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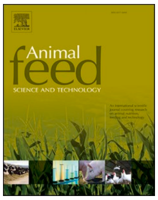

Nutrient composition and digestibility by growing pigs of amino acids and energy vary between wheat middlings from Europe and the United States

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ABSTRACT

Two experiments were conducted to test the hypothesis that there are no differences in composition, apparent total tract digestibility (ATTD) of gross energy (GE), or standardized ileal digestibility (SID) of amino acids (AA) in wheat middlings sourced from flour mills in Europe or in the U.S. For both experiments, ten sources of wheat middlings were used. Five sources were procured from Europe and the other five sources were procured from the U.S. The ten sources of wheat middlings varied in starch from 79 to 286 g/kg (as-fed) and total dietary fiber varied from 324 to 508 g/kg. In experiment 1, 88 castrated male pigs (27.2 ± 2.5 kg) were individually housed in metabolism crates and allotted to eleven diets with eight replicate pigs per diet. A corn-soybean meal diet and ten diets containing corn, soybean meal, and each source of wheat middlings as the only energy sources were formulated. Feces and urine were collected using the marker-to-marker approach with 5-day adaptation and 4-day collection periods. The ATTD of GE and the concentration of digestible energy (DE) in wheat middlings from one of the European sources were less ($P < 0.05$) than in the other sources. Likewise, wheat middlings from Europe had reduced concentrations of DE and metabolizable energy (12.10 and 11.42 MJ/kg, dry matter basis) compared with wheat middlings from the U.S (12.69 and 12.32 MJ/kg, dry matter basis). In experiment 2, eleven pigs (52.8 ± 3.6 kg) with a T-cannula in the distal ileum were allotted to an 11 × 8 Youden square design with eleven diets and eight periods resulting in eight replicates per diet. A nitrogen-free diet and ten diets containing each source of wheat middlings as the only AA-containing ingredient were formulated. Results indicated that the SID of most AA in wheat middlings from two of the European sources was less ($P < 0.05$) than in the other sources. As a consequence, the average SID of AA for wheat middling from Europe was less than the SID of AA in wheat middlings from the U.S. In conclusion, energy concentrations and AA digestibility values for wheat middling from Europe were less than in wheat middlings from the U.S., which is likely due to increased concentration of dietary fiber in wheat middlings from Europe. Greater variability in energy and AA digestibility values was also observed in the five sources of wheat middlings from Europe compared with wheat middlings from the U.S., which is possibly a result of differences among European flour mills in the production process.

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 matte; GE, gross energy; IDF, insoluble dietary fiber; ME, metabolizable energy; MJ, mega joule; SID, standardized ileal digestibility; SDF, soluble dietary fiber; TDF, total dietary fiber.

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Table 1

Analyzed nutrient composition of the ten sources of wheat middlings (as fed basis).

	European sources							U.S. sources						
Item	G	S	F	H	I	Mean	SD	01	02	03	04	05	Mean	SD
Dry matter, g/kg	906.5	899.4	902.1	901.8	904.5	902.9	2.7	893.1	885.3	898.7	910.2	894.8	896.4	9.1
Gross energy, MJ/kg	16.9	16.6	17.1	17.1	16.6	16.9	0.2	16.5	17.0	16.9	16.7	16.6	16.7	0.2
Crude protein, g/kg	154.6	153.5	154.5	152.4	173.8	157.8	9.0	164.8	168.5	168.4	153.4	138.2	158.7	13.0
AEE[a], g/kg	44.4	33.4	35.8	40.0	31.8	37.1	5.1	43.3	41.7	44.6	37.3	41.4	41.7	2.8
Starch, g/kg	143.0	286.0	223.0	79.0	223.0	190.8	80.5	232.0	183.0	165.0	202.0	263.0	209.0	39.1
SDF[a and ba], g/kg	29.0	34.0	45.0	30.0	29.0	33.4	6.8	33.0	31.0	21.0	38.0	24.0	29.4	6.9
IDF[a], g/kg	464.0	301.0	339.0	478.0	338.0	384.0	81.0	291.0	384.0	393.0	367.0	326.0	352.2	42.8
TDF[a], g/kg	493.0	335.0	384.0	508.0	367.0	417.4	78.1	324.0	415.0	414.0	405.0	350.0	381.6	41.9
Ash, g/kg	60.9	38.4	48.0	54.0	51.3	50.5	8.3	66.9	52.0	55.0	58.9	46.3	55.8	7.7
Rest fraction[b], g/kg	10.6	53.1	56.8	68.4	57.6	49.3	22.4	62.1	25.1	51.7	53.6	55.9	49.6	14.3
Indispensable amino acids, g/kg														
Arg	10.6	8.3	9.3	10.9	11.1	10.0	1.2	11.1	11.5	11.4	10.4	9.3	10.7	0.9
His	4.2	3.5	3.7	4.1	4.4	4.0	0.4	4.3	4.5	4.6	4.1	3.7	4.2	0.4
Ile	4.7	4.4	4.7	4.5	5.7	4.8	0.5	5.2	5.4	5.2	4.9	4.5	5.0	0.4
Leu	9.1	8.3	9.1	8.8	10.9	9.2	1.0	10.4	10.2	10.4	9.3	8.8	9.8	0.7
Lys	6.4	5.5	5.9	6.5	6.9	6.2	0.5	7.2	7.4	7.4	6.5	6.3	7.0	0.5
Met	2.1	2.0	2.2	2.0	2.6	2.2	0.2	2.9	2.5	2.4	2.1	2.0	2.4	0.4
Phe	5.8	5.4	5.7	5.5	7.0	5.9	0.6	6.5	6.5	6.6	5.9	5.6	6.2	0.4
Thr	4.8	4.2	4.8	4.8	5.6	4.8	0.5	5.5	5.6	5.4	4.8	4.4	5.1	0.5
Trp	1.6	1.3	1.4	1.3	1.8	1.5	0.2	1.4	1.9	1.7	1.6	1.4	1.6	0.2
Val	7.0	6.0	6.8	6.9	8.0	6.9	0.7	7.5	7.8	7.8	7.0	6.3	7.3	0.6
Dispensable amino acids, g/kg														
Ala	7.2	6.0	7.2	7.4	7.9	7.1	0.7	8.2	8.3	8.2	7.3	6.6	7.7	0.7
Asp	10.8	8.7	10.1	11.4	11.2	10.4	1.1	12.3	12.4	12.3	10.7	9.6	11.5	1.3
Cys	3.2	3.2	3.2	3.2	3.3	3.2	0.0	3.5	3.7	3.5	3.4	3.1	3.4	0.2
Glu	27.7	28.7	27.5	23.6	34.6	28.4	4.0	30.9	30.6	31.0	28.4	26.9	29.6	1.8
Gly	8.4	7.5	7.8	8.4	8.4	8.1	0.4	8.7	9.2	9.1	8.3	7.4	8.5	0.7
Ser	5.7	5.2	5.5	5.6	6.7	5.7	0.6	6.3	6.3	6.2	5.7	5.3	6.0	0.4
Tyr	3.7	3.8	3.8	3.8	4.4	3.9	0.3	4.2	4.3	4.3	3.7	3.7	4.0	0.3
Lys:CP	4.1	3.6	3.8	4.3	4.0	4.0	0.3	4.4	4.4	4.4	4.2	4.6	4.4	0.1

[a] AEE, acid hydrolyzed ether extract; SDF, soluble dietary fiber; IDF, insoluble dietary fiber; TDF, total dietary fiber.

