

# Pelleting and starch characteristics of diets containing different corn varieties

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**ABSTRACT:** This experiment determined the effects of die thickness and conditioning temperature on pelleting and starch characteristics in diets containing conventional or Enogen Feed corn (Syngenta Seeds, LLC). Treatments were arranged as a 2 × 2 × 3 factorial of corn type [conventional (CON) and Enogen Feed corn [EFC]], die thickness [5.6 and 8 length:diameter (L:D)], and conditioning temperature (74, 79, and 85 °C). Diets were steam conditioned (Wenger twin staff preconditioner, Model 150) and pelleted (CPM, Model 1012-2) with a 4- × 22.2-mm (L:D 5.6) or 4- × 31.8-mm (L:D 8) pellet die. Conditioner retention time was set at 30 s and production rate was set at 15 kg/min. All treatments were represented within three replicate days. Pellets were composited and analyzed for gelatinized starch and pellet durability index (PDI). Conditioning temperature, hot pellet temperature, production rate, and pellet mill energy consumption were recorded throughout each processing run. Data were analyzed using the GLIMMIX procedure in SAS (v. 9.4, SAS Institute Inc., Cary, NC) with pelleting run as the experimental unit and day as the

blocking factor. Pelleting with a larger die L:D improved PDI ( $P = 0.01$ ) and increased ( $P = 0.02$ ) pellet mill energy consumption. Increasing conditioning temperature from 74 to 85 °C increased (linear,  $P < 0.03$ ) PDI and tended to decrease energy consumption (quadratic,  $P = 0.07$ ). There was a corn × conditioning temperature interaction ( $P = 0.01$ ) for gelatinized starch in conditioned mash. Enogen Feed corn diets steam conditioned at 85 °C had the greatest quantity of gelatinized starch. Cooked starch in conditioned mash and pellets was greater ( $P < 0.01$ ) for EFC diets compared to CON diets and increased (linear,  $P < 0.01$ ) with increasing conditioning temperature in conditioned mash. Similarly, starch gelatinization was greater ( $P < 0.01$ ) in pelleted EFC diets compared to CON diets and was increased (linear,  $P = 0.05$ ) by increasing conditioning temperature from 74 to 85 °C. In conclusion, increasing die L:D and increasing conditioning temperature improved PDI. Starch gelatinization was increased when diets were pelleted at the highest conditioning temperature of 85 °C, and EFC diets resulted in greater starch gelatinization than conventional corn.

**Key words:** conditioning temperature, die thickness, Enogen Feed corn, pelleting, starch gelatinization

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## INTRODUCTION

Starch is the primary energy source in livestock diets and constitutes up to 50% of monogastric diets. Starch is largely supplied by grains, and in the

United States, specifically corn. Much research has been dedicated to evaluating grain-processing methods that increase starch availability, such as grinding and thermal processing (Rowe et al., 1999; Hancock and Behnke, 2001; Lundblad et al., 2011). For pelleting in particular, the process by which starch availability is increased is through a process known as starch gelatinization. Gelatinization is a four-step process that irreversibly solubilizes raw starch granules through the addition of heat and moisture. In the conditioner, mash feed is mixed with heat and moisture in the form of steam, which begins a conformational change in the dietary components of the feed, and starch granules begin to swell. As feed exits the conditioner, it is passed through the pellet mill die to form pellets. This process generates frictional heat, which drives starch gelatinization. Gelatinized starch values range from 6% to 7% in conditioned mash, similar to unconditioned mash, and from 11% to 12% in pellets (Lewis et al., 2015). Gelatinized starch increases starch availability in the animal, and Rojas et al. (2016) reported an increase in apparent ileal digestibility of starch from 96.4% in mash diets to 97.7% in pelleted swine diets.

