Animal Feed Science and Technology 268 (2020) 114602

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci

Digestibility of amino acids, fiber, and energy by growing pigs, and concentrations of digestible and metabolizable energy in yellow dent corn, hard red winter wheat, and sorghum may be influenced by extrusion

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ARTICLE INFO

Keywords:
Extrusion
Gelatinization
Feed processing
Grains
Starch
Swine

ABSTRACT

Two experiments were conducted to determine effects of extrusion on energy and nutrient digestibility in cereal grains fed to growing pigs. One source of yellow dent corn, one source of hard red winter wheat, and one source of sorghum were ground to approximately 300 microns and each source of grain was divided into 2 batches. One batch of each grain was extruded, whereas the other batch was used without further processing. In Exp. 1, 7 diets were formulated to determine ileal starch and amino acid (AA) digestibility in the grains. Three diets contained the non-extruded grains and 3 diets contained the extruded grains. The last diet was an N-free diet that was used to determine basal endogenous losses of AA from the pigs. Seven growing barrows (initial body weight = 14.2 ± 0.9 kg) had a T-cannula installed in the distal ileum and were allotted to a 7 × 7 Latin square. Each experimental period lasted 7 days with the initial 5 days being the adaptation period and ileal digesta were collected on days 6 and 7. Results indicated that extruded grains had greater ($P < 0.001$) apparent ileal digestibility (AID) of starch than non-extruded grains. Extrusion also increased standardized ileal digestibility (SID) of crude protein (CP) and all AA except Lys and Pro in corn, but the SID of CP and AA in wheat and sorghum was not affected by extrusion. In Exp. 2, 6 diets were used. Three diets contained the non-extruded corn, wheat, or sorghum, and 3 diets contained the extruded grains. Forty eight growing barrows (initial body weight = 15.1 ± 3.7 kg) were allotted to a randomized complete block design. Pigs were housed individually in metabolism crates and feces and urine were collected separately for 5 days after 5 days of adaptation. The apparent total tract digestibility (ATTD) of gross energy was increased by extrusion of corn or sorghum, but that was not the case for wheat (interaction, $P < 0.001$). The ATTD of neutral detergent fiber in wheat was reduced by extrusion, but not in corn and sorghum (interaction, $P < 0.001$). However, extrusion reduced ($P < 0.05$) the ATTD of acid detergent fiber in all grains. Extrusion increased the digestible energy (DE) and

Abbreviations: AA, amino acids; ADF, acid detergent fiber expressed inclusive of residual ash; 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; ME, metabolizable energy; aNDF, neutral detergent fiber assayed with a heat stable amylase and expressed inclusive of residual ash; SID, standardized ileal digestibility

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[1] Partial funding for this research from Evonik Nutrition & Care GmbH (Hanau, Germany) is greatly appreciated.

https://doi.org/10.1016/j.anifeedsci.2020.114602
Received 1 December 2019; Received in revised form 13 June 2020; Accepted 22 June 2020

metabolizable energy (ME) in corn and sorghum (DM-basis) compared with non-extruded grains, but there was no increase in DE and ME (DM-basis) if wheat was extruded (interaction, $P <$ 0.001). In conclusion, extrusion increased the AID of starch in all grains and the ATTD of energy and the DE and ME in corn and sorghum. The SID of most AA in corn was also increased by extrusion.

1. Introduction

Extrusion of cereal grains may be used to improve growth performance of weanling pigs (Hancock and Behnke, 2001) because the heat and pressure in combination with addition of moisture that is applied during extrusion may gelatinize the starch in the grains. Extrusion may also improve the digestibility of starch and amino acids (AA) in field peas (Sun et al., 2006; Stein and Bohlke, 2007), and extrusion of corn in combination with other ingredients improves energy and AA digestibility (Liu et al., 2015; Rojas et al., 2016). Extrusion of mixed diets may also increase the concentration of digestible energy (DE) and of metabolizable energy (ME) and the response seems to be more pronounced in high fiber diets than in low fiber diets indicating that extrusion may increase the solubility of dietary fiber (Rojas et al., 2016).

The extrusion parameters that most likely result in increased digestibility of AA and starch are the application of steam and heat during the extrusion process, which may change the three dimensional structure of proteins and gelatinize the starch. The temperature as well as the time of heating are also important parameters because overheating will result in reduced AA digestibility.

Although cereal grains generally have low concentrations of dietary fiber it is possible that if extrusion results in increased digestibility of starch or AA, the digestibility of energy may also increase, but data to verify this hypothesis have not been published. As a consequence, it is currently not possible to formulate diets by taking extrusion effects into account because data for the uplift in AA and energy digestibility for cereal grains are not available. Therefore, the objective of these experiments was to test the hypothesis

Table 1
Chemical composition of non-extruded and extruded cereal grains[a].

