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

Caitlin E. Evans, * Marut Saensukjaroenphon, * Jordan T. Gebhardt, † Charles R. Stark, * and Chad B. Paulk**

*Department of Grain Science and Industry, College of Agriculture, Kansas State University, Manhattan, KS, 66506, United States.

†Department of Diagnostic Medicine/Pathobiology, College of Veterinary Medicine, Kansas State University, Manhattan, KS, 66506, United States.

1 Contribution no. 21-176-J from the Kansas Agric. Exp. Stn., Manhattan, KS 55606-0210
2 Corresponding author: cpaulk@ksu.edu

© The Author(s) 2021. Published by Oxford University Press on behalf of the American Society of Animal Science.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (http://creativecommons.org/licenses/by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact journals.permissions@oup.com
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 $2 \times 3$ 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 $2 \times 2$ 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 as 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
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 (Behnke, 2001; Cutlip et al., 2008; Mohensin and Zaske, 1976; Thomas et al., 1997). 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).

**Materials and Methods**

**Feed Manufacturing**

A total of 41 MT of a swine finishing diet (Table 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 m³ 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 Master, Crawfordsville, IN) equipped with a 4.8 mm diameter × 44.5 mm effective length die (Table 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 1800, 1350, and 900 rpm, respectively (Table 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.
Data Collection

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):

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

where I is average motor amperage,

E is voltage,

PF is power factor set to 0.85,

PR is production rate expressed in MT/h.

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:

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):

\[
PDI (%) = \frac{\text{Recovered Pellet Weight}}{\text{Initial Pellet Weight}} \times 100
\]

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 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. 3, the same manner as the tumble box method. All samples were analyzed in duplicate and results averaged.

**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.

\[
\text{Stability} \ (\%) = \frac{R_S}{R_{\text{Avg}}} \times 100
\]

Eq. 4

where \( R_S \) is the enzyme recovery of the individual sample,

\( R_{\text{Avg}} \) is the average enzyme recovery of the desired reference sample group.

**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 \( P \leq 0.05 \).
Results and Discussion

Feed Manufacturing

The effect of conditioning temperature and die speed on pelleting parameters are shown in Table 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 in 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 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 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.

**Pellet Durability**

Pellet durability index was assessed using both mechanical (tumble box) and pneumatic (NHP 100) agitation (Table 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.

**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 affect 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 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 pressing process at 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 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.
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.

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.
Literature Cited

AOAC International. 2006. Official methods of analysis. 18th ed. Assoc. Off. Anal. Chem. Soc., Champaign, IL.

ASAE. 1995. Method of determining and expressing fineness of feed materials by sieving. ASAE Standard S319.2. pp. 646-649. ASABE. St Joseph, MI.

ASAE. 2012. Densified products for bulk handling – definitions and method. ASAE Standard S269.5, pp. 91. ASABE. St. Joseph, MI.

Behnke, K. C. 2001. Factors influencing pellet quality. Feed Tech. 5: 19-22.

Bychkov, A. L., V. A. Bukhtoyarov, and O. I. Lomovsky. 2011. Denaturation of cellulolytic enzymes in the presence of water. Chemistry for Sustainable Development, 19: 441-445.

Cutlip, S. E., J. M. Hott, N. P. Buchanan, A. L. Rack, J. D. Latshaw, and J. S. Moritz. 2008. The effect of steam-conditioning practices on pellet quality and growing broiler nutritional value. J. Appl. Poult. Res. 17:249-261.

Kort, R., H. Wecker, C. Fiehler, A. Ogles, J. Froetschner, C. Stark, and C. Paulk. 2020. Moisture content throughout the pelleting process and subsequent effects on pellet quality. J. Anim. Sci. 98 (Suppl. S3): 228. doi.org/10.1093/jas/skaa054.399.

Leaver, R. H. 1988. The Pelleting Process. Andritz Sprout Inc., Muncy, PA.

Mohensin N. and J. Zaske. 1976. Stress relaxation and energy requirements in compaction of unconsolidated materials. J. Agric. Eng. Res. 21: 123-205.

Perdana, J., M. B. Fox, M. A. I. Schutyser, and R. M. Boom. 2012. Enzyme inactivation kinetics: coupled effects of temperature and moisture content. Food Chemistry 133: 116-123.