Starch digestion is largely driven by amylase, a glycolytic enzyme that degrades starch into sugars, which are more readily available for absorption in the small intestine. Recent advancements in corn breeding have led to the development of corn varieties that naturally express enzyme activity. One such variety is Enogen Feed corn (Syngenta Seeds, LLC), a high amylase corn originally developed for use in the ethanol industry (Syngenta Crop Protection, LLC, 2019). This variety utilizes in-seed technology that produces an  $\alpha$ -amylase enzyme within the kernels. Increased amylase activity of Enogen Feed corn is designed to assist in the rapid degradation of starch to sugars, thereby providing more available energy for growth. The enzyme is active across a broad range of temperatures and pH conditions when moisture is adequate (Syngenta Crop Protection, LLC, 2019). Similar conditions are prevalent in the pelleting process, yet there has been no research to date evaluating the effect of a high amylase corn variety in the pelleting process. Therefore, this experiment was designed to evaluate the effects of corn type, die thickness, and conditioning temperature on pelleting and starch characteristics of a swine diet.

## MATERIALS AND METHODS

Treatments were arranged as a  $2 \times 2 \times 3$  factorial of corn type (conventional [CON] and

Enogen Feed corn [EFC]), die thickness (5.6 and 8 length:diameter [L:D]), and conditioning temperature (74, 79, and 85 °C). Conventional yellow dent #2 corn was sourced from North East Kansas. Conventional and Enogen Feed corn were ground to approximately 600  $\mu\text{m}$  using a three-high roller mill (RMS, Model 924). For the EFC treatments, ground Enogen Feed corn replaced conventional ground corn on a kg:kg basis (Table 1). Diets were mixed in a 907-kg horizontal counterpoise mixer (Hayes & Stolz, Fort Worth, TX), steam conditioned (25  $\times$  140 cm twin shaft preconditioner, Model 150, Wenger, Sabetha, KS) for 30 s at 74, 79, or 85 °C, and subsequently pelleted using a 30-horsepower pellet mill (1012-2 HD Master Model, California Pellet Mill, Crawfordsville, IN) equipped with a 22.2-  $\times$  4-mm (L:D 5.6) or 31.8-  $\times$  4-mm (L:D 8) pellet die. Conditioner retention time was calculated by adjusting the conditioner screw speed and dividing the amount of feed in the conditioner by the production rate. Production rate was set at 15 kg/min, approximately 100% of the rated throughput for the pellet mill, and steam pressure was 1.65 bar. All treatments were replicated on three separate days, thus achieving three replications of each of the 12 treatments. Die thickness was randomized across day and corn type was randomized within die to minimize the effects of pelleting order. A conventional corn-soybean meal flush diet was used to warm the mill up to 74 °C before each day of pelleting. Two hundred seventy-two kilograms of the first corn type diet was pelleted on the first die, according to randomization, at all three

**Table 1.** Composition (as-fed basis) of a pelleted corn-soybean meal-based swine diet<sup>a</sup>

Ingredient	%, as is
Ground corn <sup>b</sup>	75.88
Soybean meal, 47% crude protein	20.07
Soybean oil	1.50
Monocalcium phosphate	0.50
Limestone	1.10
Salt	0.35
L-lysine HCl	0.26
DL-methionine	0.02
L-threonine	0.05
Trace mineral premix	0.13
Vitamin premix	0.13
HiPhos 2700 <sup>c</sup>	0.03

<sup>a</sup>Diets were mixed in a 907-kg Hayes & Stolz horizontal counterpoise mixer with a 60-s dry mix time and 120-s wet mix time.

<sup>b</sup>Enogen Feed corn (Syngenta Seeds, LLC) replaced conventional yellow dent ground corn on a kg:kg basis.

<sup>c</sup>DSM Nutritional Products, Parsippany, NJ.

conditioning temperatures in ascending order. The pellet mill was flushed with a diet not containing Enogen Feed corn and the second corn type diet was pelleted in the same manner. Once completed, the pellet mill was shut down and the die was changed.