Item, g/kg	Corn		Wheat		Sorghum	
Extruded	–	+	–	+	–	+
Dry matter	886.9	910.8	886.2	906.7	882.3	910.7
Gross energy, MJ/kg	16.1	16.4	16.1	16.1	16.0	16.4
Acid-hydrolyzed ether extract	34.1	37.4	20.1	25.7	31.3	37.3
Ash	12.3	11.1	16.0	16.8	11.5	12.1
Neutral detergent fiber[b]	86.1	63.7	117.8	98.9	83.6	61.8
Acid detergent fiber	27.7	19.3	36.7	31.6	36.5	23.7
Tannic acid	–	–	–	–	1.6	1.5
Total starch	590.7	669.1	547.5	584.8	592.3	639.7
Gelatinized starch	60.4	607.3	67.5	546.8	63.4	563.8
Gelatinized starch, % of total	10.2	90.8	12.3	93.5	10.7	88.1
Crude protein	78.0	76.0	133.1	134.4	94.9	92.7
Lys to crude protein, %	3.21	3.21	2.70	2.75	2.11	2.05
Indispensable amino acids						
Arg	3.6	3.7	6.3	6.4	3.4	3.1
His	2.1	2.1	3.0	3.0	2.0	1.8
Ile	2.6	2.5	4.5	4.5	3.5	3.1
Leu	8.6	8.4	8.5	8.5	12.0	10.0
Lys	2.5	2.5	3.6	3.7	2.0	1.9
Met	1.8	1.6	2.1	2.0	1.6	1.4
Phe	3.5	3.7	6.0	6.0	4.5	4.2
Thr	2.8	2.7	3.7	3.7	2.9	2.6
Trp	0.6	0.6	1.6	1.6	1.0	0.9
Val	3.6	3.5	5.6	5.5	4.5	4.0
Total	31.6	31.2	44.8	44.9	37.4	33.0
Dispensable amino acids						
Ala	5.5	5.3	4.5	4.7	8.4	7.0
Asp	5.3	5.2	6.5	6.7	6.0	5.3
Cys	1.6	1.6	3.0	2.9	1.7	1.5
Glu	13.8	13.3	36.8	36.3	19.1	16.1
Gly	3.0	3.0	5.3	5.3	2.9	2.7
Pro	6.1	6.1	13.1	13.0	7.9	6.5
Ser	3.6	3.5	5.9	5.8	4.0	3.6
Total	38.7	38.0	75.1	74.6	49.8	42.7

[a] All values except dry matter were adjusted to 88 % dry matter.
[b] Neutral detergent fiber was assayed with a heat stable amylase and expressed inclusive of residual ash.

that the ileal digestibility of AA and starch, and the apparent total tract digestibility (ATTD) of acid detergent fiber (ADF), neutral detergent fiber (aNDF), and gross energy (GE) as well as the DE and ME in corn, wheat, and sorghum are increased by extrusion.

2. Materials and methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for 2 experiments. Pigs were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

One source of yellow dent corn, one source of hard red winter wheat, and one source of grain sorghum were ground using a hammermill (Bliss Industries, LLC, Model Eliminator, Ponca City, OK, USA) to a particle size of 300 μm ± 50 μm and divided into 2 batches. One batch of each grain was used without further processing, whereas the other batch was extruded (Table 1). Therefore, a total of 6 batches of grain were used. Both batches of each grain were transported to the University of Illinois where diets for both experiments were prepared and the two animal experiments were conducted.

The extruded grains were processed using an Extru-tech E325 single-screw extruder (Extru-tech, Sabetha, KS, USA), using parameters described by Hongtrakul et al. (1998) and recommended by the manufacturer for swine diets. Briefly, barrel jacket temperature was 138 °C, internal pressure was 21.2 kg/cm^2, and production rate was 2.3 kg/min to reach a 100 °C exit temperature.

2.1. Exp. 1. Ileal digestibility of starch and amino acids

2.1.1. Diets and animals

Seven diets were formulated (Tables 2 and 3). Three diets contained the non-extruded corn, wheat, or sorghum and 3 additional diets contained the extruded grains. The last diet was an N-free diet that was used to determine basal endogenous losses of AA from the pigs. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 4.0 g/kg chromic oxide as an indigestible marker.

Seven growing barrows (initial body weight = 14.2 ± 0.9 kg and final body weight = 32.1 ± 5.1 kg) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a 7 × 7 Latin square design with 7 diets and 7 periods. Therefore, there were 7 observations per treatment.

2.1.2. Housing, feeding, and sample collection

Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted T-bar floors. Each pen was equipped with a feeder and a nipple drinker. Pigs were fed their diets in an amount equivalent to 3.4 times the maintenance energy requirement (i.e., 197 kcal per kg body weight$^{0.6}$; NRC, 2012) and water was available at all times. The daily feed allotment was provided at 0700 h. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. An AA mixture was provided to all pigs during the initial 5 days of each period to avoid AA deficiency, but the mixture was not fed on days 6 and 7 (Table 4). The initial 5 days of each period was considered the adaptation period to the diet, but ileal digesta were collected for 8 h on days 6 and 7 using standard procedures (Stein et al., 1998). In short, a plastic bag was attached to the

Table 2
Composition of experimental diets (as-is basis, Exp. 1).

Item, g/kg	Corn		Wheat		Sorghum		N-free
Extruded	–	+	–	+	–	+	–
Grain	935.0	935.0	938.5	938.5	935.5	935.5	–
Soybean oil	30.0	30.0	30.0	30.0	30.0	30.0	40.0
Solka floc	–	–	–	–	–	–	40.0
Dicalcium phosphate	16.0	16.0	8.0	8.0	15.0	15.0	21.5
Limestone	8.0	8.0	12.5	12.5	8.5	8.5	4.5
Cornstarch	–	–	–	–	–	–	528.0
Lactose	–	–	–	–	–	–	200.0
Sucrose	–	–	–	–	–	–	150.0
Chromic oxide	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Magnesium oxide	–	–	–	–	–	–	1.0
Potassium carbonate	–	–	–	–	–	–	4.0
Sodium cloride	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-mineral premix[a]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Total	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0

[a] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as $_{DL}$-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 3
Analyzed chemical compositions of experimental diets[a] (Exp. 1).

