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Non ruminant nutrition

Effects of corn hardness and drying temperature on digestibility of energy and nutrients in diets fed to growing pigs

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Abstract

Two experiments were conducted to test the hypothesis that corn kernel hardness and drying temperature influence the ileal digestibility of starch and amino acids (**AA**), as well as apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and total dietary fiber (**TDF**) in diets for growing pigs. Two corn varieties with average or hard endosperm were grown and harvested under similar conditions, and after harvest, each variety was divided into 2 batches that were dried at 35 and 120 °C, respectively. Therefore, four batches of corn were used. In experiment 1, 10 pigs (67.00 ± 2.98 kg) with a T-cannula installed in the distal ileum were allotted to a replicated 5 × 5 Latin square design with 5 diets and 5 periods giving 10 replicates per diet. A nitrogen-free diet and four diets containing each source of corn as the only AA source were formulated. Results indicated that neither variety of corn nor drying temperature influenced apparent ileal digestibility of starch in the grain. The standardized ileal digestibility of most AA was less ($P < 0.05$) in corn dried at 120 °C compared with corn dried at 35 °C resulting in concentrations of most standardized ileal digestible AA being less ($P < 0.05$) in corn dried at 120 °C than in corn dried at 35 °C. In experiment 2, 40 pigs (20.82 ± 1.74 kg) were housed in metabolism crates and allotted to 4 diets with 10 replicate pigs per diet. The four corn-based diets used in experiment 1 were also used in experiment 2. Feces and urine were collected using the marker-to-marker approach with 5-d adaptation and 4-d collection periods. Results indicated that diets containing hard endosperm corn had greater ($P < 0.05$) ATTD of TDF than diets containing average endosperm corn. The ATTD of GE in hard endosperm corn was also greater ($P < 0.05$), and concentrations of digestible energy and metabolizable energy in hard endosperm corn were greater ($P < 0.01$) than in average endosperm corn. Diets containing corn dried at 120 °C had greater ($P < 0.05$) ATTD of TDF compared with diets containing corn dried at 35 °C; however, drying temperature did not influence the ATTD of GE. In conclusion, endosperm hardness did not influence the digestibility of AA and starch; however, drying corn at 120 °C reduced digestible AA concentrations. Hard endosperm corn had greater ATTD of GE and TDF, but drying temperature did not influence energy digestibility.

Lay Summary

Drying temperatures and corn varieties that inherently differ in kernel hardness, virtuousness, and protein solubility index may influence nutrient digestibility in corn. However, information about interactive effects of corn source (i.e., endosperm hardness) and drying method on nutrient digestibility is limited. Therefore, two experiments were conducted to test the hypothesis that corn source and drying temperature influence energy and nutrient digestibility in corn. Two corn varieties (i.e., average or hard endosperm) were planted in plots with similar soil and similar agronomic conditions and harvested in the same week. Both corn sources were dried at 35 °C or 120 °C. Results indicated that endosperm hardness did not influence the apparent ileal digestibility of starch or standardized ileal digestibility (SID) of amino acids (AA) in pigs; however, values for SID of most AA in corn dried at 120 °C were less than in corn dried at 35 °C. Hard endosperm corn also had greater apparent total tract digestibility of gross energy and total dietary fiber than corn with average endosperm, but drying temperature did not influence energy digestibility. Further research is needed to determine the optimum drying temperature and corn variety to maximize nutritional value in corn.

Key words: amino acids, corn, digestibility, drying temperature, energy, pigs

Abbreviations: AA, amino acids; AEE, acid hydrolyzed ether extract; AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; IDF, insoluble dietary fiber; ME, metabolizable energy; SDF, soluble dietary fiber; SID, standardized ileal digestibility; TDF, total dietary fiber

Introduction

Corn is commonly used in high proportions in diets formulated to pigs or poultry, and therefore, often is the main source of energy in pig and poultry diets (Spencer et al., 2000). Corn can be grown under a wide range of environmental conditions and has the highest yield potential among cereal grains (Rouf Shah et al., 2016). Data for nutrient composition, standardized ileal digestibility (**SID**) of crude protein (**CP**) and amino acids (**AA**), as well as concentrations of digestible energy (**DE**) and metabolizable energy (**ME**) in corn, have been established (NRC, 2012). However, corn varieties may differ in kernel hardness, vitreousness, and protein solubility index, which may influence post-harvest resistance to insects and fungi

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(Córdova-Noboa et al., 2021b). Differences in kernel vitreousness can be attributed to organization of the starch granules in the endosperm because vitreous endosperm is enclosed by protein storage bodies and surrounded by a matrix of endosperm cells, whereas soft/average endosperm has little cellular structure of starch granules (Philippeau et al., 2000). The more vitreous the kernels are, the harder is the kernel, which may affect the digestibility of energy and nutrients in the grain (Gayral et al., 2015), but to our knowledge, research to determine impacts of corn kernel hardness on energy and nutrient digestibility by pigs has not been conducted.