**Table 2.** Nutrient composition (as-fed basis) of conventional yellow dent corn and Enogen Feed corn diets<sup>a</sup>

Nutrient	Conventional	Enogen Feed corn
Mash diets <sup>b</sup>		
Moisture, %	11.72	11.12
Crude protein, %	15.7	15.9
Crude fiber, %	2.0	2.4
Fat (oil), %	4.0	3.8
Ash, %	3.62	3.57
Pelleted diets <sup>c</sup>		
Moisture, %	11.08	10.53
Crude protein, %	15.6	15.8
Crude fiber, %	2.1	2.4
Fat (oil), %	4.4	4.4
Ash, %	3.71	3.72

<sup>a</sup>Enogen Feed corn (Syngenta Seeds, LLC) replaced conventional yellow dent ground corn on a kg:kg basis.

<sup>b</sup>Diets were mixed in a 907-kg Hayes & Stolz horizontal counter-poise mixer with a 60-s dry mix time and 120-s wet mix time.

<sup>c</sup>Diets were steam conditioned (25 × 140 cm Wenger twin staff preconditioner, Model 150) for 30 s at 74, 79, or 85 °C and pelleted (CPM, 1012-2 HD Master Model) using a 22.2- × 4-mm (L:D 5.6) or 31.8- × 4-mm (L:D 8) pellet die.

A conventional corn-soybean meal flush was again used to warm the mill up to 74 °C before pelleting on the second die, and pelleting procedures followed the pattern previously mentioned. Each treatment was pelleted in approximately 8 min.

### Data Collection

Conditioning temperature, hot pellet temperature (HPT), production rate, and pellet mill energy consumption were recorded at three time points during each treatment run (Table 3). Within each replicate, three conditioned mash and three pellet samples were collected per treatment. Conditioned mash samples were collected as feed exited the conditioner prior to the pellet die and immediately frozen. Frozen conditioned mash samples were composited into a single sample for starch analysis. Pellet samples were collected as feed exited the pellet die, cooled for 15 min in an experimental counter-flow cooler, and composited into two samples. Composite pellet samples were analyzed for total starch, gelatinized starch, cooked starch, and pellet durability index (PDI). Samples for starch analysis were sent to the Wenger Technical Center Laboratory (Sabetha, KS) and analyzed by methods outlined by Mason et al (1982). Briefly, samples were ground to a fine particle size using a coffee grinder. One 0.5-g subsample was hydrolyzed in

**Table 3.** Pelleting characteristics of swine diets containing either conventional or Enogen Feed corn<sup>a</sup>

Die L:D:	5.6			8			SEM <sup>c</sup>	Probability, <sup>b</sup> <					
	74	79	85	74	79	85		Corn	Die	Linear <sup>d</sup>	Quadratic <sup>d</sup>	Corn × die	Die × temp
Production rate, kg/min													
CON	15.3	15.4	15.4	15.3	15.3	15.4	0.08	–	–	–	–	–	–
EFC	15.3	15.5	15.3	15.4	15.3	15.5							
Condition temp, °C													
CON	74.2	79.6	85.1	74.1	79.7	84.7	0.16	–	–	–	–	–	–
EFC	73.8	79.6	85.1	74.1	79.8	84.6							
Hot pellet temp, °C													
CON	79.3	83.0	87.3	80.8	84.2	87.6	0.56	0.01	0.01	0.01	0.15	0.79	0.73
EFC	81.3	83.4	87.3	82.1	84.8	88.6							
PDI, %													
CON	81.2	83.7	87.9	87.9	89.0	92.0	2.42	0.11	0.01	0.03	0.39	0.08	0.91
EFC	78.8	78.1	81.4	89.1	88.9	91.4							
Energy consumption, kWh/ton													
CON	13.4	12.9	13.1	14.1	13.7	13.7	0.45	0.12	0.02	0.38	0.07	0.36	0.70
EFC	14.0	13.1	14.0	14.2	13.8	14.0							

<sup>a</sup>Diets were steam conditioned (25 × 140 cm Wenger twin staff preconditioner, Model 150) for 30 s at 74, 79, or 85 °C and pelleted (CPM, 1012-2 HD Master Model) using a 22.2- × 4-mm (L:D 5.6) or 31.8- × 4-mm (L:D 8) pellet die.

