Research Article

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Comparative digestibility of energy and nutrients and fermentability of dietary fiber in eight cereal grains fed to pigs

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Abstract

BACKGROUND: Cereal grains provide a large portion of caloric intake in diets for humans, but not all cereal grains provide the same amount of energy. Therefore, an experiment was conducted to determine and compare the metabolizable energy (ME), the apparent ileal digestibility (AID), and the apparent total tract digestibility (ATTD) of gross energy (GE) and nutrients in eight cereal grains when fed to pigs.

RESULTS: Rice had greater ($P < 0.05$) AID of GE than other cereal grains, greater ($P < 0.05$) AID of starch than yellow dent corn, dehulled barley, rye, and wheat, and greater ($P < 0.05$) ATTD of GE than yellow dent corn, rye, sorghum, and wheat. Dehulled barley, rye, and sorghum had less ($P < 0.05$) AID of starch than other cereal grains. Dehulled barley had greater ($P < 0.05$) ATTD of GE than rye. Dehulled oats had the greatest ($P < 0.05$) ME compared with other cereal grains, whereas rye had the least ($P < 0.05$) ME.

CONCLUSION: Dehulled oats provide more energy to diets and should be used if the goal is to increase caloric intake. In contrast, sorghum and rye may be more suitable to control diabetes and manage body weight of humans.

Keywords: cereal grains; energy digestibility; pigs; starch; total dietary fiber

INTRODUCTION

Cereal grains are the major source of energy in most diets for humans and animals. The cereal grains that are commonly used for human consumption include corn, dehulled barley, dehulled oats, rice, rye, sorghum, and wheat. In developed countries, cereal grains are mostly consumed as processed and refined products, but interest in using raw whole grains has increased because consumption of whole grains improves overall digestive health[1] and is beneficial in preventing and managing metabolic diseases.[2,3] The protective effects of whole cereal grains against metabolic diseases may be a result of the dietary fiber in the cereal grains.[2,3] However, the presence of dietary fiber in the diet reduces energy and nutrient digestibility,[4] but it is not known if the fiber in all cereal grains has similar effects on the digestibility of energy and nutrients in the diet.

Although a reduction in the caloric value and carbohydrate digestibility in cereal grains may benefit individuals with diabetes and individuals who want to limit or avoid weight gain, a reduction in the digestibility of other nutrients may result in less than optimal nutrition. A reduced caloric value may also not be desirable in developing countries where the caloric intake may be below requirements. It is, however, not known how different cereal grains contribute to the caloric value of a diet. It is also not known if the fiber in different cereal grains is fermented to the same degree.

Determining energy and nutrient digestibility values in food ingredients in humans is expensive and tedious. However, nutrient and energy digestibility may be determined using pigs as a model for humans.[5]

The objective of this experiment, therefore, was to compare the concentration of digestible energy (DE) and metabolizable energy (ME) among cereal grains when using the pig as a model for humans. The second objective was to compare the apparent ileal digestibility (AID) and the apparent total tract digestibility (ATTD) of gross energy (GE) and nutrient components among different cereal grains when fed to growing pigs.

EXPERIMENTAL

The protocol was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois at Urbana-Champaign. Twenty-four growing barrows (initial body weight 30.7 ± 3.2 kg) that were the offspring of G-performer boars mated to Fertilium 25 females (Genetiporc, Alexandria, MN, USA) were fitted with a T-cannula in the distal ileum as described by Stein *et al.*[6] Pigs were allowed to recover after surgery for 10 days and they were allowed *ad libitum* access to water and a corn–soybean meal diet during the recovery period. Pigs were housed in individual metabolism cages in an environmentally controlled room. Each metabolism cage was equipped with a feeder and a nipple drinker, and with a screen that allowed

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for total, but separate, collection of feces and feed refusals, and a funnel that allowed for total collection of urine. Pigs were randomly allotted to eight diets that were fed during each of three periods in a completely randomized design. During each period, each diet was fed to three pigs. Therefore, each diet was fed to a total of nine pigs during the experiment and no pig was given the same diet more than once.

Eight cereal grains including yellow dent corn, Nutridense corn, dehulled barley, dehulled oats, polished white rice, rye, sorghum, and wheat were used in the experiment (Table 1). Yellow dent corn and Nutridense corn were procured from ExSeed Genetics LLC (Research Triangle Park, NC, USA). Polished white (Jasmine) rice was purchased from Walmart (Urbana, IL, USA), and the remaining cereal grains were sourced from Siemer Enterprises, Inc. (Teutopolis, IL, USA). All grains were ground in a hammer mill using a 1.6-mm screen. Eight diets were formulated with each cereal grain being the sole source of carbohydrates, crude protein (CP), acid hydrolyzed ether extract (AEE), starch, GE, and total dietary fiber (TDF) in one diet (Table 2). Each diet included 974 g kg^{-1} of each cereal grain, 8 g kg^{-1} dicalcium phosphate, 7 g kg^{-1} limestone, and 4 g kg^{-1} salt. Vitamins and minerals were added at 3 g kg^{-1} to all diets to meet or exceed the requirements for growing pigs.[7] All diets also contained 4 g kg^{-1} titanium dioxide (Kronos Titanox, Houston, TX, USA) as an indigestible marker.

