended (linear, $P = 0.055$) to have reduced ADG in response to increasing fines levels in the diets. This supported a tendency ($P = 0.070$) for poorer G:F in pigs continuously fed pelleted diets containing 30 or 40% fines compared to pigs fed mash or diets with rotated fines level, with pigs continuously fed 20% fines intermediate. The results of this study indicate that pelleting feed for finishing pigs does not improve animal performance compared to mash diets. Further, diets containing more than 40% pellet fines were shown to depress G:F compared to mash. Thus, pellet quality should remain an important consideration when pelleting diets for swine.

Key Words: pelleting, pellet fines, pellet quality, finishing pig

4.2 INTRODUCTION

Manufacturing pelleted animal feed has many advantages compared to mash diets, including increased bulk density, reduced component segregation, and improved handling characteristics (Thomas et al., 1996). While these numerous improvements are appealing, they are incurred at additional cost, typically stemming from equipment investment and increased energy usage. Thus, for pelleting to remain a feasible option, there must be improvements in animal performance that compensate for the increased cost of manufacture.

The main benefits for feeding pelleted feed to swine are improvements in both gain and feed efficiency compared to mash diets (Wondra, 1995; Potter et al., 2010; Paulk et al., 2011; De Jong et al., 2013). Wondra (1995) estimated that pelleted diets resulted in a 4 to 6% improvement in ADG compared to feeding mash. Researchers continue to debate the reason behind the pelleting response with theories including enhanced feed palatability, reduced feed wastage, and a possible improvement in nutritional value as a result of thermal treatment (Skoch et al., 1983 and Wondra, 1995). Additional reports have also shown the impact of pellet quality on the magnitude of the pelleting response. Stark (1994) reported a tendency for 6% reduction in G:F when fines were increased from 0 to 60% of a finishing diet for swine. Similarly, Nemechek (2012) observed a 7% reduction in G:F when fines increased from approximately 10 to 50% of a finishing diet. Both studies emphasized the importance of maintaining pellet quality with low percent fines to capture the full performance benefits of feeding pellets to swine.

Manufacturing strategies associated with reducing fines include increasing the conditioning time and temperature, increasing the pellet die thickness, and reducing pellet mill throughput. These options, however, require additional time and sometimes equipment, which may not be feasible in a production system that is already operating at capacity. The constraints placed on the manufacturing process either because of lack of time or equipment can lead to variable pellet quality. Thus, depending on the manufacturing and even downstream handling, pigs may receive diets of various pellet qualities over time. It is unclear how pellet quality variation over time will affect pig performance in finishing.

Therefore, the objectives of this trial were to determine how the level and variation over time of pellet fines impacts the growth performance of finishing pigs.

4.3 MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. Pigs were housed the Kansas State University Swine Teaching and Research Center in Manhattan, KS in an environmentally controlled finishing building. Each pen (1.52 m × 2.44 m) was equipped with a single hole, dry self-feeder (Farmweld, Teutopolis, IL) and 2 nipple waterers to provide *ad libitum* access to feed and water. Pens had concrete slatted flooring with a pit for manure storage. Pigs were fed a common corn-soybean meal mash diet for approximately 20 d upon entering the facility, until pigs reached their starting weights.

A total of 200 finishing pigs (241 × 600, DNA Genetics, Columbus, NE), initially 64 kg BW were used in a 56 -d experiment. Pens of pigs were allotted to 1 of 5 dietary treatments, with 3 gilts and 2 barrows per pen and 8 pens per treatment. Pigs and feeders were weighed every 14 d to calculate average daily gain (**ADG**), average daily feed intake (**ADFI**), and gain to feed ratio (**G:F**). Dietary formulation was constant across all treatments with feed form altered. Treatments consisted of a mash control diet, pelleted diet with 20% fines, pelleted diet with 40% fines, pelleted diet with 60% fines, and pelleted diet with alternating fines levels between 20, 40 and 60%. In the last treatment fines level was rotated weekly for the 56-d trial period as follows: 60, 20, 40, 20, 20, 40, 20, 60% fines, respectively.