[b] The rest fraction was calculated as DM – (ash + crude protein + starch + AEE + TDF).

Table 2
Analyzed mineral composition of the ten sources of wheat middlings (as fed basis).

	European sources							U.S. sources						
Item	01	02	03	04	05	Mean	SD	01	02	03	04	05	Mean	SD
Ca, g/kg	0.9	1.0	1.1	1.1	1.5	1.1	0.2	1.2	1.0	1.4	1.4	1.2	1.2	0.2
P, g/kg	13.5	7.8	9.2	12.1	9.8	10.5	2.3	11.4	11.8	11.9	11.4	9.9	11.3	0.8
Phytic acid, g/kg	37.8	20.1	21.9	33.1	26.9	28.0	7.5	28.1	32.5	33.9	32.7	28.7	31.2	2.6
Phytate-bound P[a], g/kg	10.7	5.7	6.2	9.3	7.6	7.9	2.1	7.9	9.2	9.6	9.2	8.1	8.8	0.8
Non-phytate P[b], g/kg	2.8	2.1	3.0	2.8	2.2	2.6	0.4	3.5	2.6	2.3	2.2	1.8	2.5	0.6
K, g/kg	14.8	9.0	11.5	12.4	11.1	11.8	2.1	9.8	10.9	11.5	9.3	9.6	10.2	0.9
Mg, g/kg	4.5	2.7	2.9	4.9	3.4	3.7	1.0	4.4	4.6	4.6	4.2	4.1	4.4	0.2
Cu, mg/kg	54	36	45	49	50	47	7	58	48	51	50	43	50	5
Zn, mg/kg	109	81	92	108	122	102	16	124	120	121	87	110	112	15
Mn, mg/kg	147	119	132	171	145	143	19	173	177	162	124	151	157	21
Fe, mg/kg	170	111	138	151	155	145	22	161	182	180	125	135	157	26

[a] Calculated as 282 g/kg of phytic acid.

[b] Calculated as total P – phytate-bound P.

1. Introduction

Diets for growing pigs commonly contain cereal co-products that are less expensive than intact grains because they have greater concentrations of dietary fiber, which cannot be digested by pigs (Jaworski et al., 2015). The undigested portion of dietary carbohydrates from cereal co-products may serve as substrate for intestinal microbes, which results in synthesis of volatile fatty acids that can be used by pigs as a source of energy (Macfarlane and Macfarlane, 2003). Among cereal co-products, wheat middlings is one of the most commonly used ingredients in pig diets. However, variation in nutrient composition may be observed in wheat middlings (Zijlstra and Beltranena, 2013), and these variations may be attributed to the milling process and to the amount of bran and germ in wheat middlings.

Wheat middlings is the co-product that is left after extraction of the endosperm to produce wheat flour for the human food industry (Rosenfelder et al., 2013). Other co-products from the flour industry include wheat shorts, wheat pollard, wheat red dog, and wheat bran. Wheat red dog, which consists of a mixture of the aleurone layer and bran, germ, and flour, has a greater nutritional value than the other wheat co-products due to a greater concentration of starch and a lower concentration of fiber (Huang et al., 2012; Casas et al., 2018; Casas and Stein, 2017). However, the composition of wheat shorts and wheat middlings is not very different (Nortey et al., 2008), and the chemical composition of wheat middlings, wheat bran, and wheat pollard is also not very different (Fanelli et al., 2024) although wheat bran sometimes appears to contain more fiber and less starch than wheat middlings (Rosenfelder et al., 2013). Nevertheless, the designation of a co-product as wheat middlings, wheat shorts, wheat bran, or wheat pollard appears to be somewhat random and mostly based on tradition and geographical location.

The composition of wheat middlings from flour mills in the U.S. has been published (NRC, 2012), and data for standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) and concentrations of digestible energy (DE) and metabolizable energy (ME) have been reported as well (Casas and Stein, 2017; Casas et al., 2018). However, it is not known if the data obtained for wheat middlings from the U.S. also are representative of wheat middlings from Europe. Therefore, two experiments were conducted to test the hypothesis that there are no differences in nutrient composition, SID of CP and AA, apparent total tract digestibility (ATTD) of gross energy (GE), or concentrations of DE and ME between wheat middlings sourced from flour mills in Europe or from flour mills in the U. S.

2. Materials and methods

Protocols for the two experiments were reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois Urbana-Champaign (Urbana, IL, USA). Pigs used in both experiments were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA). Ten sources of wheat middlings were used in both experiments (Tables 1 and 2). Five sources were procured from Europe (i.e., Germany, Spain, France, Hungary, and Italy), and the other five sources were from the U.S. (i.e., U.S. 01, U.S. 02, U.S. 03, U.S. 04, U.S. 05).

2.1. Animals, treatments, and experimental procedure

2.1.1. Experiment 1: digestibility of energy

A basal diet based on corn and soybean meal was formulated (Tables 3 and 4). Ten additional diets containing corn, soybean meal, and 400 g/kg of each of the ten sources of wheat middlings were also formulated. Wheat middlings and corn and soybean meal were the only sources of energy in the diets, and the ratio between corn and soybean meal was constant among all diets. Vitamins and minerals were included to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012). Eighty-eight castrated

Table 3
Ingredient composition of the corn-soybean meal diet and diets containing wheat middlings, experiment 1.

Ingredient, g/kg	Corn-soybean meal	Wheat middlings[a]
Corn	656.5	388.9
Soybean meal	320.0	189.7
Wheat middlings	-	400.0
Calcium carbonate	8.0	12.4
Dicalcium phosphate	6.5	-
Salt	4.0	4.0
Vitamin-mineral premix[b]	5.0	5.0

[a] Ten diets were formulated using ten different sources of wheat middlings.

[b] The vitamin-mineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D3 as cholecalciferol, 1660 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

Table 4
Analyzed composition of experimental diets (as fed basis), experiment 1.