<sup>b</sup>There was no evidence for a corn type × die thickness × conditioning temperature interaction ( $P > 0.46$ ) or corn type × conditioning temperature interaction ( $P > 0.14$ ) for HPT, PDI, or energy consumption.

<sup>c</sup>Pooled standard error of least squares means ( $n = 3$ ).

<sup>d</sup>Linear and quadratic contrasts were used to evaluate the effect of conditioning temperature.

distilled water at room temperature, while a second 0.5-g subsample was boiled with distilled water. Samples were incubated with glucoamylase, and free D-glucose was measured. To obtain a baseline glucose reading, samples were analyzed without the enzyme digestion step. Baseline glucose measurements were then subtracted from the total glucose reading after the enzymatic digestion step to determine free D-glucose coming from gelatinized starch. The quantity of free glucose analyzed in the room temperature sample represents the percentage of starch that was gelatinized during processing, and the quantity of free glucose in the boiled sample represents the percentage of total starch in the sample. Cooked starch was then calculated as the percentage of gelatinized starch divided by the percentage of total starch multiplied by 100.

For analysis of PDI, fines were sifted off from cooled pellets using a U.S. No. 5 (4 mm) sieve. One hundred grams of the sifted pellets were placed into a Holmen 100 pellet tester and agitated with air for 60 s. Following agitation, the sample was again sifted through a No. 5 sieve and the remaining pellets were weighed. Pellet durability index was calculated as the percentage of the initial pellet sample remaining after agitation with air.

### Statistical Analysis

Data were analyzed using the GLIMMIX procedure in SAS (v. 9.4, SAS Institute Inc., Cary, NC), with the pelleted feed from a single treatment run as the experimental unit and day as the blocking factor. Hot pellet temperature, PDI, energy consumption, and starch characteristics of pellets were analyzed with the main effects of corn type, die thickness, conditioning temperature, and all possible interactions. Conditioned mash starch data was analyzed with the main effects of corn type and conditioning temperature and the interaction between the two. For all data, linear and quadratic contrasts were used to evaluate the effect of conditioning temperature. Results were considered significant if  $P \leq 0.05$  and were considered marginally significant if  $P > 0.05$  and  $P \leq 0.10$ .

## RESULTS

Nutrient composition of CON and EFC diets are presented in Table 2. Production rate and conditioning temperature were as expected for each treatment. There was no evidence ( $P > 0.21$ ) for a corn type  $\times$  die thickness  $\times$  conditioning temperature interaction for any of the pelleting or

starch responses analyzed in this study (Table 3). Additionally, there was no evidence ( $P > 0.14$ ) for a corn type  $\times$  conditioning temperature interaction for HPT, PDI, or pellet mill energy consumption.

There was no evidence for a corn type  $\times$  die thickness or die thickness  $\times$  conditioning temperature interaction for HPT. Inclusion of EFC ( $P < 0.01$ ), a thicker pellet die ( $P < 0.01$ ), and increasing conditioning temperature from 74 to 85 °C (linear,  $P < 0.01$ ) resulted in increased HPT.

There was a tendency ( $P = 0.08$ ) for a corn type  $\times$  die thickness interaction for PDI. Pellet durability index for CON and EFC treatments were similar when diets were pelleted using the L:D 8 die. However, PDI for CON diets was greater than EFC diets when pelleted using the L:D 5.6 die. Additionally, PDI increased (linear,  $P = 0.03$ ) with increasing conditioning temperature.

Pellet mill energy consumption was greater for the L:D 8 pellet die ( $P = 0.02$ ) and tended to decrease (quadratic,  $P = 0.07$ ) with increasing conditioning temperature. There was no evidence of difference ( $P = 0.12$ ) in energy consumption due to corn type.