Diets were manufactured in accordance with CGMP's (current Good Manufacturing Practices) at Kansas State University O.H. Kruse Feed Technology Innovation Center in Manhattan, KS. Corn was ground with a roller mill (RMS Model 924, Sioux Falls, SD) and particle size (approximately 550 microns) was identical across treatments. Feed was mixed in 909 kg batches in a 1.63 m^3 twin shaft counterpose mixer (Hayes and Stolz, model TRDB63-0152, Fort Worth, TX). Dry ingredients were mixed for 60 s prior to the addition of liquid fat and then mixed for an additional 120 s. Pelleted diets were manufactured on a 100 HP pellet mill (CPM, model 3016-4 Master, Crawfordsville, IN) equipped with a 4 mm diameter × 35 mm effective length die and a target production rate of 4.5 MT/h. Prior to pelleting, feed was conditioned for approximately 30 s at 77°C in a single pass conditioner with a steam pressure of 1.52 bar. Pellets were recirculated through the mixer to generate additional fines via mechanical breakdown prior to screening (EBM Manufacturing, Inc., model 244BDGFF, Norfolk, NE) to remove and collect fines smaller than 3.1 mm. Recovered fines were then mixed with the sifted pellets to achieve the desired pellet to fine ratio. Feed was sacked to avoid possible fines segregation prior to reaching the feeder. To ensure correct pellet to fine ratio, 2 feed sacks were randomly selected from each treatment and the percent fines measured based on the material able to pass through a U.S. No. 6 (3.4 mm) sieve. Pellet durability index (**PDI**) was determined for phase 1 and phase 2 pellets using the standard and modified tumble box methods according to S269.5 (ASAE, 2012). Pellets were sifted pre and post analysis with a U.S. No. 6 (3.4 mm) sieve for fines removal. The modified tumble box method included the addition of three 19-mm hex-nuts to the tumbling chamber to increase the agitation stress on the pellets.

Feed samples were taken at the feeder during each phase and composited for analysis. All diets were analyzed for dry matter (AOAC Official Method 934.01, 2012), crude protein

(AOAC Official Method 990.03, 2012), acid detergent fiber (ADF, AOAC Official Method 973.18, 2012), calcium (AOAC Official Method 985.01, 2012), and phosphorous (AOAC Official Method 985.01, 2012) by Ward Laboratories (Kearney, NE).

Data were analyzed using the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC) with pen as the experimental unit as a randomized complete block. design. Linear and quadratic contrasts were utilized to test the response to increasing pellet fines in the diet. Results were considered significant if $P \leq 0.05$, and a trend if $0.05 < P \leq 0.10$.

4.4 RESULTS AND DISCUSSION

Chemical analysis of diets (Table 4.2) indicated slightly elevated levels of CP in Phase 1 (18.0 to 18.4%) and Phase 2 (15.7 to 16.8%) compared to formulated values (Table 4.1; 15.5 and 13.8%, respectively). The overall, consistent level in CP across treatments indicate that there was simply a difference in the actual CP of ingredients used to manufacture the diets compared to the theoretical matrix value used for formulation. Analysis of the percent fines in Phase 1 (27.2, 44.7, and 63.3%) and Phase 2 (25.8, 46.9, and 64.1%) agreed with planned treatment levels of 20, 40, and 60% fines inclusion.

Overall, there were no observed differences (Table 4.3; $P > 0.131$) in ADG, ADFI or d-56 BW between pigs fed mash or pelleted diets, regardless of the percent fines or feeding duration. However, pigs continuously fed the same pellet quality throughout the trial tended (linear, $P = 0.055$) to have reduced ADG in response to increasing fines levels in the diets. This supported a tendency ($P = 0.070$) for poorer G:F in pigs continuously fed pelleted diets containing 40 or 60% fines compared to pigs fed mash or diets with rotated fines level, with pigs continuously fed 20% fines intermediate.

The lack of overall pelleting response observed in the current trial is similar to observations of Stark (1994) who reported no differences ($P > 0.05$) in ADG, ADFI, or G:F when feeding pelleted diets with a range of 0 to 60% fines compared to mash. This is in contrast to the majority of research comparing pelleted and mash diets in finishing pigs, which have shown significant improvements ($P < 0.05$) ranging from 4 to 6% and 5 to 7% in ADG and G:F with pellets, respectively (Wondra et al., 1995; Hancock and Behnke, 2001; Potter et al., 2001; Paulk et al, 2011; Nemechek et al., 2015b;). The most likely reason for the deviation from this response in the current study and Stark (1994) is the poor pellet quality, which negated any observable benefits of pelleting when compared to mash.