Item	Corn-soybean meal	European sources					U.S. sources				
		01	02	03	04	05	01	02	03	04	05
Dry matter, g/kg	883.7	892.4	886.5	891.0	887.9	885.9	879.5	878.2	876.7	889.1	878.8
Gross energy, MJ/kg	15.9	16.2	16.2	16.2	16.3	16.1	16.2	16.3	16.3	16.0	16.2

male pigs (initial body weight: 27.24 ± 2.54 kg) were allotted to a randomized complete block design with 11 diets, 4 blocks, and 2 replicate pigs per diet in each block for a total of 8 replicate pigs per diet. Pigs were allotted to experimental diets in each block based on body weight. Pigs were placed in individual metabolism crates (0.81 × 2.59 m) equipped with a self-feeder, a nipple waterer, and slatted floors. A screen floor and a urine pan were installed under the slatted floors to allow for the total collection of feces and urine. Pigs were fed experimental diets for 12 days and the daily feed ration, which was fed in two equal meals each day, was calculated as 3.2 times the ME requirement for maintenance [i.e., 0.825 mega joule (MJ)/kg × body weight$^{0.60}$; NRC, 2012]. Pigs had free access to water throughout the experiment and feed disappearance was recorded daily. The initial 5 days of the feeding period were considered the adaptation period to the diet, whereas urine and fecal materials were collected from the feed fed from day 6 to day 10 according to standard procedures using the marker-to-marker approach (Adeola, 2001). Urine samples were collected in urine buckets over a preservative of 50 mL of hydrochloric acid. Fecal samples and 10 % of the collected urine were stored at −20 °C immediately after collection.

2.1.2. Experiment 2: amino acid digestibility

Eleven diets were prepared (Tables 5 and 6). Ten diets contained one source of wheat middlings as the only source of protein and AA, and the last diet was a nitrogen-free diet that was used to determine basal endogenous losses of CP and AA. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets contained 0.40 % chromic oxide as an indigestible marker. Diet samples were collected at the time of diet mixing.

Eleven castrated male pigs (initial body weight: 52.8 ± 3.6 kg) were allotted to an 11 × 8 Youden square design with 11 diets and eight 7-day periods based on initial body weight. There was, therefore, 8 replicate pigs per treatment. Pigs had a T-cannula installed in the distal ileum when they had a body weight of approximately 20 kg (Stein et al., 1998) and they were used in a different experiment before beign allotted to the present experiment. 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. A feeder and a nipple drinker were installed in each pen. All pigs were provided feed at a daily level of 3.2 times the estimated ME requirement for maintenance throughout the experiment and water was available at all times. Because all diets contained AA in quantities below the requirements for growing pigs, an AA mixture was provided to all pigs during the initial 5 days of each period, but not on days 6 and 7. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. The initial 5 days of each period were considered an adaptation period to the diet. Ileal digesta were collected for 9 h on days 6 and 7 using standard operating procedures. In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever filled with digesta - or at least once every 30 min - and immediately frozen at –20 °C to prevent bacterial degradation of the 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. At the conclusion of the last period, all ileal digesta sampels were thawed, mixed, and sub-sampled, and the sub-samples were lyophilized (Lagos and Stein, 2019).

2.2. Sample analyses

2.2.1. Experiment 1: digestibility and concentration of energy

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. Ingredients, diets, fecal, and urine samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Fecal, ingredient, and diet samples were also analyzed for dry matter (DM; Method 930.15; AOAC Int, 2019). Ingredients were analyzed for ash (Method 942.05; AOAC Int, 2019), and for minerals (i.e., Ca, P, K, Mg, Cu, Fe, Mn, and Zn) using inductively coupled plasma optical emissions spectrometry (ICP-OES; Avio 200, PerkinElmer, Waltham, MA, USA). Sample preparation included dry ashing at 600 °C for 4 h (Method 942.05; AOAC Int, 2019) and wet digestion with nitric acids (Method 3050 B; U.S. U.S. U.S. Environmental Protection Agency, 2000). Ingredients were also analyzed for starch using the glucoamylase procedure (Method 979.10; AOAC Int, 2019). The ten sources of wheat middlings were analyzed for insoluble dietary fiber (IDF) and soluble dietary fiber (SDF) according to method 991.43 (AOAC Int, 2019) using the Ankom Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber (TDF) was calculated as the sum of IDF and SDF. Ingredients were also analyzed for acid-hydrolyzed ether extract (AEE) by acid hydrolysis using 3 *N* HCl and the acid hydrolysis filter bag technique (Ankom HCl Hydrolysis System; Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int, 2019) in an AnkomXT^{15} Extractor (Ankom Technology, Macedon, NY, USA). Ingredients were analyzed for phytic acid according to the method by Ellis et al. (1977). All analyses were conducted in duplicates.

Table 5
Ingredient composition of experimental diets, experiment 2[a,b].

Ingredient, g/kg	Wheat middlings	Nitrogen-free
Wheat middlings	450.0	-
Cornstarch	330.0	676.0
Sucrose	150.0	200.0
Soybean oil	40.0	40.0
Solka floc	-	40.0
Dicalcium phosphate	1.0	21.5
Calcium carbonate	16.0	4.5
Vitamin-mineral premixc	5.0	5.0
Potassium carbonate	-	4.0
Chromium oxide	4.0	4.0
Salt	4.0	4.0
Magnesium oxide	-	1.0

[a] Ten diets using ten different sources of wheat middlings were formulated.

[b] 100 g of an AA mixture was provided from d 1 to 5 of each period to each pig, The AA mixture contained the following AA (g/kg): Glycine, 597.2; L-Lysine HCL, 135.0; L-Phenylalanine, 57.9; L-Threonine, 57.9; L Valine, 48.3; DL-Methionine, 44.4; L-Isoleucine, 42.5; and L-Tryptophan, 13.5.

[c] The vitamin-mineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D3 as cholecalciferol, 1660 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

Table 6
Analyzed composition of experimental diets (as fed basis), experiment 2.