There was no evidence for a corn type  $\times$  conditioning temperature interaction ( $P > 0.12$ ) for average moisture, total starch, or cooked starch in conditioned mash (Table 4). Corn type had no effect on average moisture in conditioned mash ( $P > 0.82$ ); however, there was an increase (linear,  $P < 0.01$ ) in moisture of conditioned mash with increasing conditioning temperature. Additionally, there was no evidence of difference ( $P > 0.42$ ) in total starch due to corn type or conditioning temperature. There was a corn type  $\times$  conditioning temperature interaction ( $P = 0.01$ ) for gelatinized starch in conditioned mash. Enogen Feed corn diets steam conditioned at 85 °C had greater gelatinized starch than all other corn type  $\times$  conditioning temperature treatments. Cooked starch of conditioned mash was greater for diets containing EFC compared to CON and increased (linear,  $P < 0.01$ ) with increasing conditioning temperature.

There were no significant interactions ( $P > 0.15$ ) for average moisture, gelatinized starch, or cooked starch in pelleted diets (Table 5). There was no evidence of difference ( $P > 0.40$ ) in pellet moisture due to corn type, die thickness, or conditioning temperature. There was a corn type  $\times$  die thickness interaction ( $P < 0.01$ ) for total starch in pellets. Total starch was greater for EFC diets pelleted using the L:D 8 compared to the L:D 5.6 die but not different from the CON diets pelleted using either the L:D 5.6 or 8 die. Pelleted EFC diets had greater ( $P < 0.01$ ) gelatinized starch than CON diets, and

**Table 4.** Starch characteristics of steam-conditioned swine diets containing either conventional or Enogen Feed corn<sup>a</sup>

Item	Conditioning temperature, °C			SEM <sup>b</sup>	Probability, <			
	74	79	85		Corn	Linear <sup>c</sup>	Quadratic <sup>c</sup>	Corn × temp
Moisture, %								
CON	17.3	17.7	18.0	0.26	0.93	0.01	0.96	0.42
EFC	17.3	17.8	17.7					
Total starch, <sup>d</sup> %								
CON	59.2	59.2	58.0	1.86	0.42	0.98	0.58	0.35
EFC	59.1	58.7	61.6					
Gelatinized starch, <sup>e</sup> %								
CON	3.9	4.4	4.0	0.22	0.01	0.01	0.93	0.01
EFC	4.4	4.4	5.6					
Cook, <sup>f</sup> %								
CON	6.4	7.3	6.9	0.41	0.01	0.01	0.64	0.12
EFC	7.3	7.4	9.1					

<sup>a</sup>Diets were steam-conditioned (25 × 140 cm Wenger twin staff preconditioner, Model 150) for 30 s at 74, 79, or 85 °C and pelleted (CPM, 1012-2 HD Master Model) using a 22.2- × 4-mm (L:D 5.6) or 31.8- × 4-mm (L:D 8) pellet die.

<sup>b</sup>Pooled standard error of least squares means ( $n = 3$ ).

<sup>c</sup>Linear and quadratic contrasts were used to evaluate the effect of conditioning temperature.

<sup>d</sup>Total starch was calculated as the percentage of free D-glucose in a 0.5-g subsample after boiling with distilled water and incubation with glucoamylase.

<sup>e</sup>Gelatinized starch was calculated as the percentage of free D-glucose in a 0.5-g subsample after hydrolysis in distilled water at room temperature and incubation with glucoamylase.

<sup>f</sup>Cooked starch was calculated as the percentage of gelatinized starch divided by the percentage of total starch multiplied by 100.

**Table 5.** Starch characteristics of pelleted swine diets containing either conventional or Enogen Feed corn<sup>a</sup>

Die L:D:	5.6			8			SEM <sup>c</sup>	Probability, <sup>b</sup> <				
	74	79	85	74	79	85		Corn	Die	Linear <sup>d</sup>	Quadratic <sup>d</sup>	Corn × die
Moisture, %												
CON	12.0	12.5	12.8	12.2	12.7	12.9	0.67	0.41	0.60	0.40	0.81	0.88
EFC	12.1	12.2	12.0	12.4	12.3	12.4						
Total starch, <sup>e</sup> %												
CON	59.4	58.2	58.1	57.3	57.3	57.4	1.44	0.34	0.19	0.18	0.94	0.01
EFC	53.2	55.6	57.4	57.5	58.9	60.2						
Gelatinized starch, <sup>f</sup> %												
CON	10.7	11.2	12.0	11.8	11.7	12.6	0.99	<0.01	0.14	0.05	0.37	0.85
EFC	12.2	12.2	14.1	13.1	13.5	15.0						
Cook, <sup>g</sup> %												
CON	18.0	19.2	20.7	20.6	20.4	22.0	1.36	<0.01	0.18	0.06	0.27	0.41
EFC	23.0	21.9	24.4	22.8	22.9	24.9						