Post-harvest handling practices (e.g., transportation, drying, storage, and further processing) may also affect nutrient digestibility (Kljak et al., 2018). In particular, heat treatment or drying methods applied to corn may affect starch gelatinization and solubility of fiber (Huang et al., 2015). However, excess heat during the air-forced drying process of corn may result in heat damage (Pahm et al., 2008). Heat damage may occur in feed ingredients when subjected to high temperatures, which influences animal nutrient digestibility and growth performance (González-Vega et al., 2011; Almeida et al., 2013). Indeed, when corn was dried at high drying temperatures (i.e., >80 °C), the digestibility of AA was reduced in broiler chickens (Kaczmarek et al., 2014), but data demonstrating effects of drying temperature on energy and nutrient digestibility in pigs are lacking. Likewise, data for the interactive effects of kernel hardness and drying method on nutrient digestibility in pig diets are limited. Therefore, two experiments were conducted to test the hypothesis that the ileal digestibility of starch, CP, and AA is influenced by corn hardness and drying temperature. The second objective was to test the hypothesis that the apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and total dietary fiber (**TDF**) is also influenced by corn source and drying temperature.

Materials and Methods

Protocols for two experiments were submitted to the Institutional Animal Care and Use Committee at the University of Illinois, Urbana-Champaign, and protocols were approved before initiation of the experiments. Pigs used in both experiments were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

Two corn varieties with average or hard endosperm (DeKalb 6357 and DeKalb 6869) were grown in 2021 in two field plots with similar soil types and using similar agronomic practices. Vitreousness or hardness of the kernels in two corn varieties were analyzed using near-infrared reflectance spectroscopy. DeKalb 6357 had 60.59% vitreousness, whereas DeKalb 6869 had 62.83% vitreousness. The two varieties were harvested at the same time and post-harvest treatments were similar. After harvest, each variety of corn was divided into two batches. The harvested grain was transported to a single-fan, natural gas, open flame, forced-air dryer (Competitor Series Dryers, model competitor 112, Grain Systems Inc. GSI, Newton, IL, USA). One batch was dried at 35 °C for approximately 9 h, whereas the other batch was dried at 120 °C for approximately 3 h to reach the target moisture of 13%. The temperature was monitored during the drying process using two digital probe thermometers inserted on both sides of the dryer. Therefore, four different batches of corn were used (Table 1). After drying, the 4 batches of corn were stored in 1,000 kg tote bags, but before grinding, each batch was mechanically sieved and cleaned. Each batch of corn was ground using a hammer mill (Model 1522, Roskamp Champion, Waterloo, IA, USA) and a particle size with a geometric mean diameter of 400 µm was targeted. Experimental diets based on each batch of ground corn were manufactured at the North Carolina State Feed Mill Education Unit, Raleigh, NC, USA, using a ribbon mixer (Model TRDB126060, Hayes & Stolz, Fort Worth, TX, USA). All diets were prepared in meal form. Following manufacturing and bagging, diets were shipped to the University of Illinois, Urbana-Champaign, IL, USA, where the animal work was conducted.

Experiment 1: Amino acid and starch digestibility

Animals, dietary treatments, and experimental procedures

Five diets were prepared (Tables 2 and 3). Four diets contained each source of corn as the only source of CP and AA. The last diet was a nitrogen-free diet that was used to measure basal ileal endogenous losses of AA and CP. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% titanium dioxide as an indigestible marker.

Ten pigs (initial body weight: 67.00 ± 2.98 kg) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and then allotted to a replicated 5 × 5 Latin square design (Kim and Stein, 2009) with five diets and five periods of 7 d. There was, therefore, 10 ($n = 10$) replicate pigs per treatment. Pigs had been used in a different experiment before being allotted to treatment diets used in this experiment, and a corn–soybean meal-based grower diet was fed to all pigs for 7 d between the two experiments. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted tribar floors, and a feeder and a nipple drinker were installed in each pen.