	European sources					U.S. sources					
Item	01	02	03	04	05	01	02	03	04	05	N-free
Dry matter, g/kg	928.8	928.0	930.5	924.1	930.2	922.5	925.5	925.4	930.6	925.9	941.4
Crude protein, g/kg	66.3	66.7	66.4	65.4	79.0	69.7	75.1	72.9	67.5	63.9	2.1
Indispensable amino acids, g/kg											
Arg	4.8	3.7	4.4	4.9	4.7	4.6	5.1	5.0	4.6	4.1	0.1
His	2.0	1.6	1.9	1.9	1.9	1.9	2.0	2.1	1.9	1.7	0.0
Ile	2.3	2.1	2.2	2.1	2.5	2.4	2.5	2.4	2.3	2.1	0.1
Leu	4.6	4.0	4.5	4.2	4.9	4.6	4.8	4.9	4.5	4.0	0.3
Lys	3.0	2.6	2.9	3.0	3.0	2.9	3.3	3.4	3.1	2.8	0.2
Met	1.1	1.0	1.0	0.9	1.2	1.1	1.2	1.1	1.0	0.9	0.0
Phe	2.9	2.6	2.8	2.6	3.1	2.9	3.1	3.1	2.8	2.5	0.1
Thr	2.3	2.0	2.3	2.2	2.5	2.4	2.6	2.5	2.3	2.1	0.1
Trp	0.8	0.6	0.7	0.7	0.7	0.6	0.8	0.7	0.8	0.6	0.2
Val	3.4	2.8	3.2	3.2	3.5	3.3	3.5	3.6	3.3	2.9	0.1
Dispensable amino acids, g/kg											
Ala	3.5	2.9	3.5	3.5	3.5	3.5	3.8	3.8	3.5	3.0	0.1
Asp	5.2	4.1	4.9	5.3	5.0	5.2	5.6	5.7	5.1	4.4	0.2
Cys	1.5	1.5	1.5	1.4	1.3	1.4	1.6	1.6	1.6	1.3	0.0
Glu	14.3	14.1	13.6	11.7	15.4	15.1	15.4	14.7	14.3	12.7	0.4
Gly	4.1	3.3	3.8	4.0	3.7	3.8	4.2	4.1	3.9	3.4	0.1
Ser	2.9	2.6	2.7	2.7	3.0	3.0	3.1	3.0	2.9	2.6	0.1
Tyr	1.7	1.6	1.8	1.6	1.7	1.7	1.9	1.8	1.6	1.5	0.1

2.2.2. *Experiment 2: amino acid digestibility*

Ileal digesta samples were thawed, mixed within animal and diet, and a sub-sample was collected for chemical analysis. Samples of all diets and each source of wheat middlings were also collected. Ileal digesta samples were lyophilized and finely ground prior to chemical analysis. Samples of diets, ileal digesta, and each source of wheat middlings were analyzed for DM as explained for experiment 1, and nitrogen was analyzed (Method 990.03; AOAC Int, 2019) using an FP628 protein analyzer (Leco Corporation, St. Joseph, MI, USA). Crude protein was calculated as analyzed nitrogen multiplied by 6.25. Ingredients, diets, and ileal digesta samples were also analyzed for AA [method 982.30 E(a, *b*, c); AOAC Int, 2019] on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc.; Pleasanton, CA, USA) using ninhydrin for post-column derivatization and nor-leucine as the internal standard. Diets and ileal digesta samples were also analyzed for chromium (Method 990.08; AOAC Int, 2019). All analyses were conducted in duplicates.

Table 7

Apparent total tract digestibility (ATTD) of gross energy (GE) and dry matter (DM), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets and in ten sources of wheat middlings[a].

		European sources						U.S. sources							
Item	Corn soybean meal	01	02	03	04	05	SD	01	02	03	04	05	SD	SEM	P-value
Diets															
GE intake, MJ/day	21.15	21.13	22.50	22.41	21.98	21.93	0.54	20.98	21.87	22.54	21.80	22.69	0.68	0.808	0.171
GE in feces, MJ/day	2.54	4.79^{b}	4.48^{bc}	4.94^{b}	5.46^{a}	4.94^{b}	0.36	4.22^{c}	4.81^{b}	5.01^{ab}	4.69^{bc}	4.61^{bc}	0.29	0.264	0.003
GE in urine, MJ/day	0.75	0.59	1.06	0.95	0.51	0.67	0.24	0.59	0.49	0.67	0.63	0.76	0.10	0.172	0.118
ATTD, GE	0.88	0.77^{c}	0.80^{a}	0.78^{bc}	0.75^{d}	0.78^{c}	0.02	0.80^{a}	0.78^{bc}	0.78^{bc}	0.79^{ab}	0.80^{a}	0.01	0.007	< 0.001
ATTD, DM	0.89	0.79^{c}	0.82^{a}	0.80^{abc}	0.77^{d}	0.79^{bc}	0.02	0.81^{a}	0.79^{bc}	0.79^{bc}	0.80^{ab}	0.81^{a}	0.01	0.007	< 0.001
DE, MJ/kg	14.00	12.54^{cd}	12.97^{a}	12.66^{abc}	12.23^{d}	12.49^{cd}	0.27	12.95^{a}	12.70^{abc}	12.68^{abc}	12.58^{bc}	12.87^{ab}	0.15	0.117	0.001
ME, MJ/kg	13.44	12.09	12.18	11.96	11.85	11.99	0.13	12.48	12.35	12.18	11.98	12.33	0.19	0.159	0.117
Ingredients															
ATTD, GE	-	0.63^{cd}	0.70^{a}	0.64^{c}	0.58^{d}	0.63^{c}	0.05	0.70^{a}	0.65^{bc}	0.65^{bc}	0.64^{c}	0.69^{ab}	0.03	0.018	< 0.001
ATTD, DM	-	0.63^{c}	0.70^{a}	0.66^{abc}	0.58^{d}	0.63^{bc}	0.04	0.69^{a}	0.64^{bc}	0.63^{bc}	0.67^{ab}	0.68^{a}	0.03	0.017	< 0.001
DE, MJ/kg DM	-	11.87^{cd}	13.16^{a}	12.26^{bc}	11.09^{d}	11.83^{cd}	0.76	13.21^{a}	12.54^{abc}	12.51^{abc}	12.04^{cd}	13.02^{ab}	0.46	0.335	< 0.001
ME, MJ/kg DM	-	11.56^{bc}	11.89^{abc}	11.20^{c}	10.94^{c}	11.37^{bc}	0.36	12.85^{a}	12.47^{ab}	12.04^{abc}	11.69^{abc}	12.43^{ab}	0.44	0.410	0.049

[a] Data are least squares means of 8 observations per treatment.

[a-d] Means within a row lacking a common superscript differ ($P < 0.05$).

2.3. Calculation and statistical analyses

After analysis of ingredients, the rest fraction for each ingredient was calculated by subtracting the sum of ash, CP, AEE, starch, and TDF from DM. Following analysis of samples from experiment 1, the ATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (NRC, 2012). In the basal diet, all energy originated form corn and soybean meal and corn and soybean meal made up 976.5 g/kg. In the test diets, all energy originated from corn, soybean meal, and wheat middlings and combined, these three ingredients made up 978.6 g/kg. Because corn and soybean meal were included in all diets at the same ratio (i.e., 2.05:1), and because corn and soybean meal combined made up 578.6 g/kg in the test diets, it was possible to calculate the contribution of DE and ME from corn and soybean meal to the DE and ME in the test diets by multiplying the DE and ME in the basal diet by (578.6/976.5). The calculated DE and ME was then subtracted from the DE or ME in the test diets and the remaining DE and ME in the test diets were assumed to originate from the 400 g/kg wheat middlings included in the diets. To calculate the DE and ME in wheat middlings, the DE and ME contributed by 400 g/kg in the test diets was divided by 0.40. Thus, the following equation was used to calculate DE in each source of wheat middlings:

DE in wheat middlings = [DE in test diet – (DE in basal diet × 578.6/976.5)/0.40].