Pope, J. T. Non-conditioning factors affecting enzyme thermostability during feed processing. 2019. North Carolina State University, Department of Poultry Science, PhD dissertation.

Pope, J. T. and A. C. Fahrenholz. 2020. The effect of the level of mixer-added water and mash conditioning temperature on parameters monitored during pelleting and phytase and xylanase thermostability. Anim Feed Sci Technol 269: 114679.

Saensukjaroehenphon, M. The effect of pelleting parameters on phytase stability and pellet quality. 2019. Kansas State University, Department of Grain Science, PhD dissertation.

Stark, C. R. Pellet quality. I. Pellet quality and its effect on swine performance. II. Functional characteristics of ingredients in the formation of quality pellets. 1994. Kansas State University, Department of Grain Science, PhD dissertation.
Stark, C. R. and P. R. Ferket. 2011. Conditioning, pelleting, and cooling. North Carolina State Extension Services.

Stevens, C. A. Starch gelatinization and the influence of particle size, steam pressure, and die speed on the pelleting process. 1987. Kansas State University, Department of Grain Science, PhD dissertation.

Thomas, M. and A. F. B. van der Poel. 1996. Physical quality of pelleted animal feed I: Criteria for pellet quality. J. Animal Feed Sci. Tech. 61: 89-112.

Thomas, M., D. J. van Zuilichem, and A. F. B. van der Poel. 1997. Physical quality of pelleted animal feed II: Contribution of processes and its conditions. J. Animal Feed Sci. Tech. 64: 173-192.

Truelock, C. N. Influence of exogenous enzymes and pelleting on feed manufacturing and broiler performance. 2020. Kansas State University, Department of Grain Science, PhD dissertation.

Turner, R. 2013. “Pellet Mill Design.” Feed Pelleting Reference Guide. E-book, WATT Global Media and Kansas State University.
Table 1. Diet composition for finishing swine

| Ingredient                                | Inclusion, % |
|-------------------------------------------|--------------|
| Corn                                      | 76.05        |
| Soybean meal                              | 20.05        |
| Soy oil                                   | 1.50         |
| Limestone                                 | 1.10         |
| Sodium chloride                           | 0.35         |
| Soy oil, 21% P                            | 0.33         |
| L-lysine HCl                              | 0.26         |
| Trace mineral premix                       | 0.13         |
| Vitamin premix                            | 0.13         |
| L-threonine                               | 0.05         |
| DL-methionine                             | 0.02         |
| Phytase                                   | 0.02         |
| Xylanase                                  | 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 D₃, 17,637 IU vitamin E, 13.3 mg vitamin B₁₂, 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. Die specifications

| Specification                                      | Value  |
|----------------------------------------------------|--------|
| Die hole diameter, mm [D]                          | 4.8    |
| Effective length, mm [L]                           | 44.5   |
| Internal die surface area, cm² [a]                 | 1477.5 |
| Holes per cm² [hₐ]                                 | 2.3    |
| Effective volume per hole, cm³ [v]                 | 0.8    |
| Feed per die in effective length, 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 $[a hₐ] \times$ volume per hole $[v] \times$ material density $[0.609 \text{ g/cm}^3]$. 
Table 3. Pellet mill speed definitions

| Shaft speed\(^1\), rpm | Die speed, rpm | Peripheral die speed, m/min |
|------------------------|----------------|----------------------------|
| 1800                   | 254            | 324                        |
| 1350                   | 190            | 243                        |
| 900                    | 127            | 162                        |

\(^1\) Main drive shaft speed set via a variable frequency drive to 100, 75, and 50%, respectively.

\(^\ast\) Standard main drive shaft speed for 100 HP pellet mill model 3016-4 (CPM Co., Crawfordsville, IN).
Table 4. The effect of conditioning temperature and die speed on pelleting parameters

|                          | Conditioning Temperature, °C |       |       |
|--------------------------|------------------------------|-------|-------|
|                          | 74°C                         | 85°C  |       |
| Die Speed, rpm           | 127                          | 190   | 254   |
| Actual die peripheral speed | 130                      | 195   | 261   | 194   | 260   |
| Die roll contact, hits/min | 260                      | 390   | 522   | 388   | 520   |
| Prod. rate, MT/h         | 4.5                          | 4.6   | 4.4   | 4.2   | 4.3   |
| Die retention, s         | 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 measured via laser tachometer prior to each pelleting run.
3 Calculated based on Saensukjaroenphon (2019) using die specifications (Table 2) and production rate.
Table 5. The effect of conditioning temperature and die speed on moisture content