All pigs were limit-fed at 3.2 times the maintenance energy requirement (i.e., 197 kcal/kg$^{0.60}$; NRC, 2012), and water was available at all times. Feed was provided daily in two equal meals at 0800 and 1600 h. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment, and the amount of feed supplied each day was recorded. The initial 5 d of each period were considered an adaptation period to the diet. Ileal digesta samples were collected for 9 h on days 6 and 7 using standard operating procedures (Stein et al., 1998). In short, the cannulas were opened, a 225-mL plastic bag was attached to the cannula barrel using a cable tie, and digesta flowing into the bag were collected. Bags were removed whenever they were full or every 30 min and replaced with a new bag. All samples were stored at −20 °C as soon as they were collected to prevent bacterial degradation of AA. On the completion of one experimental period, animals were deprived of feed overnight, and the following morning, a new experimental diet was offered.

Sample analyses

At the conclusion of the experiment, ileal digesta samples were thawed, mixed within animal and diet, and a sub-sample was collected for chemical analysis. A sample of each source of corn and each diet was also collected. Digesta samples were lyophilized and finely ground before chemical analysis. Samples of diets, digesta, and ingredients were analyzed for *N* (Method 990.03; AOAC Int., 2019) on an FP628 protein analyzer (Leco

Table 1. Analyzed nutrient composition of four batches of corn, as-fed basis[1,2]

Item	Corn, average endosperm		Corn, hard endosperm	
	35 °C	120 °C	35 °C	120 °C
Dry matter, %	88.95	87.56	89.47	90.28
Crude protein, %	6.27	6.79	6.64	7.22
Gross energy, kcal/kg	3,883	3,858	3,957	3,962
Starch, %	66.30	65.60	66.70	66.20
Acid hydrolyzed ether extract, %	3.44	3.74	3.57	3.44
Soluble dietary fiber, %	0.70	0.70	1.10	1.00
Insoluble dietary fiber, %	10.30	10.10	10.40	10.60
Total dietary fiber, %	11.00	10.80	11.40	11.60
Indispensable amino acids, %				
Arg	0.32	0.35	0.33	0.34
His	0.18	0.20	0.20	0.21
Ile	0.22	0.25	0.26	0.27
Leu	0.64	0.74	0.75	0.81
Lys	0.24	0.26	0.26	0.25
Met	0.18	0.20	0.21	0.20
Phe	0.28	0.32	0.32	0.34
Thr	0.23	0.25	0.25	0.26
Trp	0.05	0.05	0.06	0.05
Val	0.29	0.33	0.33	0.35
Dispensable amino acids, %				
Ala	0.44	0.50	0.50	0.53
Asp	0.42	0.47	0.47	0.47
Cys	0.16	0.18	0.16	0.16
Glu	1.07	1.22	1.22	1.31
Gly	0.29	0.31	0.29	0.30
Ser	0.29	0.31	0.31	0.33
Tyr	0.20	0.22	0.21	0.23
Lys:CP	3.83	3.83	3.92	3.46

[1]Vitreousness: 60.59%, average endosperm corn: DeKalb 6357, and 62.83%, hard endosperm corn: DeKalb 6869. Vitreousness was analyzed by near-infrared reflectance spectroscopy (AB Vista, Plantation, FL, USA).
[2]The mean particle size of the average endosperm corn and hard endosperm corn was 369 and 429 µm, respectively.

Corporation, St. Joseph, MI, USA) and CP was calculated (i.e., analyzed $N \times 6.25$). These samples were also analyzed for dry matter (**DM**; Method 930.15; AOAC Int., 2019), and starch was analyzed using the glucoamylase procedure (Method 979.10; AOAC Int., 2019). Samples of diets, digesta, and ingredients were also analyzed for AA on a Hitachi AA Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA, USA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard [Method 982.30 E (a, b, c); AOAC Int., 2019]. Ingredients were analyzed for acid hydrolyzed ether extract (**AEE**) by acid hydrolysis using 3 *N* HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA; Method 2003.06; AOAC Int., 2019). Diets and digesta samples were analyzed for titanium (Myers et al., 2004).

Calculations and statistical analysis

Values for apparent ileal digestibility (**AID**) of DM, starch, CP, and AA in the four corn diets were calculated (Stein et al., 2007). The basal ileal endogenous losses of CP and AA were calculated from pigs fed the N-free diet and values for SID of CP and AA in each corn diet were calculated by correcting AID values for the basal ileal endogenous losses (Stein et al., 2007).

Data were analyzed as a 2 × 2 factorial using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC, USA). Homogeneity of variances was confirmed using the UNIVARIATE procedure, and outliers were detected as observations that deviated from the treatment mean by±3 times the interquartile range. The model included corn variety, drying temperature, and the interaction between corn variety and drying temperature. Period, square, and pig were random effects. Means were calculated using the LSMEANS statement of SAS. Pig was the experimental unit, and results were considered significant at $P \leq 0.05$ and considered a tendency at $P \leq 0.10$.