Item, g/kg	Corn		Wheat		Sorghum		N-free
Extruded	–	+	–	+	–	+	–
Dry matter	896.6	914.8	895.0	909.4	891.0	914.5	935.4
Starch	546.6	551.5	532.9	519.5	549.3	638.0	445.6
Crude protein	71.3	72.1	123.0	122.6	89.0	76.2	9.0
Indispensable amino acids							
Arg	3.4	3.5	5.9	5.9	3.3	3.0	0.1
His	2.0	1.9	2.8	2.7	1.9	1.7	0.1
Ile	2.5	2.4	4.1	4.1	3.4	2.9	0.1
Leu	8.2	8.1	8.0	8.0	11.5	9.4	0.2
Lys	2.4	2.3	3.2	3.4	1.8	1.7	0.2
Met	1.7	1.5	1.9	1.8	1.5	1.3	0.1
Phe	3.6	3.6	5.7	5.6	4.6	3.8	0.2
Thr	2.7	2.5	3.4	3.5	2.8	2.4	0.1
Trp	0.6	0.6	1.5	1.5	1.0	0.9	0.2
Val	3.3	3.3	5.2	5.1	4.2	3.8	0.2
Dispensable amino acids							
Ala	5.1	5.1	4.2	4.4	7.9	6.5	0.1
Asp	5.1	5.0	6.1	6.2	5.7	5.0	0.1
Cys	1.6	1.5	2.8	2.7	1.6	1.4	0.1
Glu	13.3	12.7	34.2	33.8	18.1	15.2	0.3
Gly	2.8	2.8	4.9	4.9	2.8	2.6	0.1
Pro	6.1	5.9	11.6	11.0	7.1	6.2	0.1
Ser	3.5	3.4	5.4	5.4	3.9	3.4	0.1

[a] All values except dry matter were adjusted to 88 % dry matter.

Table 4
Composition of amino acids mixture[a] (Exp. 1).

Amino acid	g/kg
Gly	579.2
L-His	21.2
L-Ile	42.5
L-Lys·HCl	135.1
DL-Met	44.4
L-Phe	57.9
L-Thr	57.9
L-Trp	13.5
L-Val	48.3
Total	1000.0

[a] One hundred grams of the mixture were fed daily to each pig during adaptation periods.

cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever filled or at least once every 30 min. Digesta samples were stored at −20 °C as soon as collected to prevent bacterial degradation of AA in the digesta. On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

2.1.3. Chemical analysis

At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was collected for analysis. Digesta samples were lyophilized and finely ground. A sample of each source of grain and of each diet was collected at the time of diet mixing. All samples including each source of grain, diets, and ileal digesta were analyzed for dry matter (DM; method 930.15; AOAC Int., 2007) and crude protein (CP; method 990.03; AOAC Int., 2007). Acid-hydrolyzed ether extract (AEE) was also analyzed in the extruded and non-extruded cereal grains using the acid hydrolysis filter bag technique and 3*N* HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA). Amino acids were analyzed by ion-exchange chromatography with ninhydrin used for postcolumn derivatization. Methionine and Cys were analyzed after oxidation with performic acid, which was neutralized with Na metabisulfite (Llames and Fontaine, 1994; European Union, 1998). Samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C and AA were quantified using the internal standard by measuring the absorption of reaction products with ninhydrin at 570 nm. Tryptophan was determined by high performance liquid chromatography with fluorescence detection (extinction

280 nm and emission 356 nm) after alkaline hydrolysis with barium hydroxide octahydrate for 20 h at 110 °C (European Union, 2000). The chromium concentration in the 7 diets and all ileal digesta samples was determined using Inductive Coupled Plasma Atomic Emission Spectrometry (method 990.08; AOAC Int., 2007). Samples were prepared using nitric acid-perchloric acid (method 968.08D(b); AOAC Int., 2007). All samples of diets, the 6 sources of cereal grains, and ileal digesta samples from pigs fed the 6 cereal-containing diets (but not digesta from pigs fed the N-free diet) were also analyzed for starch, using the glucoamylase procedure (method 979.10; AOAC Int., 2007). Gelatinized starch in the cereal grains was analyzed as explained by Lewis et al. (2015). Cereal grains were also analyzed for ash (method 942.05; AOAC Int., 2007). Concentrations of ADF in cereal grains, which was expressed inclusive of residual ash, and aNDF, which was assayed with a heat stable amylase and expressed inclusive of residual ash, were analyzed using Ankom Technology method 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY, USA). Sorghum was analyzed for tannic acid as described by Taylor et al. (2007).

2.1.4. Calculations and statistical analysis

Values for AID of starch, CP, and AA in each diet were calculated according to Stein et al. (2007) and the basal endogenous flow to the distal ileum of CP and each AA was determined based on the flow obtained after feeding the N-free diet (Stein et al., 2007). By correcting the AID of CP and each AA for the basal endogenous losses, SID values for CP and each AA were calculated (Stein et al., 2007). Because all starch, CP, and AA in the diets originated from the grain included in each diet, the calculated values for AID of starch, CP, and AA and the SID of CP and AA in each diet also represent the AID and SID in each cereal grain.