<sup>a</sup>Diets were steam-conditioned (25 × 140 cm Wenger twin staff preconditioner, Model 150) for 30 s at 74, 79, or 85 °C and pelleted (CPM, 1012-2 HD Master Model) using a 22.2- × 4-mm (L:D 5.6) or 31.8- × 4-mm (L:D 8) pellet die.

<sup>b</sup>There was no evidence for a corn type × die thickness × conditioning temperature interaction, a corn type × conditioning temperature interaction, or a die thickness × conditioning temperature interaction ( $P > 0.15$ ) for starch responses of pelleted diets analyzed in this study.

<sup>c</sup>Pooled standard error of least squares means ( $n = 3$ ).

<sup>d</sup>Linear and quadratic contrasts were used to evaluate the effect of conditioning temperature.

<sup>e</sup>Total starch was calculated as the percentage of free D-glucose in a 0.5-g subsample after boiling with distilled water and incubation with glucoamylase.

<sup>f</sup>Gelatinized starch was calculated as the percentage of free D-glucose in a 0.5-g subsample after hydrolysis in distilled water at room temperature and incubation with glucoamylase.

<sup>g</sup>Cooked starch was calculated as the percentage of gelatinized starch divided by the percentage of total starch multiplied by 100.

gelatinized starch increased (linear,  $P = 0.05$ ) with increasing conditioning temperature. Similarly, cooked starch was greatest ( $P < 0.01$ ) for the EFC diets and tended to increase (linear,  $P = 0.06$ ) with increasing conditioning temperature.

## DISCUSSION

Results of this experiment demonstrated that increasing die L:D from 5.6 to 8 improved pellet quality but increased pellet mill energy consumption. Behnke (2001) described the same positive correlation between die L:D and pellet durability and attributed this to the increased pressure and resistance generated by a larger die L:D. When die hole diameter remains constant, a pellet die with a larger die L:D is thicker than a die with a smaller L:D. Thus, feed retention within the die is longer with a thicker die and is a primary factor in determining pellet durability. Die L:D has also been shown to be positively correlated with pellet mill energy consumption. An experiment examining the effect of seven different dietary and pelleting factors on pellet durability and energy consumption demonstrated an increase in pellet mill energy consumption with increasing die L:D (Fahrenholz, 2012). In fact, among the six other variables examined, including corn particle size, percentage of fat, percentage of distiller's dried grains with solubles (DDGS), production rate, conditioning temperature, and conditioning retention time, die L:D ratio was one of the most influential factors affecting energy consumption, second only to conditioning temperature. The reasoning behind the negative effect of die L:D on pellet mill efficiency when pelleting corn-soybean meal-based diets has not been explained. However, it is hypothesized that additional energy is needed to move mash feed through a 32-mm die compared to a 22-mm die due to the added friction that is generated from greater feed to die hole wall contact when using a thicker pellet die.

Increasing conditioning temperature from 74 to 85 °C linearly improved PDI without increasing energy consumption. Once again, these results compare to those of Fahrenholz (2012) who reported greater pellet durability and lower pellet mill energy consumption at higher conditioning temperatures. A general rule of thumb for steam conditioning livestock diets is that moisture content of the mash feed increases by 1% for every 14 °C increase in conditioning temperature. Therefore, an improvement in PDI with increasing conditioning temperature is likely due to the increase in moisture, which acts as a binding agent, plasticizing the soluble fractions

of the diet and increasing the agglomeration of dietary components (Lundblad et al., 2009). The effect of conditioning temperature on pellet mill energy consumption may also be explained by the increase in moisture content of conditioned feed. Additional moisture at higher conditioning temperatures helps to lubricate the feed as it passes through the pellet die, thus lowering the amount of friction that may influence energy consumption.