Experiment 2: Digestibility of energy and total dietary fiber

Animals, dietary treatments, and experimental procedures

The four corn-based diets used in experiment 1 were also used in experiment 2. Forty pigs (initial body weight: 20.82 ± 1.74 kg)

Table 2. Ingredient composition of diets used in experiments 1 and 2, as-fed basis[1]

Item	Corn, average endosperm		Corn, hard endosperm		N-free
	35 °C	120 °C	35 °C	120 °C	
Corn, average endosperm (35 °C)	96.62	—	—	—	—
Corn, average endosperm (120 °C)	—	96.62	—	—	—
Corn, hard endosperm (35 °C)	—	—	96.62	—	—
Corn, hard endosperm (120 °C)	—	—	—	96.62	—
Soybean oil	—	—	—	—	4.00
Solca flok[2]	—	—	—	—	4.00
Dicalcium phosphate	1.60	1.60	1.60	1.60	2.15
Limestone	0.80	0.80	0.80	0.80	0.45
Cornstarch	—	—	—	—	67.92
Sucrose	—	—	—	—	20.00
Titanium dioxide	0.40	0.40	0.40	0.40	0.40
Magnesium oxide	—	—	—	—	0.10
Potassium carbonate	—	—	—	—	0.40
Sodium chloride	0.40	0.40	0.40	0.40	0.40
Vitamin premix[3]	0.03	0.03	0.03	0.03	0.03
Micro mineral premix[4]	0.15	0.15	0.15	0.15	0.15

[1]The N-free diet was used only in experiment 1.
[2]Fiber Sales and Development Corp., Urbana, OH, USA.
[3]The vitamin premix provided per kg of complete diet: 6,614 IU of vitamin A as vitamin A acetate, 992 IU of vitamin D3, 19.8 IU of vitamin E, 2.64 mg of vitamin K as menadione sodium bisulfite, 0.03 mg of vitamin B12, 4.63 mg of riboflavin, 18.52 mg of d-pantothenic acid as calcium panthonate, 24.96 mg of niacin, and 0.07 mg of biotin.
[4]The micro mineral premix provided per kg of complete diet: 33 mg of Mn as manganous oxide, 110 mg of Fe as ferrous sulfate, 110 mg of Zn as zinc sulfate, 16.5 mg of Cu as copper sulfate, 0.30 mg of I as ethylenediamine dihydroiodide, and 0.30 mg of Se as sodium selenite.

were allotted to the 4 diets with 10 replicate pigs per diet using a randomized complete block design with body weight being the blocking factor. All diets were fed in meal form. Pigs were placed in individual metabolism crates equipped with a self-feeder, a nipple waterer, and a slatted floor to allow for the total, but separate, collection of urine and fecal materials.

Pigs were limit-fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal/kg$^{0.60}$; NRC, 2012), which were provided each day in two equal meals at 0800 and 1600 h. Throughout the experiment, pigs had free access to water. The initial 5 d were considered the adaptation period to the diet, and urine and fecal materials were collected from the feed provided during the following 4 d according to standard procedures using the marker-to-marker method (Adeola, 2001). Urine samples were collected in urine buckets over a preservative of 50 mL 3 *N* hydrochloric acid. Fecal samples and 20% of the collected urine were stored at −20 °C immediately after collection.

Sample analyses

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis (Kim et al., 2009). Fecal samples were thawed and mixed within pig and diet and then dried in a 50 °C forced-air drying oven prior to analysis. Ingredients, diets, and fecal samples were analyzed for DM (Method 930.15; AOAC Int., 2019) and soluble dietary fiber (**SDF**) and insoluble dietary fiber (**IDF**) according to method 991.43 (AOAC Int., 2019) using the Ankom TDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of SDF and IDF. Fecal, urine, diet, and ingredient samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA).

Calculations and statistical analysis

Following chemical analysis, the ATTD of GE and TDF was calculated for each diet, and DE and ME in each diet were calculated as well (Adeola, 2001). Data were analyzed as explained for experiment 1 with the exception that block was considered the random effect for experiment 2.