Normal distribution of data was verified using PROC UNIVARIETE of SAS and data were analyzed using the PROC MIXED of SAS (SAS, 2018). Outliers were identified if the values deviated from the 1 st or 3rd quartiles by more than 3 times the interquartile range. The model included source of grain, processing, and the interaction between source of grain and processing as main effects and pig and period as random effects. Least squares means were calculated and means were separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

2.2. Exp. 2. Digestibility of fiber and energy and energy concentrations

2.2.1. Animals, housings, and diets

Forty-eight growing barrows (initial body weight: 15.1 ± 3.7 kg) were allotted to a randomized complete block design with 2 blocks of 24 pigs, 6 diets, and 4 pigs per diet in each block, for a total of 8 replicate pigs per diet. Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple drinker, a slatted floor and a urine tray to allow for the total, but separate, collection of urine and fecal materials. Three diets that contained the non-extruded corn, wheat, or sorghum, and 3 diets that contained the extruded grains were formulated (Table 5). Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

2.2.2. Feeding and sample collection

Pigs were fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal/kg × body weight$^{0.60}$; NRC, 2012), and feed was provided each day in 2 equal meals at 0700 and 1500 h. Throughout the study, pigs had free access to water. Feed consumption was

Table 5
Ingredient composition and analyzed nutrient composition of experimental diets (Exp. 2).

Item, g/kg	Corn		Wheat		Sorghum	
Extruded	–	+	–	+	–	+
Ingredient composition, as-fed basis						
Grain	969.0	969.0	972.5	972.5	969.5	969.5
Dicalcium phosphate	16.0	16.0	8.0	8.0	15.0	15.0
Ground limestone	8.0	8.0	12.5	12.5	8.5	8.5
Sodium chloride	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-mineral premix[a]	3.0	3.0	3.0	3.0	3.0	3.0
Total	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Analyzed nutrient composition, 88 % dry matter basis						
Dry matter	878.7	911.0	880.4	901.4	866.4	914.4
Gross energy, MJ/kg	15.7	15.9	15.6	15.8	15.9	15.7
Crude protein	74.5	79.5	129.5	133.5	92.0	83.9
Neutral detergent fiber[b]	92.7	69.6	104.0	80.2	84.3	65.3
Acid detergent fiber	22.3	15.4	24.4	20.5	32.4	17.0

[a] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as $_{DL}$-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[b] Neutral detergent fiber was assayed with a heat stable amylase and expressed inclusive of residual ash.

recorded daily and diets were fed for 12 days. The initial 5 days were considered the adaptation period to the diet, whereas urine and fecal materials were collected from the feed provided during the following 5 days according to standard procedures using the marker to marker approach (Adeola, 2001). Urine was collected in buckets over a preservative of 50 mL of 6*N* HCl. Fecal samples and 20 % of the collected urine were stored at −20 °C immediately after collection.

2.2.3. Chemical analysis

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis. Fecal samples were thawed and mixed within pig and diet, and then dried in a 50 °C forced air drying oven prior to analysis.

Fecal samples were ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ, USA). Urine samples were also mixed and a subsample was dripped onto cotton balls that were placed in a plastic bag and lyophilized (Kim et al., 2009). Diets, ingredients, ground fecal samples, and lyophilized urine samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Diets, ingredients, and fecal samples were also analyzed for DM, CP, ADF, and aNDF.

2.2.4. Calculations and statistical analysis

Following analysis, ATTD of GE, ADF, and aNDF was calculated for each diet and the DE and ME in each diet were calculated as well (NRC, 2012). By dividing the DE and ME of each diet by the inclusion rate of the cereal grain in the diet, the DE and ME in both non-extruded and extruded corn, sorghum, and wheat were calculated.

Data were analyzed as a randomized complete block design with the pig as the experimental unit using the PROC MIXED of SAS (SAS, 2018). Normality of data was confirmed using the PROC UNIVARIATE of SAS. Outliers were identified if the values deviated from the 1 st or 3rd quartiles by more than 3 times the interquartile range. Grain source (corn, wheat, or sorghum), processing (extruded or non-extruded), and the interaction between grain source and processing were the fixed effects, and pig, block, and replicate within block were random effects. Least squares means were calculated and separated using the PDIFF statement with Tukey's adjustment in PROC MIXED. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

3. Results

All pigs remained healthy and consumed their diets with little feed refusals during both experiments.

3.1. Exp. 1. Ileal digestibility of starch and AA

There was no interaction between source of grain and processing for the AID of starch (Table 6). However, the extruded grains

Table 6
Apparent ileal digestibility of starch, crude protein (CP), and amino acids (AA) in non-extruded and extruded cereal grains fed to growing pigs (Exp. 1).