Diets containing EFC had poorer PDI compared to CON when feed was pelleted using the 5.6 L:D die, but PDI was similar for both corn types when pelleted using the 8 L:D die, with corn type not affecting pellet mill energy consumption. No differences in processing parameters were observed that provide an explanation for the observed response. Pelleting with a thicker pellet die improved PDI enough to ameliorate any differences between the corn types. Moritz et al. (2002) described a positive correlation between PDI and starch gelatinization, concluding that gelatinized starch acts as a binding agent to improve PDI. In the present study, the inclusion of EFC in pelleted diets increased gelatinized starch compared to pelleted CON diets, but there was no evidence for improvement in PDI. In addition, there was no evidence for difference that pellet die L:D affected starch gelatinization, although increasing die L:D improved PDI. Thus, the interaction of corn type and die L:D and the possible influence of starch gelatinization on PDI needs to be further investigated.

Starch gelatinization was increased when diets were pelleted at the highest conditioning temperature of 85 °C, and EFC diets resulted in greater gelatinized starch than CON diets. The observed relationship between conditioning temperature and starch gelatinization is in agreement with the findings of Lewis et al. (2015) who reported a 19% increase in gelatinized starch when conditioning temperature increased from 77 to 88 °C. Although gelatinized starch values of conditioned mash in the experiment herein were lower than that observed previously (4.5% vs. 7.3%, respectively; Lewis et al., 2015), pelleted CON diets averaged 11.7% gelatinized starch, similar to previous work. A significant finding of Lewis et al. (2015) was the predominant increase in gelatinized starch that occurred across the pellet die rather than in the conditioner. Lewis et al. (2015) reported that gelatinized starch of conditioned mash samples was statistically similar to that of cold mash, whereas gelatinized starch in pellets was greater than both the cold mash and conditioned mash. These findings support those of the current experiment, which demonstrated an

increase in gelatinized starch in pellets compared to conditioned mash. Because there is no available research on the effect of EFC in the pelleting process, it is hypothesized that the high amylase activity in the corn is responsible for the increase in gelatinized starch in pelleted EFC diets compared to pelleted CON diets. [Vasanthan et al. \(2001\)](#) evaluated the effect of  $\alpha$ -amylase, extrusion temperature, and moisture on the degree of starch hydrolysis in extruded barley flours. Not only was starch hydrolysis increased with increasing temperature and moisture, but the authors also reported an increase in the degree of starch hydrolysis when exogenous  $\alpha$ -amylase concentration increased from 2% to 4%. It has been previously discussed that starch gelatinization increases through heat processing, and it is known that gelatinization of starch enhances the rate of starch hydrolysis ([Holm et al., 1988](#)); therefore, starch hydrolysis via amylase could complement starch gelatinization during pelleting and vice versa.

In conclusion, the results of this experiment indicate when using the pelleting parameters outlined herein that there are not any significant effects on pellet mill energy consumption and only slight increases in HPT when EFC is added in place of CON in monogastric diets. Although pelleting with a larger die L:D improves pellet quality, caution should be used as thicker pellet dies can dramatically increase HPT and pellet mill energy consumption. Additionally, pelleting can be used as a means of increasing starch gelatinization in corn-soybean meal-based diets with the majority of gelatinization occurring across the pellet die. Finally, diets containing EFC may have an even greater potential of increasing gelatinized starch during pelleting compared to CON due to the high amylase activity present in EFC.