Results

Moisture in the four batches of corn was less than 13% and CP was greater than 6% with Lys in each batch of corn being within the expected range. Average endosperm corn and hard endosperm corn had a mean GE concentration of 3,871 and 3,962 kcal/kg, respectively. Concentration of starch in both sources of corn was greater than 65%, and AEE was within the expected range. Insoluble dietary fiber concentrations were much greater than concentrations of SDF in all sources of corn. The mean particle size of the average endosperm corn was 369 µm and for the hard endosperm corn, a mean particle size of 429 µm was obtained.

Experiment 1: Amino acid digestibility

Diet analyses indicated that the intended concentrations of CP and AA were present in all diets. All pigs remained healthy during the experimental period, and feed refusals were negligible.

No interaction was observed between corn hardness and drying temperature for AID of DM, starch, CP, or AA

Table 3. Analyzed nutrient composition of diets, as-fed basis

Item	Corn, average endosperm		Corn, hard endosperm		N-free
	35 °C	120 °C	35 °C	120 °C	
Dry matter, %	90.36	90.85	90.35	90.64	93.42
Crude protein, %	5.91	6.33	6.17	6.82	0.14
Starch, %	63.80	61.20	61.60	62.70	—
Gross energy, Mcal/kg	3.74	3.71	3.82	3.83	—
Soluble dietary fiber, %	0.60	0.70	1.00	1.10	—
Insoluble dietary fiber, %	10.20	9.90	10.00	9.80	—
Total dietary fiber, %	10.80	10.60	11.00	10.90	—
Indispensable amino acids, %					
Arg	0.32	0.32	0.30	0.31	0.01
His	0.18	0.19	0.18	0.20	0.00
Ile	0.22	0.24	0.24	0.26	0.02
Leu	0.63	0.72	0.71	0.81	0.02
Lys	0.25	0.24	0.24	0.24	0.01
Met	0.17	0.17	0.18	0.18	0.01
Phe	0.28	0.31	0.31	0.34	0.01
Thr	0.23	0.24	0.24	0.26	0.01
Trp	0.05	0.05	0.05	0.05	0.02
Val	0.29	0.31	0.30	0.33	0.01
Dispensable amino acids, %					
Ala	0.43	0.47	0.47	0.52	0.01
Asp	0.42	0.43	0.43	0.47	0.01
Cys	0.15	0.15	0.15	0.15	0.00
Glu	1.04	1.16	1.14	1.29	0.03
Gly	0.29	0.29	0.27	0.29	0.01
Ser	0.27	0.29	0.29	0.31	0.01
Tyr	0.20	0.21	0.19	0.21	0.00

(Table 4). Neither corn hardness nor drying temperature influenced the AID of starch in corn. Likewise, the AID of DM did not differ between hard endosperm corn and average endosperm corn. Hard endosperm corn had greater ($P < 0.05$) AID of Leu, Phe, Ala, and Glu compared with average endosperm corn. The AID of Ile and Met also tended to be greater ($P < 0.10$) in hard endosperm corn compared with average endosperm corn. Corn dried at 120 °C had reduced ($P < 0.05$) AID of DM compared with corn dried at 35 °C. The AID of Arg, Lys, Met, and Cys was less ($P < 0.05$) in corn dried at 120 °C than in corn dried at 35 °C. Likewise, corn dried at 120 °C tended to have reduced ($P < 0.10$) AID of Trp, Asp, and Ser.

No interaction between corn hardness and drying temperature was observed for the SID of CP and AA (Table 5). No differences were observed between hard endosperm corn and average endosperm corn for the SID of CP and AA, except that the SID of Leu tended ($P < 0.10$) to be greater in hard endosperm corn than in average endosperm corn. The SID of CP, Arg, His, Lys, Met, Thr, Ala, Asp, Cys, Glu, Ser, and Tyr was less ($P < 0.05$) in corn dried at 120 °C compared with corn dried at 35 °C. The SID of Ile, Trp, and Val also tended to be less ($P < 0.10$) in corn dried at 120 °C than in corn dried at 35 °C. As a result, concentrations of standardized ileal digestible CP and most AA were less in corn dried at 120 °C than in corn dried at 35 °C.

Experiment 2: Digestibility of energy and total dietary fiber

No interaction was observed between corn hardness and drying temperature for ATTD of SDF, IDF, TDF, and GE in experimental diets (Table 6). Diets containing hard endosperm corn had greater ($P < 0.05$) ATTD of SDF, IDF, and TDF than those containing average endosperm corn. Diets containing corn dried at 120 °C had greater ($P < 0.05$) ATTD of IDF and TDF compared with diets containing corn dried at 35 °C.