Item	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	–	+	–	+	–	+		Grain	Extrusion	Grain × extrusion
Observations, *n*	7	6	6	7	6	6	–	–	–	–
Starch	0.907	0.992	0.941	0.988	0.932	0.990	0.0127	0.419	< 0.001	0.277
CP	0.555^{c}	0.758^{ab}	0.765^{ab}	0.809^{a}	0.688^{b}	0.697^{b}	0.0253	< 0.001	< 0.001	0.003
Indispensable AA										
Arg	0.702^{c}	0.843^{a}	0.793^{abc}	0.808^{ab}	0.717^{bc}	0.751^{abc}	0.0241	0.037	0.003	0.027
His	0.727^{b}	0.822^{a}	0.810^{a}	0.826^{a}	0.694^{b}	0.684^{b}	0.0155	< 0.001	0.013	0.006
Ile	0.660^{c}	0.807^{ab}	0.792^{ab}	0.837^{a}	0.738^{b}	0.756^{b}	0.0172	< 0.001	< 0.001	0.002
Leu	0.777^{c}	0.878^{a}	0.810^{bc}	0.849^{ab}	0.809^{bc}	0.819^{bc}	0.0135	0.454	< 0.001	0.005
Lys	0.600	0.775	0.694	0.742	0.588	0.677	0.0285	0.018	< 0.001	0.059
Met	0.811^{c}	0.897^{a}	0.827^{bc}	0.865^{ab}	0.793^{c}	0.815^{c}	0.0119	0.001	< 0.001	0.025
Phe	0.768^{d}	0.865^{ab}	0.850^{abc}	0.876^{a}	0.804^{cd}	0.813^{bcd}	0.0134	0.001	< 0.001	0.006
Thr	0.498^{c}	0.657^{ab}	0.644^{ab}	0.716^{a}	0.583^{bc}	0.594^{bc}	0.0269	0.001	0.001	0.035
Trp	0.436^{c}	0.606^{b}	0.740^{a}	0.782^{a}	0.670^{ab}	0.662^{ab}	0.0287	< 0.001	0.007	0.014
Val	0.650^{c}	0.785^{ab}	0.761^{ab}	0.802^{a}	0.722^{bc}	0.731^{ab}	0.0185	0.004	0.001	0.006
Total	0.698^{c}	0.821^{a}	0.780^{ab}	0.817^{a}	0.744^{bc}	0.758^{abc}	0.0166	0.017	< 0.001	0.006
Dispensable AA										
Ala	0.704^{cd}	0.840^{a}	0.675^{d}	0.739^{bcd}	0.778^{abc}	0.791^{ab}	0.0186	0.001	< 0.001	0.009
Asp	0.633^{b}	0.782^{a}	0.689^{ab}	0.736^{a}	0.696^{ab}	0.719^{ab}	0.0210	0.958	< 0.001	0.013
Cys	0.652^{b}	0.760^{a}	0.824^{a}	0.835^{a}	0.666^{b}	0.645^{b}	0.0190	< 0.001	0.046	0.008
Glu	0.766^{e}	0.876^{bc}	0.910^{ab}	0.932^{a}	0.801^{de}	0.822^{cd}	0.0131	< 0.001	< 0.001	0.001
Gly	0.289^{c}	0.551^{ab}	0.612^{a}	0.640^{a}	0.340^{bc}	0.330^{bc}	0.0545	< 0.001	0.045	0.038
Pro	0.284	0.718	0.818	0.868	0.520	0.533	0.1204	0.012	0.088	0.138
Ser	0.638^{d}	0.771^{abc}	0.788^{ab}	0.816^{a}	0.694^{cd}	0.706^{bcd}	0.0190	< 0.001	0.001	0.007
Total	0.608^{c}	0.795^{ab}	0.830^{ab}	0.858^{a}	0.697^{bc}	0.719^{bc}	0.0295	< 0.001	0.003	0.012

[a−e]Within a row, means without a common superscript differ ($P < 0.05$).

had greater ($P < 0.001$) AID of starch than non-extruded grains. The AID of CP and AA in wheat and sorghum was not affected by extrusion, but extruded corn had greater AID of CP and all AA except Lys and Pro than non-extruded corn (interaction, $P < 0.05$). For some, but not all, AA wheat had greater ($P < 0.05$) AID than corn and sorghum, whereas only a few differences between corn and sorghum were observed.

The endogenous losses of AA that were determined in this experiment were within the wide range of previously reported values (Table 7). The SID of CP in corn was increased by extrusion, but that was not the case for wheat and sorghum (interaction, $P < 0.01$). The SID of AA in wheat and sorghum was also not affected by extrusion, but extruded corn had greater SID of all AA except Lys and Pro compared with non-extruded corn (interaction, $P < 0.05$). The SID of Ile, Phe, Cys, and Glu in wheat was greater ($P < 0.05$) compared with values in corn and sorghum.

3.2. Exp. 2. Digestibility of fiber and energy and energy concentrations

There were no differences among grains for feed intake and GE intake (Table 8). The intake of aNDF decreased ($P < 0.05$) if pigs were fed extruded grains compared with non-extruded grains, which is likely a result of the reduced concentration of aNDF in the extruded grain compared with the non-extruded grain. Likewise, extrusion also reduced the concentration of ADF, which likely is the reason the intake of ADF was reduced by extrusion of sorghum. However, but extrusion did not affect ADF intake if pigs were fed corn or wheat (interaction, $P < 0.05$).

Pigs fed the diet containing extruded sorghum had reduced fecal GE compared with pigs fed the diet containing non-extruded sorghum, but the fecal GE was not affected by extrusion of corn or wheat (interaction, $P < 0.05$). There was no interaction between the source of grain and extrusion of ingredients for fecal aNDF output, but the effect of extrusion on fecal output of ADF was different among grains (interaction, $P < 0.05$). However, there were no interactions between the source of grain and extrusion for total urine output and urine output of GE. The ATTD of GE was increased by extrusion of corn or sorghum, but that was not the case for wheat (interaction, $P < 0.001$). The ATTD of aNDF in diets containing wheat was reduced by extrusion, but the ATTD of aNDF in corn and sorghum was not affected by extrusion (interaction, $P < 0.001$). Extrusion reduced ($P < 0.05$) the ATTD of ADF in all grains. The DE and ME in all diets containing the 3 sources of extruded grain were improved compared with the non-extruded grain, but the increase was greater for diets containing sorghum than for the wheat or corn diets (interaction, $P < 0.001$).