## LITERATURE CITED

- Behnke, K. C. 2001. Factors influencing pellet quality. *Feed Technol.* 5:19–22.
- Fahrenholz, A. C. 2012. Evaluating factors affecting pellet durability and energy consumption in a pilot feed mill and comparing methods for evaluating pellet durability [PhD dissertation]. Kansas State University, Manhattan, KS.
- Hancock, J. D., and K. C. Behnke. 2001. Use of ingredient and diet processing technologies (grinding, mixing, pelleting, and extruding) to produce quality feeds for pigs. In: Lewis, A. J., L. L. Southern, editors. *Swine nutrition*. Boca Raton, FL. pp. 469–498.
- Holm, J., I. Lundquist, I. Björck, A. C. Eliasson, and N. G. Asp. 1988. Degree of starch gelatinization, digestion rate of starch in vitro, and metabolic response in rats. *Am. J. Clin. Nutr.* 47:1010–1016. doi:[10.1093/ajcn/47.6.1010](https://doi.org/10.1093/ajcn/47.6.1010).
- Lewis, L. L., C. R. Stark, A. C. Fahrenholz, J. R. Bergstrom, and C. K. Jones. 2015. Evaluation of conditioning time and temperature on gelatinized starch and vitamin retention in a pelleted swine diet. *J. Anim. Sci.* 93:615–619. doi:[10.2527/jas.2014-8074](https://doi.org/10.2527/jas.2014-8074)
- Lundblad, K. K., J. D. Hancock, K. C. Behnke, E. Prestløkken, L. J. McKinney, and M. Sørensen. 2009. The effect of adding water into the mixer on pelleting efficiency and pellet quality in diets for finishing pigs without and with use of an expander. *Anim. Feed Sci. Technol.* 150:295–302. doi:[10.1016/j.anifeedsci.2008.10.006](https://doi.org/10.1016/j.anifeedsci.2008.10.006)
- Lundblad, K. K., S. Issa, J. D. Hancock, K. C. Behnke, L. J. McKinney, S. Alavi, E. Prestløkken, J. Fledderus, and M. Sørensen. 2011. Effects of steam conditioning at low and high temperature: expander conditioning and extruder processing prior to pelleting on growth performance and nutrient digestibility in nursery pigs and broiler chickens. *Anim. Feed Sci. Technol.* 169:208–218. doi:[10.1016/j.anifeedsci.2011.06.008](https://doi.org/10.1016/j.anifeedsci.2011.06.008)
- Mason, M., B. Gleason, and G. Rokey. 1982. A new method for determining degree of cook. In: *Proceedings of the American Association of Cereal Chemists Conference*; October 24–28, San Antonio, TX; p. 123–124.
- Moritz, J. S., K. J. Wilson, K. R. Cramer, R. S. Beyer, L. J. McKinney, W. B. Cavalcanti, and X. Mo. 2002. Effect of formulation density, moisture and surfactant on feed manufacturing, pellet quality and broiler performance. *J. Appl. Poult. Res.* 11:155–163. doi:[10.1093/japr/11.2.155](https://doi.org/10.1093/japr/11.2.155)
- Rojas, O. J., E. Vinyeta, and H. H. Stein. 2016. Effects of pelleting, extrusion, or extrusion and pelleting on energy and nutrient digestibility in diets containing different levels of fiber and fed to growing pigs. *J. Anim. Sci.* 94:1951–1960. doi:[10.2527/jas.2015-0137](https://doi.org/10.2527/jas.2015-0137).
- Rowe, J. B., M. Choct, and D. W. Pethick. 1999. Processing cereal grains for animal feeding. *Aust. J. Agric. Res.* 50:721–736. doi:[10.1071/AR98163](https://doi.org/10.1071/AR98163)
- Syngenta Crop Protection, LLC. Meeting the Growing Demand for American Ethanol. 2019– [accessed November 6, 2020]. <http://www.syngenta-us.com/corn/enogen>.
- Vasanthan, T., J. Yeung, and R. Hoover. 2001. Dextrinization of starch in barley flours with thermostable alpha-amylase by extrusion cooking. *Starch/Stärke.* 53:616–622. [https://doi.org/10.1002/1521-379X\(200112\)53:12<616::AID-STAR616>3.0.CO;2-M](https://doi.org/10.1002/1521-379X(200112)53:12<616::AID-STAR616>3.0.CO;2-M)