Pigs fed the hard endosperm corn diets tended to have reduced ($P < 0.10$) fecal GE loss compared with pigs fed the average endosperm corn diets. As a result, the ATTD of GE in hard endosperm corn was greater ($P < 0.05$), and concentrations of DE and ME (as-fed) in hard endosperm corn were greater ($P < 0.01$) compared with average endosperm corn. Drying temperature did not influence the ATTD of GE or concentrations of DE and ME in corn.

Discussion

Analyzed concentrations of CP, AEE, and GE in in each of the four batches of corn used in this experiment were close to published values for conventional corn (Sauvant et al., 2004; NRC, 2012; Thomas et al., 2020). The analyzed values for starch and TDF in the two corn varieties were also in accordance with previous data for corn (NRC, 2012; Thomas et

Table 4. Apparent ileal digestibility (AID) of dry matter, starch, crude protein (CP), and amino acids (AA) in four batches of corn, experiment 1[1,2]

Item	Corn source				Drying temperature			
	Average endosperm	Hard endosperm	SEM	*P*-value	35 °C	120 °C	SEM	*P*-value
Dry matter, %	69.0	70.1	1.45	0.483	71.2	68.0	1.44	0.026
Starch, %	91.8	91.7	0.74	0.975	91.9	91.6	0.74	0.633
Crude protein, %	39.7	40.5	3.76	0.827	42.8	37.1	3.81	0.125
Indispensable AA, %								
Arg	59.8	59.9	3.09	0.958	62.4	56.7	3.26	0.031
His	64.4	64.8	1.74	0.774	65.6	63.6	1.74	0.152
Ile	52.3	56.4	1.80	0.056	55.4	53.5	1.79	0.370
Leu	71.5	74.9	1.00	0.011	73.7	72.8	1.03	0.505
Lys	22.9	20.5	3.64	0.502	25.3	17.4	3.75	0.022
Met	73.0	75.3	1.18	0.094	75.9	72.5	1.12	0.012
Phe	62.9	66.5	1.21	0.022	65.4	64.2	1.25	0.458
Thr	34.9	38.1	2.30	0.147	38.0	35.1	2.30	0.197
Trp	51.1	49.4	2.73	0.553	52.9	47.7	2.75	0.058
Val	51.9	54.6	1.67	0.205	54.4	52.2	1.67	0.297
Dispensable AA, %								
Ala	57.9	61.8	2.21	0.028	61.4	58.5	2.16	0.121
Asp	45.0	48.1	2.26	0.189	48.7	44.6	2.21	0.084
Cys	54.8	55.4	2.11	0.822	58.9	51.6	2.08	0.002
Glu	69.0	71.8	1.31	0.029	71.2	69.8	1.29	0.284
Gly	24.1	20.5	3.91	0.411	21.0	24.0	3.93	0.501
Ser	53.7	56.9	2.16	0.137	57.3	53.4	2.16	0.065
Tyr	56.1	56.1	1.56	0.994	57.4	54.8	1.54	0.168

[1]Data are least squares means of 20 observations per treatment (i.e., average endosperm vs. hard endosperm; 35 °C and 120 °C).
[2]Corn source × drying temperature effects were not significant; therefore, only main effects are indicated.

al., 2020; Espinosa et al., 2021). Analyzed nutrients in the four batches of corn indicate that drying temperature did not change nutrient composition, which concurs with reported data (Li et al., 2014).

Experiment 1: Amino acid and starch digestibility

Most SID values for AA obtained in hard endosperm corn and average endosperm corn were in agreement with reported data (Pedersen et al., 2007; NRC, 2012), but SID values for Lys were less compared with values reported by NRC (2012). However, the SID of Lys obtained in this experiment was close to the SID of Lys reported by Espinosa et al. (2021) for conventional corn, which may be due to processing conditions and natural differences among corn varieties (Pedersen et al., 2007).

The AID of starch was in agreement with data for corn ground to approximately 650 µm (Rojas and Stein, 2015). Endosperm hardness may influence pig nutrient digestibility, intestinal integrity, and feeding behavior due to differences in starch structure (e.g., concentration of resistant and damaged starch; Kaczmarek et al., 2014; Córdova-Noboa et al., 2021a). However, the lack of differences in the AID of starch and SID of AA between hard endosperm corn and average endosperm corn indicates that endosperm hardness does not influence starch and AA digestibility under the conditions of this experiment. The observed lack of difference in AA digestibility is in agreement with data reported by Kil et al. (2014) indicating no difference in AA digestibility among corn sources of different origins. However, the observed lack of difference in AID of starch is in contrast with data indicating that starch retention was greater in broiler chickens fed corn diets with average kernel hardness compared with hard kernels (Córdova-Noboa et al., 2021a), but it is likely that due to the gizzard in broiler chickens, they respond differently than pigs to differences in endosperm hardness in corn. Starch digestibility in corn is influenced by particle size and extrusion (Rojas and Stein, 2015; Rojas et al., 2016; Rodriguez et al., 2020), but based on results of this experiment, it does not appear that kernel hardness influences starch digestibility.