If calculated on an as-fed basis, extrusion increased ($P < 0.05$) the DE and ME in all three grains (Table 9). Extrusion also increased the DE and ME on a DM-basis in corn and sorghum compared with non-extruded grains, but there was no increase in DE and ME (DM-basis) if wheat was extruded (interaction, $P < 0.001$; Table 9). The ME (DM-basis) in non-extruded corn was greater ($P < 0.05$) than in non-extruded wheat and the ME (DM-basis) in extruded corn and sorghum was greater ($P < 0.05$) than in

Table 7
Standardized ileal digestibility (SID) of crude protein (CP), and amino acids (AA) in non-extruded and extruded cereal grains fed to growing pigs[1] (Exp. 1).

Item	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	–	+	–	+	–	+		Grain	Extrusion	Grain × Extrusion
Observations, *n*	7	6	6	7	6	6	–	–	–	–
CP	0.748[c]	0.949[a]	0.877[ab]	0.921[ab]	0.822[bc]	0.877[ab]	0.0253	0.094	< 0.001	0.007
Indispensable AA										
Arg	0.830[b]	0.971[a]	0.868[ab]	0.882[ab]	0.854[b]	0.898[ab]	0.0241	0.504	0.002	0.031
His	0.795[bc]	0.891[a]	0.860[ab]	0.875[a]	0.766[c]	0.762[c]	0.0155	< 0.001	0.009	0.008
Ile	0.734[c]	0.882[a]	0.836[ab]	0.882[a]	0.792[bc]	0.820[ab]	0.0172	0.006	< 0.001	0.003
Leu	0.814[c]	0.917[a]	0.849[bc]	0.888[ab]	0.836[bc]	0.851[bc]	0.0135	0.154	< 0.001	0.007
Lys	0.674	0.849	0.747	0.794	0.686	0.776	0.0285	0.341	< 0.001	0.056
Met	0.840[c]	0.929[a]	0.854[bc]	0.892[ab]	0.825[c]	0.851[bc]	0.0119	0.002	< 0.001	0.025
Phe	0.805[c]	0.903[a]	0.873[ab]	0.900[a]	0.833[bc]	0.847[abc]	0.0134	0.006	< 0.001	0.007
Thr	0.664[b]	0.832[a]	0.773[ab]	0.844[a]	0.744[ab]	0.775[ab]	0.0269	0.067	< 0.001	0.048
Trp	0.612[b]	0.780[a]	0.807[a]	0.848[a]	0.773[a]	0.777[a]	0.0287	< 0.001	0.006	0.021
Val	0.735[b]	0.871[a]	0.816[a]	0.857[a]	0.789[ab]	0.807[ab]	0.0185	0.091	< 0.001	0.008
Total	0.772[c]	0.897[a]	0.834[abc]	0.871[ab]	0.807[bc]	0.830[abc]	0.0166	0.145	< 0.001	0.008
Dispensable AA										
Ala	0.779[b]	0.916[a]	0.765[b]	0.827[b]	0.826[b]	0.850[ab]	0.0186	0.020	< 0.001	0.015
Asp	0.740[c]	0.891[a]	0.777[bc]	0.823[ab]	0.790[bc]	0.826[abc]	0.0210	0.767	< 0.001	0.018
Cys	0.757[b]	0.866[a]	0.882[a]	0.895[a]	0.769[b]	0.756[b]	0.0190	< 0.001	0.029	0.010
Glu	0.814[b]	0.926[a]	0.929[a]	0.951[a]	0.836[b]	0.864[b]	0.0131	< 0.001	< 0.001	0.002
Gly	0.790[b]	1.059[a]	0.902[ab]	0.931[ab]	0.867[ab]	0.887[ab]	0.0545	0.666	0.025	0.047
Pro	1.198	1.669	1.297	1.373	1.304	1.435	0.1204	0.655	0.025	0.177
Ser	0.771[c]	0.909[a]	0.873[ab]	0.901[a]	0.814[bc]	0.844[abc]	0.0190	0.011	< 0.001	0.009
Total	0.853[c]	1.048[a]	0.962[abc]	0.992[ab]	0.893[bc]	0.947[abc]	0.0295	0.179	0.001	0.017

[a–c]Within a row, means without a common superscript differ ($P < 0.05$).

[1] Values for SID were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses (g/kg of dry matter intake) were determined as: CP, 15.64; Arg, 0.50; His, 0.15; Ile, 0.21; Leu, 0.35; Lys, 0.20; Met, 0.06; Phe, 0.15; Thr, 0.50; Trp, 0.11; Val, 0.32; Ala, 0.44; Asp, 0.61; Cys, 0.19; Glu, 0.72; Gly, 1.63; Pro, 6.33; and Ser, 0.52.

Table 8
Apparent total tract digestibility (ATTD) of nutrients and concentrations of digestible energy (DE) and metabolizable energy (ME) in diets containing non-extruded or extruded cereal grains, as-fed basis (Exp. 2).