The ME in each source of wheat middlings was calculated using the same equation.

The contribution of energy from corn and soybean meal to the diets containing wheat middlings was subtracted from the DE and ME of these diets, and the DE and ME in each source of wheat middlings were calculated by difference (Adeola, 2001). The ATTD of GE and DM in each source of wheat middlings was also calculated by difference. In experiment 2, the apparent ileal digestibility (AID) and the SID of CP and each AA were calculated according to Stein et al. (2007).

Data from both experiments were analyzed using the MIXED procedure of SAS (SAS Institute Inc, 2016). Pig was the experimental unit. Homogeneity of the variances and normality of data were confirmed using the UNIVARIATE procedure of SAS. The model included diet or ingredient (i.e., wheat middlings) as the fixed effect. Block and replicate within block were considered random effects in experiment 1, whereas replicate was the random effect in experiment 2. Treatment means were calculated using LSMeans in SAS, and if significant, means were separated using the PDIFF option of SAS. Contrast statements were used to compare values for wheat middlings from Europe with wheat middlings from the U.S. For experiment 1, a Spearman correlation analysis was used to analyze correlations between energy and nutrients in wheat middlings and calculated values for DE and ME. Results were considered significant at $P \leq 0.05$ and considered a tendency at $0.05 < P \leq 0.10$.

3. Results

3.1. Nutrient composition of wheat middlings

The GE in the ten sources of wheat middlings ranged from 16.5 MJ/kg to 17.1 MJ/kg, whereas AEE ranged from 31.8 to 44.6 g/kg (Table 1). Starch in wheat middlings from EU source 04 was 79 g/kg, which was less compared with the other EU sources. As a result, the standard diviation for starch in wheat middlings from Europe was greater compared with wheat middlings from the U.S. All wheat middlings ranged from 324 to 508 g/kg in TDF, and regardless of source, insoluble dietary fiber was much greater than soluble dietary fiber. Wheat middlings from EU sources 01 and 04 had the greatest TDF (i.e., 493 and 508 g/kg, respectively), whereas U.S. source 01 had the least concentration of TDF (i.e., 324 g/kg).

The CP in the ten sources of wheat middlings ranged from 138 to 174 g/kg. Wheat middlings sourced from Europe contained approximately 150 g/kg CP except for wheat middlings from source 05, which contained 174 g/kg CP. As a result, the AA in wheat middlings from source 05 was greater compared with other European sources. Wheat middlings from the U.S. contained 150 to 160 g/kg CP except for source 05 which contained 138 g/kg CP. Therefore, AA in source 05 were less compared with European sources and other wheat middlings from the U.S. The mean Lys:CP in the ten sources of wheat middlings was 4.2 with U.S. sources having greater Lys:CP (i.e., 4.4) compared with European sources (i.e., 4.0). The rest fraction in wheat middlings from Europe ranged from 10.6 to 68.4 g/kg with an average of 49.3 g/kg, and in the wheat middlings from the U.S., the rest fraction ranged from 25.1 to 62.1 g/kg with an average of 49.6 g/kg. The average concentration of Ca and P in the ten sources of wheat middlings was 1.2 ± 0.2 g/kg and 10.9 ± 1.7 g/kg, respectively (Table 2).

3.2. Digestibility and concentration of energy

There were no differences in GE intake or GE output in urine among diets containing the ten sources of wheat middlings (Table 7). Pigs fed the diet containing wheat middlings from EU source 04 had the greatest ($P < 0.01$) fecal GE loss, whereas pigs fed the diet with U.S. source 01 wheat middlings had the least ($P < 0.01$) fecal GE loss. As a result, the diet containing wheat middlings from EU source 04 had the least ($P < 0.01$) ATTD of GE and DM and the least ($P < 0.01$) concentration of DE (DM basis), whereas pigs fed the diet with U.S. source 01 or the diet with EU source 02 had the greatest ($P < 0.01$) ATTD of GE and DM and the greatest ($P < 0.01$) concentration of DE (DM basis). On a DM basis, DE in wheat middlings used in this experiment ranged from 11.09 to 13.21 MJ/kg, and ME ranged from 10.94 to 12.85 MJ/kg.

Pigs fed wheat middlings from Europe had greater ($P = 0.042$) fecal GE loss compared with pigs fed wheat middlings from the U.S. (Table 8). The average ATTD of both GE and DM in wheat middlings from Europe was 0.64, and this value was less ($P = 0.034$ and 0.037, respectively) compared with the average ATTD of GE and DM in wheat middlings from the U.S. (i.e., 0.67 and 0.66 for GE and DM, respectively). Wheat middlings from Europe had reduced concentrations of DE and ME (DM basis) compared with wheat middlings from the U.S. ($P = 0.012$ and 0.001, respectively).

The correlation analysis demonstrated there were tendencies for positive correlations between AEE and starch in wheat middlings and ME in the ingredients (Table 9). However, negative correlations between GE and TDF and DE and ME were observed. No correlations between CP and DE or ME were observed.

3.3. Amino acid digestibility

Diet analyses indicated that the intended concentration of CP and AA were present in all diets. The AID and SID of Trp and Gly were not different among sources, and the SID of Arg and Lys did not differ among the ten sources of wheat middlings (Table 10). Differences ($P < 0.05$) in AID and SID of CP were observed with EU sources 01 and 04 having the least AID and SID of CP. Differences ($P < 0.05$) in AID and SID of Ile, Leu, Met, Phe, Thr, Val, Ala, Asp, Cys, Glu, Ser, and Tyr were observed among sources. The SID of His also tended ($P < 0.10$) to be different among sources, and generally, wheat middlings from EU sources 01 and 04 had reduced ($P < 0.05$) SID of AA compared with other sources. As a consequence, the AID and SID of His, Leu, Lys, Asp, Cys, Glu, and Ser of wheat middlings from Europe were less ($P < 0.05$) compared with wheat middlings from the U.S (Table 11). The SID of Ile also tended to be greater ($P < 0.10$) in wheat middlings from the U.S. compared with SID of Ile in European sources. Due to reduced AID and SID of CP and AA in wheat middlings from sources 01 and 04, increased variability in CP and AA digestibility values was observed in the wheat middlings from Europe (i.e., mean SD for SID of CP and AA = 0.06) compared with the variability in digestibility values in wheat middlings from the U. S. (i.e., mean SD for SID of CP and AA = 0.02).