Corn can be dried under dry weather conditions or by using air-forced dryers (Córdova-Noboa et al., 2020), but varying temperatures during drying of corn may influence nutrient digestibility and pig growth performance. Body weight gain was reduced when broiler chickens were fed diets with corn dried at 140 °C compared with broilers fed diets with corn dried at 60 °C (Kaczmarek et al., 2014). Indeed, the observation in this experiment that AID of DM and SID of CP and AA in corn dried at 120 °C was reduced compared with AID and SID values in corn dried at 35 °C demonstrates that use of high temperatures to dry corn negatively influences AA digestibility, which may be the reason for the reduced growth performance of broiler chickens observed by Kaczmarek et al. (2014). This observation is in agreement with data indicating that true N digestibility and AA availability of corn decreased if high drying temperatures were applied (i.e., 125 °C; Rivera et al., 1978). Excess heat may reduce digestibility and concentrations of AA due to formation of Maillard reaction

Table 5. Standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in four batches of corn, experiment 1[1,2,3]

Item	Corn source				Drying temperature			
	Average endosperm	Hard endosperm	SEM	*P*-value	35 °C	120 °C	SEM	*P*-value
Crude protein, %	74.9	73.8	3.76	0.779	78.3	69.9	3.79	0.028
Indispensable AA, %								
Arg	83.1	84.4	3.08	0.658	86.4	80.4	3.28	0.023
His	79.2	79.2	1.74	0.982	80.7	77.6	1.73	0.030
Ile	74.2	76.5	1.82	0.280	77.2	73.7	1.79	0.095
Leu	82.3	84.6	1.01	0.096	84.6	82.4	1.00	0.102
Lys	65.4	63.9	3.66	0.672	67.8	60.9	3.75	0.043
Met	81.3	83.1	1.18	0.178	83.9	80.6	1.12	0.011
Phe	78.2	80.3	1.24	0.167	80.6	78.1	1.22	0.105
Thr	68.0	69.4	2.32	0.569	71.0	66.3	2.28	0.037
Trp	77.4	75.7	2.74	0.543	79.2	74.1	2.75	0.064
Val	72.4	74.2	1.69	0.426	75.2	71.5	1.66	0.083
Dispensable AA, %								
Ala	81.7	83.5	2.22	0.344	85.1	80.3	2.17	0.007
Asp	73.4	74.9	2.27	0.529	77.0	71.5	2.22	0.021
Cys	72.6	73.2	2.11	0.829	76.6	69.4	2.08	0.002
Glu	83.0	84.5	1.32	0.255	85.3	82.4	1.29	0.028
Gly	115.7	115.9	3.88	0.962	115.9	115.5	3.90	0.929
Ser	80.2	81.7	2.17	0.521	83.8	78.3	2.15	0.009
Tyr	75.5	76.0	1.58	0.810	77.9	73.8	1.54	0.040

[1]Data are least squares means of 20 observations per treatment (i.e., average endosperm vs. hard endosperm; 35 °C and 120 °C).
[2]Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 23.71; Arg, 0.82; His, 0.30; Ile, 0.56; Leu, 0.81; Lys, 1.17; Met, 0.16; Phe, 0.50; Thr, 0.85; Trp, 0.14; Val, 0.68; Ala, 1.13; Asp, 1.32; Cys, 0.30; Glu, 1.69; Gly, 2.76; Ser, 0.80; and Tyr, 0.44.
[3]Corn source × drying temperature effects were not significant; therefore, only main effects are indicated.