Item[a]	Corn		Wheat		Sorghum		SEM	P-value		
Extruded	–	+	–	+	–	+		Grain	Extrusion	Grain × Extrusion
Observations, *n*	8	7	8	8	8	8	–	–	–	–
Intake										
Feed intake, g/day	723	722	609	694	610	615	56.6	0.160	0.521	0.698
GE, MJ/day	11.3	11.9	9.5	11.2	9.5	10.0	0.90	0.139	0.225	0.754
aNDF, g/day	67	52	63	57	51	42	4.8	0.009	0.016	0.669
ADF, g/day	16[ab]	12[bc]	15[abc]	15[abc]	19[a]	11[c]	1.2	0.553	< 0.001	0.007
Fecal excretion										
Dry feces output, g/day	68[ab]	51[ab]	67[ab]	73[a]	72[ab]	46[b]	6.3	0.179	0.019	0.037
GE, MJ/day	1.33[ab]	0.89[b]	1.24[ab]	1.31[ab]	1.46[a]	0.86[b]	0.117	0.373	0.002	0.019
aNDF, g/day	25	23	27	31	18	12	2.3	< 0.001	0.650	0.084
ADF, g/day	7[b]	7[b]	12[a]	14[a]	8[b]	5[b]	0.8	< 0.001	0.626	0.031
Urinary excretion										
Urine output, g/day	1,462	2,883	1,955	1,898	1,103	1,772	679.0	0.550	0.229	0.562
GE, MJ/day	0.20	0.35	0.29	0.37	0.18	0.29	0.042	0.083	0.002	0.707
ATTD, g/kg										
GE	0.882[b]	0.924[a]	0.869[bc]	0.883[b]	0.848[c]	0.915[a]	0.0056	< 0.001	< 0.001	< 0.001
aNDF	0.631[bc]	0.550[c]	0.581[bc]	0.450[d]	0.646[ab]	0.712[a]	0.0190	< 0.001	0.003	< 0.001
ADF	0.558	0.428	0.207	0.046	0.605	0.518	0.0273	< 0.001	< 0.001	0.392
Energy values, MJ/kg										
DE	13.8[c]	15.2[a]	13.6[cd]	14.2[b]	13.3[d]	14.9[a]	0.09	< 0.001	< 0.001	< 0.001
ME	13.5[b]	14.7[a]	13.1[c]	13.7[b]	13.0[c]	14.4[a]	0.10	< 0.001	< 0.001	< 0.001

[a–d]Within a row, means without a common superscript differ ($P < 0.05$).
[a] GE = gross energy; aNDF = neutral detergent fiber assayed with a heat stable amylase and expressed inclusive of residual ash; ADF = acid detergent fiber expressed inclusive of residual ash.

Table 9
Concentrations of digestible energy (DE) and metabolizable energy (ME) in non-extruded and extruded cereal grains fed to pigs (Exp. 2).

Item, MJ/kg	Corn		Wheat		Sorghum		SEM	P-value		
Extruded	–	+	–	+	–	+		Grain	Extrusion	Grain × Extrusion
Observations, *n*	8	7	8	8	8	8	–	–	–	–
As-fed basis										
DE	14.3[c]	15.7[a]	14.0[cd]	14.6[b]	13.7[d]	15.4[a]	0.09	< 0.001	< 0.001	< 0.001
ME	14.0[b]	15.2[a]	13.5[c]	14.1[b]	13.4[c]	14.9[a]	0.10	< 0.001	< 0.001	< 0.001
Dry matter basis										
DE	16.2[b]	17.2[a]	15.9[b]	16.1[b]	15.8[b]	16.8[a]	0.10	< 0.001	< 0.001	0.001
ME	15.9[bc]	16.6[a]	15.3[d]	15.5[cd]	15.4[cd]	16.2[ab]	0.12	< 0.001	< 0.001	0.018

extruded wheat.

4. Discussion

4.1. Effects of extrusion on nutrient composition of grains

Concentrations of CP, AA, fiber components, AEE, and GE in the un-extruded corn, wheat, and sorghum were in agreement with reported values (Sauvant et al., 2004; NRC, 2012; Stein et al., 2016). Starch concentrations in corn and wheat were also within the range of reported values (NRC, 2012; Stein et al., 2016), but the concentration of starch in sorghum was less than previously reported (NRC, 2012; Stein et al., 2016).

The increased DM in the extruded cereal grains compared with the un-extruded grains is likely a result of the thermal processing and the subsequent drying that takes place when grains are extruded (Hancock and Behnke, 2001). There was also an increase in DM if feed ingredients or diets containing multiple feed ingredients were extruded (Skoch et al., 1983; Rojas et al., 2016). In contrast, it seemed that some of the aNDF or ADF in the original grains may have been solubilized during extrusion with heat and moisture during the process of extrusion. Therefore, this indicates that extrusion reduced the concentrations of aNDF and ADF in all grains used in this experiment. The observation that total starch increased after extrusion may be a result of encapsulated starch being released, which may have been a result of the fiber matrix being solubilized. We are not aware of previous experiments were a reduction in aNDF and ADF and an increase in starch in cereal grains was observed as an outcome of extrusion, but these changes in nutrient composition may contribute to improved nutritional value of extruded cereal grains.

Any thermal treatment of feed ingredients may result in heat damage of proteins and subsequently reduction in the concentration of Lys (Fontaine et al., 2007; Rutherfurd and Moughan, 2007; Pahm et al., 2008) and reduction in Lys as a percentage of CP (Stein et al., 2009; González-Vega et al., 2011). However, the observation that the concentration of Lys, both as analyzed and as a percentage of CP did not change after extrusion indicates that proteins were not damaged during extrusion.