4. Discussion

The analyzed GE in the ten sources of wheat middlings was in agreement with previously reported values (NRC, 2012; Casas et al., 2018). The starch-rich endosperm in wheat is removed during flour milling, which results in wheat co-products containing 150 to 200 g/kg starch (NRC, 2012). The analyzed mean value for starch in wheat middlings used in the experiment was less compared with some published data (Huang et al., 2014; Harlow et al., 2016), but in agreement with data reported by NRC (2012) and Casas et al. (2018). This indicates that 700 to 800 g/kg of the starch in wheat is extracted during flour milling. The average concentration of TDF in wheat middlings observed in this experiment concurs with the value reported by Jaworski and Stein (2017), and analyzed concentrations of Ca and P were within the range of reported values (NRC, 2012). The analyzed values for CP were also in agreement with previously reported values (Huang et al., 2012; NRC, 2012).

The fact that the rest fractions were close to 50 g/kg in wheat middlings from both Europe and the U.S. indicates that not all nutrients were accounted for in the analysis of CP, ash, AEE, starch, and TDF. Most likely, the fractions not analyzed include free sugars, sucrose, maltose, and fructooligosaccharides because to account for all components in an ingredient, analysis of the low molecular weight carbohydrates is needed (Navarro et al., 2018). Indeed, when analyzing 10 sources of wheat middlings from the U.S., free sugars, sucrose, maltose, and fructooligosaccharides totalled 78.4 g/kg (Casas et al., 2018), which further indicates that the rest fraction calculated for the wheat midlings used in the present experimetns likely consisted of low molecular weight sugars.

The difference procedure was used to determine concentrations of DE and ME in the ten sources of wheat middlings, and a consequence of using the difference procedure is that reliable results for test ingredients will be obtained only if the DE and ME of the corn-soybean meal basal diet are accurate. Values for DE and ME obtained for the corn-soybean meal diet in the present experiment were in close agreement with previous data (Casas et al., 2018), which gives confidence that calculated values for DE and ME in wheat middlings are accurate. The DE and ME in wheat middlings used in the experiment were less than some published values (Sauvant et al., 2004; NRC, 2012), but in agreement with other reported data (Nortey et al., 2008; Huang et al., 2014; Casas et al., 2018). The observed reduction in concentrations of DE and ME in one of the sources of wheat middlings from Europe is likely due to the increased concentration of TDF as well as the reduced concentration of starch in that source. In general, the concentration of fiber in wheat middlings increases as the concentration of starch decreases (Rosenfelder et al., 2013), which is likely the reason for the greater DE and

Table 8
Apparent total tract digestibility (ATTD) of gross energy (GE) and dry matter (DM), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets and in wheat middlings sourced from Europe and U.S.

Item	European sources	U.S. sources	SEM	P-value
Diets				
GE intake, MJ/day	21.99	21.96	0.716	0.909
GE in feces, MJ/day	4.89	4.64	0.230	0.042
GE in urine, MJ/day	0.77	0.63	0.111	0.150
ATTD, GE	0.78	0.79	0.004	0.034
ATTD, DM	0.79	0.80	0.004	0.037
DE, MJ/kg	12.60	12.77	0.069	0.039
ME, MJ/kg	12.02	12.31	0.078	0.004
Ingredients				
ATTD, GE	0.64	0.67	0.011	0.022
ATTD, DM	0.64	0.66	0.011	0.037
DE, MJ/kg DM	12.10	12.69	0.196	0.012
ME, MJ/kg DM	11.42	12.32	0.220	0.001

Table 9
Spearman correlation coefficients between gross energy (GE), crude protein (CP), acid-hydrolyzed ether extract (AEE), starch, total dietary fiber (TDF), and digestible energy (DE) and metabolizable energy (ME) in ingredients.

	Correlation coefficient	
Item	DE	ME
GE	-0.40***	-0.30**
CP	-0.04	0.05
AEE	0.08	0.22*
Starch	0.49***	0.22*
TDF	-0.48***	-0.25**

***P < 0.01 **P < 0.05 *P < 0.10.

ME in the wheat middlings from the U.S. compared with wheat middlings from Europe. Indeed, a linear reduction in DE in wheat co-products was observed as fiber increased (Huang et al., 2014). The observed variability in concentrations of ME among sources of wheat middlings is likely a result of variation in nutrient composition of the parent grain or differences among flour mills in the production process (Casas and Stein, 2017). The positive correlations between starch and DE and ME and the negative correlation between TDF and DE and ME that was observed were expected and also aligns with equations to predict net energy of feed ingredients (Noblet et al., 1994). In previous work with wheat shorts, a negative correlation between neutral detergent fiber and DE and a positive correlation between starch and DE were observed (Huang et al., 2012). In an experiment with wheat co-products differing in concentrations of dietary fiber, negative correlations between neutral detergent fiber and DE and ME and positive correlations between starch and DE and ME were also reported (Huang et al., 2014). The reason for these observations most likely is that the DE and ME of fiber are less than of starch (Kil et al., 2013). The reason for the negative correlation between GE and DE and ME likely is that increased TDF also increases GE in the ingredients. Although AEE contains more energy than carbohydrates and protein, only a tendency for a positive correlation between AEE and ME was observed, which likely is because intact fat in feed ingredients sometimes has low digestibility (Kim et al., 2013).

The AID and SID for CP and most AA in wheat middlings determined in the present experiment were in agreement with reported values (Huang et al., 2012; NRC, 2012), but greater than values reported by Casas and Stein (2017) for wheat middlings sourced from the U.S. Calculated values for SID of Lys in wheat middlings used in this experiment were less than published values (Nortey et al., 2008; NRC, 2012), and this is likely a result of heat damage (González-Vega et al., 2011). The observed reduction for SID of Lys may also have been due to differences among wheat varieties used to produce the wheat middlings or in processing conditions. The reduced AID and SID of CP and most AA in wheat middlings from two of the European sources compared with the other sources is possibly due to the increased concentration of TDF in these sources, because elevated levels of TDF results in increased secretion of mucin and increased diet-specific endogenous losses of AA (Souffrant, 2001), which subsequently results in reduced SID of AA. The observed reduction in AA digestibility in wheat middlings from Europe is likely also due to the reduced Lys:CP in these sources. The degree of heat damage in a feed ingredient may be estimated by calculating the Lys:CP ratio (Stein et al., 2009; Cozannet et al., 2010), and the current data indicate that wheat middlings from Europe are more heat damaged compared with U.S. sources, which is likely due to excessive drying of the grain or use of excessive heat during processing. Drying of corn at 120 °C, rather than 35 °C, resulted in reduced SID of AA (Espinosa et al., 2023), and it is, therefore, possible that drying of wheat at elevated temperatures also reduces SID of AA. However, because we do not have information about the drying temperatures used for the wheat grain, we cannot confirm this hypothesis.