The body weight of each pig was recorded at the start of each period and the daily feed allotments were calculated as two times the estimated maintenance requirement for energy for each pig (i.e. 106 kcal ME $kg^{-0.75}$).[7] The daily feed allowance was supplied in two equal meals that were provided at 08.00 and 17.00 h except on digesta collection days when pigs were fed at 06.00 and 18.00 h. Water was available at all times.

Each period lasted 14 days. The initial 5 days of each period was considered the adaptation period to the diet. During these days, in addition to their daily feed ration, pigs were provided 50 g of an amino acid mixture at each feeding to reduce the impact of feeding pigs a diet that is deficient in CP.[8] Chromic oxide was added to the diets in the morning meal of day 6 and ferric oxide was added in the morning meal of day 11. Quantitative collection of feces was initiated upon the appearance of chromic oxide and ceased upon the appearance of ferric oxide in the feces as described by Pedersen *et al.*[8] Quantitative collection of urine was also initiated in the morning of day 6 and ceased in the morning of day 11. A preservative of 50 mL of 6 mol L^{-1} HCl was added to the urine collection buckets, which were emptied twice daily after the total volume of urine had been recorded and a 20% sub-sample had been collected and stored at -20°C.[8] Freshly voided feces were collected in the morning of day 6 and pH of the fecal samples was immediately measured using a pH meter (Accumet Basic; Fisher Scientific, Pittsburgh, PA, USA). Fecal samples (20 g) were mixed with 2 mol L^{-1} HCl in a 1:1 ratio and the samples were stored at -20°C until the concentrations of short-chain fatty acids (SCFA) were analyzed.[9] Ileal digesta were collected on days 13 and 14 for 10 h each day as described by Pedersen *et al.*[8] The pH of the ileal digesta from each pig was measured at 09.00, 11.00, 13.00, 15.00 and 17.00 h on each collection day.

At the conclusion of the experiment, ileal digesta and urine samples were thawed and mixed within animal and diet, and a sub-sample was collected for chemical analyses. Samples of each diet and each cereal grain were also collected. Ileal digesta and urine samples were lyophilized and ileal digesta were ground prior to chemical analyses. All fecal samples were dried in a forced air oven at 60°C and ground prior to chemical analyses.

Cereal grains, diets, ileal digesta and fecal samples were analyzed for dry matter (AOAC method 930.15),[10] CP (AOAC method 990.03),[10] ash (AOAC method 942.05),[10] and TDF (AOAC method 985.29).[10] Samples were also analyzed for AEE by boiling the samples in 3 mol L^{-1} HCl[11] followed by ether extraction (AOAC method 2003.06).[10] Gross energy of diets, cereal grains, ileal digesta and fecal samples were determined using bomb calorimetry (Model 6300; Parr Instruments, Moline, IL, USA). The concentration of titanium in the diets, ileal digesta, and fecal samples were analyzed based on the procedure by Myers *et al.*[12]

Diets and cereal grains were analyzed for total starch[13] and resistant starch.[14,15] Water binding capacity was measured in three separate samples of each diet.[16] Briefly, 1000 ± 5 mg of sample was weighed into pre-dried centrifuged tubes and the sample was hydrated with 30 mL of distilled water for 48 h. After centrifugation ($2850\times g$, 20°C), the supernatant was separated from the sample by inverting the tube and allowing water to drain from the pellet. The fresh and dried weights of the pellets were recorded.

Particle size distribution was also determined in three samples of each diet by pouring 50 g of the diet on a stack of pre-weighed sieves (US Standard Testing Sieves; Fisher Scientific Co., Pittsburgh, PA, USA). The pore sizes of the sieves were 300, 600, 850, 1200 and 1700 µm. The cereal grains and diets were separated into different particle size fractions by shifting the set of sieves mechanically for 15 min using a portable sieve shaker (Model RX-24; Tyler Industrial Products, Mentor, OH, USA). After 15 min, the weight of material accumulated on each sieve was recorded.

Viscosity of the ileal digesta was measured using a Brookfield LV-DV-II+ Viscometer (Brookfield Eng. Lab. Inc., Middleboro, MA, USA). Containers containing frozen ileal digesta were placed in a water bath until sample temperature reached 39°C. The sample was then stirred and 30 mL of sample was placed in a 100 mL glass beaker and viscosity was measured as described by Dikeman *et al.*[17] The viscosity of each ileal digesta was measured within a range of shear rates (2, 4, 6 and 8) and within a range of spindle revolutions (1–4 rpm).