4.2. Effects of extrusion on digestibility of AA and starch

Values for the SID of AA in un-extruded corn, wheat, and sorghum were within the range of reported values (Stein et al., 2006; Widyaratne and Zijlstra, 2007; NRC, 2012; Stein et al., 2016). When grains are processed with appropriate moisture, pressure, and heat during extrusion, the shape of grain particles are modified and more nutrients can be accessed by digestive enzymes (Amornthewaphat and Attamangkune, 2008; NRC, 2012). Therefore, the change in anatomy of the grains during extrusion may increase digestibility of AA, fiber, and energy. The observed increase in the AID of starch in corn, wheat, and sorghum indicates that extrusion improves small intestinal starch absorption, which is in agreement with results observed for field peas and mixed diets (Stein and Bohlke, 2007; Rojas et al., 2016). This increase is most likely a result of the observed increase in gelatinization of starch, which is a process in which the intermolecular bonds in the starch granule are broken, and thus allowing more space between molecules to hold water (Ai, 2013). Therefore, gelatinized starch is more available for intestinal enzymes. Gelatinized starch is usually less than 10 % in un-extruded grain, but the concentration of gelatinized starch in corn may increase by more than 3 fold during extrusion (Veum et al., 2017), but in the current experiment, extrusion increased gelatinized starch to around 90 % of total starch in all grains. Extrusion also increased rapidly digestible starch and decreased resistant starch in barley, field peas, and in a diet containing potato starch and wheat bran, which resulted in increased AID of starch by pigs (Sun et al., 2006). Thus, increased gelatinization of starch is the most likely reason for the increased AID of starch that was observed in the extruded grains compared with the non-extruded grains.

The increase in the AID and SID of AA that was observed as corn was extruded is in agreement with data from experiments where the AID of AA was increased by extrusion of feed ingredients or complete diets (Chae et al., 1997; Stein and Bohlke, 2007; Htoo et al., 2008; Rojas et al., 2016). The reason for this increase may be that heat from extrusion changes the 3-dimensional structure of protein, and thus increases access of digestive enzymes to the peptide bonds (Duodu et al., 2003). The main protein in corn is zein, whereas the main protein in sorghum is kafirin and the main protein in wheat is glutenin, which gives special elastic properties to the protein. It is possible the different proteins react differently to extrusion, which may explain why digestibility in corn protein, but not in sorghum and wheat protein, increased by extrusion. However, more research is needed to verify this hypothesis.

4.3. Effects of extrusion on ATTD of aNDF and ADF

Values for the ATTD of aNDF and ADF in non-extruded cereal grains that were obtained in the present experiment were comparable with values observed previously (Herkelman et al., 1990; Navarro et al., 2018) but the extruded corn had greater ATTD of aNDF compared with previous data (Herkelman et al., 1990). To our knowledge, effects of extrusion on the ATTD of aNDF and ADF in wheat and sorghum have not been reported.

The interaction that was observed for the ATTD of aNDF was a result of reduced ATTD of aNDF in corn and increased ATTD of aNDF in sorghum. This may be due to tannin being present in sorghum and not in corn. One of the tannins in sorghum is procyanidins, which binds to fiber, protein, and minerals, and there is a negative correlation between procyanidins concentrations and ATTD of aNDF in birds (Reed, 1987). During extrusion, the procyanidins may be depolymerized, which results in degradation of the bond between procyanidins and fiber (Gu et al., 2008) with a subsequent increase in the ATTD of aNDF as was observed in this experiment. In contrast, in corn, there are no tannins so extrusion will not result in an increase in the ATTD of aNDF due to degradation of the tannin-fiber bond. However, extrusion of corn-fiber resulted in reduced concentration of aNDF in the grain presumably due to solubilization of some of the aNDF in the fiber. This likely left the most insoluble fiber in the extruded grains, which resulted in reduced fermentation by the pigs, and this was registered as a reduced ATTD of aNDF.

4.4. Effects of extrusion on ATTD of energy and DE and ME

The ATTD of GE and the concentrations of DE and ME in non-extruded corn and wheat were within the range of reported values, but the ATTD of GE and DE and ME in non-extruded sorghum were less than values previously observed (Sauvant et al., 2004; NRC, 2012; Stein et al., 2016), which may be a result of the lower starch concentration in the sorghum used in this experiment. The DE and ME in extruded corn and wheat were also within the range of published values (Herkelman et al., 1990; Barneveld et al., 2005; Liu et al., 2016). In contrast, the DE in extruded sorghum that was obtained in this experiment was greater than values reported by Barneveld et al. (2005).

The observation that the ATTD of GE and DE and ME increased if corn and sorghum were extruded is in agreement with previous data for extruded corn, wheat, sorghum, field peas, and soybean meal (Marty and Chavez, 1993; Stein and Bohlke, 2007; Rodrigues et al., 2016). The increased ME is likely a result of the increased AID of starch and AA that were observed in Exp. 1 and possibly greater solubilization of fiber. The ATTD of aNDF and ADF in wheat were less compared with corn and sorghum, but it is not clear if that is the reason for a lack of response to extrusion in wheat. It is also possible that because wheat had the greatest AID of starch among the un-extruded grains, the increase in AID of starch that was observed as a consequence of extrusion was not large enough to significantly increase ME of the extruded wheat.

5. Conclusion

Nutrient composition in grains changed after extrusion with a reduction in acid detergent fiber and neutral detergent fiber. The standardized ileal digestibility of most amino acids in corn, but not in sorghum and wheat, increased after extrusion and extrusion increased apparent ileal digestibility of starch in corn, wheat, and sorghum. As a result, the apparent total tract digestibility of energy was also increased by extrusion. The metabolizable energy (dry matter basis) in corn and sorghum was also increased by extrusion, but that was not the case for wheat.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Acknowledgements

Financial support for this research from Evonik Nutrition & Care GmbH is greatly appreciated.

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