| Die speed, rpm | Moisture, % | Probability, \( P < \) |
|---------------|-------------|-------------------------|
|               | 74°C, 85°C  | 74°C, die speed\(^2\) | 2 × 2 factorial\(^3\) |
| 127           | 190         | 254                     | SEM | Linear | Quad | Temp | RPM | Temp × RPM |
| Mash          | 13.3        | 13.6                    | 13.7 | 0.32   | 0.024 | 0.436 | 0.502 | 0.463 | 0.994 |
| Condition Mash | 17.1      | 16.8                    | 16.9 | 0.42   | 0.495 | 0.493 | 0.519 | 0.674 | 0.949 |
| Hot Pellet    | 16.2        | 16.8                    | 16.6 | 0.26   | 0.057 | 0.017 | 0.969 | 0.037 | <0.001 |
| Cool Pellet   | 13.6        | 13.7                    | 13.9 | 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 6. The effect of conditioning temperature and die speed on specific energy consumption (SEC) of the pellet mill and pellet quality

| Conditioning Temperature, °C | 74°C | 85°C | SEM | 74°C, die speed | Probability, P < |
|-----------------------------|------|------|-----|----------------|-----------------|
| Die speed, rpm              | 127  | 190  | 254 | 190            | 254             |
| SEC, kWh/MT                 | 10.9 | 8.9  | 9.0 | 9.6            | 9.1             | 0.41            | 0.001 | 0.001 | 0.578 | 0.106 | 0.074 |
| Linear                      |      |      |     |                |                 |                |
| Quad                        |      |      |     |                |                 |                |
| Temp                        | 0.001| 0.001| 0.001| 0.001| 0.001| 0.001| 0.001| 0.245| 0.313|
| RPM                         | 0.106| 0.074| 0.074| 0.074| 0.074| 0.074| 0.074| 0.106| 0.074|
| Temp × RPM                  | 0.074| 0.074| 0.074| 0.074| 0.074| 0.074| 0.074| 0.074| 0.074|

PDI, %

| Method    | 74°C | 85°C | SEM | 74°C, die speed | Probability, P < |
|-----------|------|------|-----|-----------------|-----------------|
| Std Tumble | 85.8 | 83.9 | 83.3 | 91.2 | 91.2 | 0.58 | 0.001 | 0.082 | 0.001 | 0.245 | 0.313 |
| Mod Tumble | 68.6 | 64.1 | 61.7 | 80.3 | 80.6 | 1.84 | 0.001 | 0.262 | 0.001 | 0.198 | 0.103 |
| NHP 30s    | 78.1 | 73.1 | 70.8 | 87.7 | 87.8 | 1.51 | 0.001 | 0.207 | 0.001 | 0.214 | 0.175 |
| NHP 60s    | 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 7. The effect of conditioning temperature and die speed on relative phytase and xylanase stability during the pelleting process

| Die speed, rpm | Conditioning Temperature, °C | Phytase Stability | |
|----------------|-----------------------------|-------------------|---|
|                | 74°C                        | 85°C              | SEM | Linear | Quad | Temp | RPM | Temp × RPM |
| 127            | 84.1                        | 87.7              | 85.0 | 84.8   | 85.8 | 3.74 | 0.086 | 0.663 | 0.769 | 0.810 | 0.612 |
| 190            | 103.6                       | 99.5              | 97.7 | 87.9   | 70.8 | 3.01 | 0.123 | 0.699 | 0.019 | 0.001 | 0.004 |
| 254            | 90.9                        | 88.0              | 86.6 | 75.8   | 61.1 | 3.09 | 0.198 | 0.799 | 0.035 | 0.001 | 0.004 |

| Xylanase Stability | CM:M | P:CM | P:M |
|--------------------|------|------|------|
| CM:M               | 102.9| 92.8 | 93.2 |
| P:CM               | 101.4| 89.0 | 89.6 |
| P:M                | 95.1 | 94.1 | 94.9 |

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.