The limitations of the current data include the facts that only 5 sources of wheat middlings were procured from each continent, and it would have been better if more sources had been included. However, due to funding limitations, it was not possble to include more sources of wheat middlings in the current experiments. It is also a limitation that we did not have information about the processing parameters or about the grains used to produce the wheat middlings, so it was not possible to relate differences among sources of wheat middlings to the original grains or the processing of the grain. Another limitation is that wheat middlings were fed only to young growing pigs and not to finishing pigs or sows although finishing pigs and sows have a greater digestibility of energy than young growing pigs. We believe results can be exptrapolated to finishing pigs and sows, but we do not have the data to prove this.

5. Conclusion

The apparent total tract digestibiltiy of gross energy and dry matter and concentration of digestible energy in one of the European sources of wheat middlings were less than in other sources of wheat middlings. Likewise, wheat middlings from Europe had reduced concentrations of digestible and metabolizable energy (dry matter basis) compared with wheat middlings from the United States. The apparent and standardized ileal digestibility of crude protein and most amino acids in wheat middlings from the European sources 01 and 04 were less than in the other sources. As a consequence, amino acid digestibility values for wheat middlings from Europe were less than in wheat middlings from the United States, which may be due to increased concentration of dietary fiber and possibly some heat damage. Variability in gross energy and amino acid digestibility values was also observed among the five sources of wheat middlings from Europe, which is likelya result of differences among flour mills in the production process used to extract flour from the grain.

Table 10

Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in ten sources of wheat middlings[a,b].

	European sources						U.S. sources							
Item	01	02	03	04	05	SD	01	02	03	04	05	SD	SEM	P-value
AID														
CP	0.34^{e}	0.51^{abc}	0.51^{abc}	0.41^{de}	0.57^{a}	0.09	0.50^{bc}	0.54^{ab}	0.49^{bc}	0.45^{cd}	0.52^{abc}	0.03	0.036	< 0.001
Indispensable AA														
Arg	0.68^{yz}	$V66^{z}$	0.70^{xyz}	0.72^{xy}	0.74^{x}	0.03	0.71^{xyz}	0.76^{x}	0.73^{xy}	0.70^{xyz}	0.74^{xy}	0.02	0.031	0.076
His	0.68^{c}	0.69^{c}	0.70^{bc}	0.72^{abc}	0.75^{a}	0.03	0.74^{ab}	0.74^{ab}	0.75^{a}	0.73^{abc}	0.72^{abc}	0.01	0.019	0.029
Ile	0.50^{d}	0.65^{ab}	0.62^{bc}	0.58^{c}	0.69^{a}	0.07	0.67^{ab}	0.66^{ab}	0.62^{bc}	0.63^{abc}	0.62^{bc}	0.03	0.027	< 0.001
Leu	0.60^{d}	0.70^{bc}	0.69^{bc}	0.66^{c}	0.76^{a}	0.06	0.73^{ab}	0.72^{ab}	0.71^{abc}	0.70^{bc}	0.68^{bc}	0.02	0.019	< 0.001
Lys	0.35^{z}	0.48^{xy}	0.47^{xy}	0.42^{yz}	0.47^{xy}	0.06	0.47^{xy}	0.55^{x}	0.49^{xy}	0.42^{yz}	0.50^{xy}	0.05	0.039	0.069
Met	0.69^{de}	0.75^{abc}	0.71^{bcd}	0.66^{e}	0.79^{a}	0.05	0.76^{ab}	0.75^{abc}	0.74^{bcd}	0.72^{bcd}	0.71^{cde}	0.02	0.020	< 0.001
Phe	0.63^{e}	0.73^{abc}	0.71^{bcd}	0.67^{de}	0.77^{a}	0.05	0.75^{ab}	0.74^{ab}	0.73^{abc}	0.71^{bcd}	0.69^{cd}	0.02	0.018	< 0.001
Thr	0.33^{c}	0.52^{ab}	0.53^{ab}	0.48^{b}	0.59^{a}	0.10	0.56^{ab}	0.55^{ab}	0.56^{ab}	0.50^{ab}	0.49^{b}	0.03	0.034	0.001
Trp	0.65	0.72	0.69	0.68	0.69	0.02	0.68	0.70	0.69	0.73	0.67	0.02	0.026	0.599
Val	0.54^{c}	0.64^{b}	0.64^{b}	0.63^{b}	0.72^{a}	0.06	0.69^{ab}	0.68^{ab}	0.67^{ab}	0.65^{ab}	0.63^{b}	0.02	0.023	0.001
Dispensable AA														
Ala	0.36^{c}	0.51^{b}	0.54^{ab}	0.50^{b}	0.61^{a}	0.09	0.55^{ab}	0.56^{ab}	0.53^{ab}	0.53^{ab}	0.50^{b}	0.02	0.034	0.001
Asp	0.46^{b}	0.57^{a}	0.59^{a}	0.59^{a}	0.63^{a}	0.07	0.64^{a}	0.64^{a}	0.62^{a}	0.60^{a}	0.57^{a}	0.03	0.031	0.002
Cys	0.56^{c}	0.71^{a}	0.65^{abc}	0.64^{bc}	0.61^{cd}	0.06	0.64^{abc}	0.68^{ab}	0.68^{ab}	0.70^{ab}	0.67^{abc}	0.02	0.026	0.004
Glu	0.75^{d}	0.83^{abc}	0.80^{c}	0.76^{d}	0.85^{a}	0.04	0.84^{ab}	0.83^{abc}	0.80^{bc}	0.81^{bc}	0.81^{bc}	0.02	0.014	< 0.001
Gly	0.25	0.21	0.34	0.28	0.29	0.05	0.28	0.33.0	0.29	0.30	0.37	0.04	0.069	0.630
Ser	0.47^{b}	0.63^{a}	0.60^{a}	0.59^{a}	0.66^{a}	0.07	0.67^{a}	0.65^{a}	0.60^{a}	0.63^{a}	0.63^{a}	0.03	0.033	0.003
Tyr	0.48^{d}	0.65^{ab}	0.66^{ab}	0.58^{c}	0.67^{a}	0.08	0.65^{ab}	0.66^{ab}	0.62^{abc}	0.59^{bc}	0.63^{abc}	0.03	0.028	< 0.001
SID														
CP	0.58^{d}	0.75^{ab}	0.74^{ab}	0.65^{cd}	0.77^{a}	0.08	0.72^{ab}	0.75^{ab}	0.70^{abc}	0.68^{bc}	0.76^{a}	0.03	0.036	< 0.001
Indispensable AA														
Arg	0.81	0.82	0.84	0.84	0.87	0.02	0.84	0.87	0.84	0.83	0.88	0.02	0.031	0.261
His	0.76^{z}	0.79^{yz}	0.79^{yz}	0.80^{xyz}	0.83^{x}	0.03	0.83^{xy}	0.82^{xy}	0.83^{xy}	0.82^{xy}	0.81^{xyz}	0.01	0.019	0.081
Ile	0.62^{d}	0.78^{ab}	0.75^{abc}	0.71^{c}	0.80^{a}	0.07	0.79^{ab}	0.77^{abc}	0.73^{bc}	0.75^{abc}	0.75^{abc}	0.02	0.027	< 0.001
Leu	0.69^{d}	0.81^{abc}	0.79^{bc}	0.77^{c}	0.85^{a}	0.06	0.82^{ab}	0.81^{abc}	0.80^{abc}	0.79^{bc}	0.79^{bc}	0.02	0.019	< 0.001
Lys	0.55	0.69	0.67	0.59	0.64	0.06	0.70	0.70	0.66	0.64	0.68.0	0.03	0.039	0.113
Met	0.74^{cd}	0.81^{ab}	0.78^{bcd}	0.73^{d}	0.84^{a}	0.05	0.82^{ab}	0.80^{ab}	0.80^{abc}	0.78^{bcd}	0.78^{bcd}	0.02	0.020	0.001
Phe	0.72^{d}	0.82^{ab}	0.80^{bc}	0.77^{c}	0.85^{a}	0.05	0.83^{ab}	0.82^{ab}	0.81^{abc}	0.80^{bc}	0.79^{bc}	0.02	0.018	0.001
Thr	0.60^{c}	0.75^{ab}	0.71^{ab}	0.68^{bc}	0.77^{a}	0.07	0.75^{ab}	0.72^{ab}	0.74^{ab}	0.70^{abc}	0.71^{ab}	0.02	0.034	0.046
Trp	0.75	0.85	0.80	0.79	0.80	0.03	0.81	0.79	0.80	0.83	0.80	0.02	0.026	0.453
Val	0.65^{c}	0.77^{ab}	0.75^{b}	0.75^{b}	0.82^{a}	0.06	0.80^{ab}	0.78^{ab}	0.77^{ab}	0.76^{ab}	0.75^{b}	0.02	0.023	0.001
Dispensable AA														
Ala	0.53^{c}	0.72^{ab}	0.71^{ab}	0.68^{b}	0.78^{a}	0.09	0.72^{ab}	0.72^{ab}	0.69^{b}	0.71^{ab}	0.70^{ab}	0.01	0.034	0.002
Asp	0.59^{b}	0.73^{a}	0.73^{a}	0.72^{a}	0.77^{a}	0.07	0.77^{a}	0.76^{a}	0.74^{a}	0.73^{a}	0.72^{a}	0.02	0.031	0.004
Cys	0.66^{c}	0.81^{a}	0.76^{ab}	0.75^{ab}	0.73^{bc}	0.05	0.75^{ab}	0.78^{ab}	0.78^{ab}	0.80^{a}	0.78^{ab}	0.02	0.026	0.009
Glu	0.81^{d}	0.89^{ab}	0.86^{bc}	0.83^{cd}	0.90^{a}	0.04	0.90^{ab}	0.88^{ab}	0.86^{bc}	0.87^{b}	0.87^{ab}	0.01	0.014	< 0.001
Gly	0.61	0.66	0.73	0.65	0.69	0.04	0.67	0.68	0.65	0.68	0.81	0.06	0.069	0.280
Ser	0.63^{b}	0.80^{a}	0.76^{a}	0.75^{a}	0.81^{a}	0.07	0.82^{a}	0.79^{a}	0.75^{a}	0.78^{a}	0.80^{a}	0.02	0.033	0.004
Tyr	0.61^{c}	0.79^{a}	0.79^{ab}	0.72^{b}	0.80^{a}	0.08	0.78^{ab}	0.77^{ab}	0.74^{ab}	0.73^{ab}	0.78^{ab}	0.02	0.028	< 0.001