Previous studies have observed inconsistencies in growth response when feeding pellets with different levels of fines. Pacheco Dominguez (2014) reported no difference ($P > 0.05$) in ADG, ADFI, and G:F when feeding a sifted pellet diet analyzed at 10.2 to 12.6% fines and a poor-quality pellet diet analyzed at 28.3 to 33.2% fines. This supported work by Starkey et al. (1991) who reported no impact on ADG, ADFI, and G:F as fines level increased from 16 to 27% of the diet. These studies indicate that feeding up to 30% fines, the maximum level observed in the trials, in a finishing diet would not affect performance. Additionally, Langdon (2015) fed diets with 0, 15, 30, 45, and 60% fines to finishing pigs with no observed difference in gain or feed efficiency, indicating that the acceptable fines level may be greater than 30% in finishing pigs. This contrasted previous work by Stark (1994), who fed fines levels of 0, 20, 40, and 60% and observed a linear trend for lower G:F as fines level increased. Similarly, Schell and van Heugten (1998) observed a linear depression in G:F when feeding 2.5, 13, 25, and 40% fines to growing pigs. Both Stark (1994) and Schell and van Heugten (1998) fed fines generated from the mechanical breakdown of pellets, while Langdon (2015) manufactured fines by grinding intact pellets. This may have contributed to the observed differences in response, as fines resulting from the normal deterioration of pellets have previously been shown to have different composition compared to intact pellets (DeJong et al., 2017). The possible changes in nutrient profile between fines and pellets would not have occurred in Langdon (2015) as a result of grinding intact pellets for fines generation.

In the present study, differences in nutrient content of fines versus pellets may have contributed to the tendency for reduced ADG as naturally occurring fines increased from 20 to 60% of the diet. Though nutrient content of fines and pellets were not directly measured in the current experiment, based on analysis of single composite samples of the complete diets, CP was 0.39% and 1.08% lower in Phase 1 and 2, respectively as fines increased from 20 to 60% of the diet. The authors recognize that analyzed levels of CP were in excess compared to formulated levels set to meet the needs of the pig and not likely to have impacted gain in this trial; however, this confirms that fines and pellet composition can vary and may impact performance as a result. The authors agree with De Jong et al. (2017) that nutrient differences may possibly arise as a result of fines level, but, at this time, it remains unclear what the potential impact on growth performance could be and warrants further evaluation. The authors speculate that the impact of fines level on growth performance may be more evident in diets formulated with small margins relative to pig requirements or when applying fat or enzymes post pelleting.

Feeder management may have also impacted the current study as well as previously published work. Feeders in the present study were adjusted to achieve approximately 75% pan coverage. For pens receiving pellets with fines level rotated weekly, feeders were emptied prior to the diet change and not adjusted for 24 hr post change. Increasing fines level in the diet corresponded with a visual increase of fines build up in the feed pans. In agreement with observations by Stark (1994) and Nemechek et al. (2015a), perhaps this was a consequence of the preferential selection of pellets by the pig (Myers et al., 2013). Though, similar intake across pigs fed 20, 40, and 60% fines continuously does not indicate a difference in feed wastage or sorting behavior within the pelleted diets, comparison with pigs fed diets with rotating fines level indicate otherwise. When feeders were cleaned weekly in preparation for a diet change, any accumulated fines from the previous diet would have been removed, whereas pens receiving the same fine levels for the duration of the trial would have continued to accumulate fines. A reduction in wastage due to sorting would explain the numerically lower ADFI (3.69 kg) in pigs fed rotating pellet quality versus pigs consistently fed 20, 40, or 60% fines (3.90, 3.95, and 3.94 kg, respectively). Furthermore, it would support the observed tendency for improved G:F in pigs fed mash and rotating pellet quality compared to 40 and 60% fines diets, which would have the greatest theoretical fines accumulation in the feeder. In hindsight, the authors should have allowed previous diets to remain in the feeder and continued to add feed to them, as that would be the most realistic compared to industry. Data from this study emphasize the importance of feeder management, especially when feeding low quality pellets, and agree with similar conclusions of Nemechek et al (2015a), Myers et al. (2013), and Stark (1994).