Table 6. Apparent total tract digestibility (**ATTD**) of dietary fiber in experimental diets and concentration of digestible energy (**DE**) and metabolizable energy (**ME**) in experimental diets and four batches of corn, experiment 2[1,2,3]

Item	Corn source				Drying temperature			
	Average endosperm	Hard endosperm	SEM	*P*-value	35 °C	120 °C	SEM	*P*-value
Diets								
ATTD of SDF[3], %	64.7	73.0	2.20	0.023	67.4	71.3	2.35	0.168
ATTD of IDF[3], %	64.1	67.8	1.38	0.039	64.0	67.9	1.38	0.044
ATTD of TDF[3], %	63.4	68.3	1.41	0.011	63.8	67.9	1.44	0.032
ATTD of GE, %	88.0	89.4	0.52	0.049	88.2	89.3	0.53	0.149
DE, kcal/kg	3,279	3,423	19	<0.001	3,334	3,367	25	0.254
ME, kcal/kg	3,201	3,348	21	<0.001	3,264	3,286	27	0.458
Ingredients								
ATTD of GE, %	88.0	89.4	0.52	0.049	88.2	89.3	0.53	0.149
DE, kcal/kg	3,403	3,553	20	<0.001	3,461	3,495	26	0.254
ME, kcal/kg	3,322	3,475	22	<0.001	3,388	3,411	28	0.459

[1]Data are least squares means of 20 observations per treatment (i.e., average endosperm vs. hard endosperm; 35 °C and 120 °C).
[2]Corn source × drying temperature effects were not significant; therefore, only main effects are indicated.
[3]SDF, soluble dietary fiber; IDF, insoluble dietary fiber; TDF, total dietary fiber.

products (Pahm et al., 2008; González-Vega et al., 2011; Almeida et al., 2013). Nevertheless, drying corn at 120 °C or even higher temperatures are not uncommon in the industry, and the reduced digestibility of AA that was observed in this experiment for corn dried at 120 °C likely is representative of what is happening under practical conditions if corn is dried at a high temperature. To avoid initiating the Maillard reaction, and thereby reduce SID of AA, it may be necessary to avoid drying corn at temperatures greater than 100 °C, Recently, it was also concluded that SID of AA was reduced if canola meal was autoclaved at a temperature greater than 110 °C (Oliveira et al., 2020).

Experiment 2: Digestibility of energy and total dietary fiber

Values for ATTD of GE and DE and ME in the sources of corn used in the experiment agree with reported data for conventional corn (NRC, 2012; Espinosa and Stein, 2018) despite a greater concentration of AEE in the corn used in this experiment compared with previous experiments. However, the digestibility of AEE in corn is relatively low (Kim et al., 2013), which may be the reason the greater AEE did not result in increased DE and ME in the corn grain.

The amount of amylose and amylopectin in corn starch depends on the maturity and endosperm hardness (Dombrink-Kurtzman and Knutson, 1997). Therefore, the difference in energy digestibility between hard and average endosperm corn indicates that kernel vitreousness influences digestion of polysaccharides (Córdova-Noboa et al., 2020). The increase in energy digestibility in hard endosperm corn may be a result of the increase in ATTD of TDF.

The greater ATTD of TDF in corn dried at 120 °C instead of at 35 °C indicates that applying heat to corn may modify the physico-chemical characteristics in corn, which consequently influences nutrient digestibility (Hancock and Behnke, 2001). This observation also agree with data demonstrating that extrusion and pelleting influence nutrient digestibility (Rojas et al., 2016; Lancheros et al., 2020; Rodriguez et al., 2020). The lack of a difference in ATTD of GE between corn dried at 35 °C and corn dried at 120 °C indicates that drying temperature does not influence energy digestibility under the conditions of this experiment. This is in agreement with Li et al. (2014), indicating that drying corn at 120 °C was not enough to increase starch gelatinization and subsequently increase energy digestibility in corn. The observed lack of a difference in the AID of starch in the ileal digestibility experiment also indicates that energy digestibility was not influenced by treatments because there is a close relationship between starch digestibility and energy digestibility in corn (Rojas and Stein, 2015; Rodriguez et al., 2020).

Conclusion

Results from this work indicated that neither corn endosperm hardness nor drying temperature influenced the AID of starch in corn. Endosperm hardness did also not influence the AID of DM or SID of most AA in corn; however, the AID of DM and SID values for CP and most AA in corn dried at 120 °C were less than in corn dried at 35 °C. This resulted in reduced concentrations of most standardized ileal digestible AA in corn dried at 120 °C compared with corn dried at 35 °C. These results indicate that if the grain industry can avoid drying corn to more than 100 °C, the risk of overheating and reduced AA digestibility in corn is greatly reduced. Hard endosperm corn had greater ATTD of TDF and GE than average endosperm corn, resulting in greater concentrations of DE and ME in hard endosperm corn. Drying temperature did not influence the ATTD of GE and energy concentrations in corn; however, the ATTD of TDF in corn dried at 120 °C was greater than in corn dried at 35 °C. Therefore, further research is needed to determine the optimum drying temperature and kernel hardness to maximize the nutritional value in corn.

Conflict of interest statement

The authors have no conflicts of interest.

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