[a] Data are least squares means of 8 observations per treatment.

[b] Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg dry matter intake) as CP, 16.94; Arg, 0.64; His, 0.17; Ile, 0.30; Leu, 0.47; Lys, 0.55; Met, 0.07; Phe, 0.27; Thr, 0.49; Trp, 0.08; Val, 0.39; Ala, 0.65; Asp, 0.72; Cys, 0.17; Glu, 0.90; Gly, 1.59; Ser, 0.48; and Tyr, 0.24.

[a-e] Means within a row lacking a common superscript differ ($P < 0.05$).

[x-z] Means within a row lacking a common superscript tended to differ ($P < 0.10$).

Table 11
Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in in wheat middlings sourced from Europe and U.S.

Item	European sources	U.S. sources	SEM	P-value
AID				
CP	0.47	0.50	0.028	0.057
Indispensable AA				
Arg	0.70	0.73	0.025	0.087
His	0.71	0.74	0.013	0.009
Ile	0.61	0.64	0.019	0.037
Leu	0.68	0.71	0.011	0.033
Lys	0.44	0.49	0.051	0.045
Met	0.72	0.73	0.013	0.216
Phe	0.70	0.72	0.001	0.078
Thr	0.49	0.53	0.018	0.027
Trp	0.69	0.69	0.015	0.647
Val	0.63	0.66	0.013	0.050
Dispensable AA				
Ala	0.50	0.54	0.021	0.104
Asp	0.57	0.61	0.020	0.009
Cys	0.63	0.67	0.014	0.012
Glu	0.80	0.82	0.010	0.018
Gly	0.27	0.31	0.050	0.237
Ser	0.59	0.63	0.021	0.014
Tyr	0.61	0.63	0.019	0.197
SID				
CP	0.70	0.72	0.028	0.099
Indispensable AA				
Arg	0.84	0.85	0.025	0.205
His	0.79	0.82	0.013	0.018
Ile	0.73	0.76	0.019	0.086
Leu	0.78	0.80	0.011	0.050
Lys	0.63	0.68	0.051	0.038
Met	0.78	0.80	0.013	0.261
Phe	0.79	0.81	0.001	0.124
Thr	0.70	0.72	0.018	0.231
Trp	0.80	0.81	0.015	0.619
Val	0.75	0.77	0.013	0.087
Dispensable AA				
Ala	0.69	0.71	0.021	0.209
Asp	0.71	0.74	0.020	0.030
Cys	0.74	0.78	0.014	0.024
Glu	0.86	0.88	0.010	0.042
Gly	0.67	0.70	0.050	0.392
Ser	0.75	0.79	0.021	0.040
Tyr	0.74	0.76	0.019	0.223

CRediT authorship contribution statement

Espinosa Charmaine D.: Investigation, Methodology, Writing – original draft. **Stein Hans H:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. **Torres-Mendoza Leidy J.:** Formal analysis, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflicts of interest.

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