4.5 CONCLUSIONS

Under the constraints of the current trial, pelleting feed for finishing pigs did not improve animal performance compared to mash diets. When pellet fines exceeded 40%, G:F was negatively impacted compared to mash. The response to increased levels of pellet fines indicates a need for further research into the impact of pellet quality on finishing pig performance.

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Table 4.1. Diet composition of experimental diets (as-fed basis)[1]

Item	Phase 1	Phase 2
Ingredient, %		
Corn[2]	77.43	81.77
Soybean meal	18.44	14.25
Choice white grease	1.50	1.50
Monocalcium phosphate, 21% P	0.80	0.80
Limestone	0.88	0.85
Sodium chloride	0.35	0.35
L-Lysine HCl	0.26	0.22
DL-Methionine	0.02	0.00
L-Threonine	0.05	0.05
L-Tryptophan	0.003	0.003
Trace mineral premix[3]	0.13	0.10
Vitamin premix[4]	0.13	0.10
Total	100.00	100.00
Calculated analysis		
Standard ileal digestible (SID) AA, %		
Lys	0.83	0.70
Ile:Lys	63.74	65.59
Met:Lys	29.23	29.54
Met + Cys:Lys	56.47	59.27
Thr:Lys	61.21	64.44
Trp:Lys	18.12	18.19
Val:Lys	72.18	75.89
Total Lys, %	0.94	0.80
ME,[6] kcal/kg	3374	3379
NE,[7] kcal/kg	2573	2599
SID Lys:ME, g/Mcal	2.46	2.07
CP, %	15.47	13.78
Ca, %	0.55	0.52

P, %	0.50	0.49
Available P, %	0.23	0.23

[1] Phase 1 diets were fed from approximately 55 to 90 kg and Phase 2 from 90 to 130 kg.
[3] 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}.
[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

Table 4.2. Analyzed diet composition and physical analysis (as-fed basis) [1]

	Phase 1				Phase 2			
		Fines Inclusion, %				Fines Inclusion, %		
	Mash	20	40	60	Mash	20	40	60
Analyzed nutrient								
Dry matter, %	88.91	89.16	88.58	88.05	89.34	88.72	89.08	88.79
Crude protein, %	18.42	18.38	17.95	17.99	16.61	16.76	15.88	15.68
Acid detergent fiber, %	2.6	2.3	2.2	2.5	2.1	1.9	2.4	2.3
Calcium, %	0.62	0.63	0.65	0.63	0.58	0.61	0.60	0.59
Phosphorous, %	0.58	0.53	0.55	0.61	0.64	0.62	0.59	0.66
Physical analysis								
Fines[2], %	---	27.2	44.7	63.3	---	25.8	46.9	64.1
PDI[3], %								
Std. Tumble	---	--------------- 82.3 ----------------			---	---------------- 80.8 ----------------		
Mod. Tumble	---	--------------- 74.6 ----------------			---	---------------- 73.3 ----------------		

[1] Phase 1 diets were fed from approximately 55 to 90 kg and Phase 2 from 90 to 130 kg.
[3] Percentage fines characterized as the material able to pass through a U.S. No. 6 (3.4 mm) sieve.
[9] Pellet durability index (PDI) determined using the standard and modified tumble box methods according to ASAE S269.4 with three 19 mm hex nuts included for modification.

Table 4.3. Effects of corn fraction and pelleting technique on nursery pig growth performance[1]

		Fines Inclusion, %			Alternating 20, 40, 60%		Probability, $P <$		
	Mash	20	40	60	Fines[2]	SEM	Trt	Fines Linear	Fines Quadratic
Initial BW, kg	63.95	63.97	64.05	64.04	64.03	1.013	1.000	0.959	0.977
Final BW, kg	132.62	133.32	130.92	131.36	132.37	1.302	0.696	0.295	0.379
ADG, kg	1.21	1.24	1.19	1.20	1.22	0.013	0.159	0.055	0.108
ADFI, kg	3.71	3.90	3.95	3.94	3.69	0.092	0.131	0.740	0.784
G:F	0.327	0.319	0.305	0.306	0.332	0.007	0.070	0.264	0.426

[1] A total of 320 pigs (DNA 241 x 600) were used in a 56-d study with 5 pigs per pen and 8 pens per treatment.
[2] Fines level was rotated weekly for the 56-d trial period as follows: 60, 20, 40, 20, 20, 40, 20, 60% fines, respectively.