Fecal samples were prepared for SCFA analysis as described by Urriola and Stein[18] except that 2 mL of the feces–HCl mixture was mixed with 8 mL of distilled water. The concentrations of SCFA in each sample were analyzed as previously described.[18,19]

The concentration of total carbohydrates in the samples was calculated by subtracting the concentration of CP, AEE and ash from the concentration of dry matter in the samples. Resistant starch of the diets and ingredients was calculated as the difference between the total starch obtained from the method of Thivend *et al.*[13] and digestible starch obtained from the method of Muir and O'Dea.[14,15] Water binding capacity of the diets was calculated as the difference between the fresh and dry weights of the pellet (in grams) divided by the dry weight of the pellet.[16]

To calculate the mean particle size of the diet, the weight of the different particle fractions on each screen (in grams) was calculated as the difference between the weight of the screen with the samples (in grams) and the weight of the empty screen (in grams). The weights of each of the particle fractions were expressed as a percentage of the total weight of the sample recovered after sieving. The cumulative weights (%) of the different fractions were then transformed to $\log_{10}$ values and mean particle size of the diets was calculated as described by Waldo *et al.*[20]

Viscosity of the ileal digesta was calculated using the Wingather software (Brookfield Eng. Lab. Inc.). The NLREG statistical software (NLREG, Brentwood, TN, USA) was used to report viscosity measurements in terms of the power law equation.[17]

Table 1. Analyzed energy and nutrient composition of cereal grains (as-fed basis)

Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat
Gross energy (kcal kg^{-1})	3921	3972	3878	4172	3717	3906	3953	3913
Dry matter (g kg^{-1})	875	870	864	876	865	882	874	873
Crude protein (g kg^{-1})	75	88	118	131	90	121	98	119
AEE (g kg^{-1})	42	56	24	75	9	27	39	32
Ash (g kg^{-1})	12	10	13	15	2	16	10	14
Organic matter (g kg^{-1})	863	860	851	861	863	866	864	860
Total starch (g kg^{-1})	647	641	642	651	751	568	669	616
Total carbohydrates (g kg^{-1})	724	701	699	658	744	706	678	686
Resistant starch (g kg^{-1})	100	109	64	62	17	14	185	11
TDF (g kg^{-1})	102	94	70	64	11	117	90	99

Total carbohydrates = dry matter − (crude protein + AEE + ash).
Resistant starch = difference between the concentration of total starch[12] and the concentration of digestible starch.[13,14]
AEE, acid-hydrolyzed ether extract; TDF, total dietary fiber (determined by AOAC method 985.29).[9]

Table 2. Analyzed energy and nutrient composition of experimental diets (as-fed basis)[a]

Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat
Gross energy (kcal kg^{-1})	3770	3815	3764	4022	3596	3740	3800	3821
Dry matter (g kg^{-1})	870	864	875	881	867	884	868	878
Crude protein (g kg^{-1})	74	83	116	127	87	113	96	121
AEE (g kg^{-1})	37	49	24	63	9	23	53	30
Ash (g kg^{-1})	35	31	35	32	27	42	42	40
Organic matter (g kg^{-1})	836	833	840	849	840	842	826	838
Total starch (g kg^{-1})	619	635	606	630	738	557	605	595
Total carbohydrates (g kg^{-1})	724	701	699	658	744	706	678	686
Resistant starch (g kg^{-1})	77	122	109	30	−6	10	126	53
TDF (g kg^{-1})	91	82	69	43	10	117	106	102

[a] Each diet was composed of 974 g kg^{-1} cereal grain, 8 g kg^{-1} dicalcium phosphate, 7 g kg^{-1} limestone, 4 g kg^{-1} titanium dioxide, 4 g kg^{-1} salt, and 3 g kg^{-1} vitamin–mineral premix.
Total carbohydrates = dry matter − (crude protein + AEE + ash).
Resistant starch = difference between the concentration of total starch[12] and the concentration of digestible starch.[13,14]
AEE, acid-hydrolyzed ether extract; TDF, total dietary fiber (determined by AOAC method 985.29).[9]

The AID of organic matter (OM), CP, AEE, TDF, total carbohydrates, starch and GE was calculated for each diet as described by Stein *et al.*,[21] and the ATTD of OM, CP, AEE, TDF, total carbohydrates, starch and GE in the diets was calculated using total collection procedures as described by Adeola.[22] Hind gut disappearance (HGD) was calculated as the difference between the concentration of nutrients in the ileal digesta and the concentration of nutrients in the feces.[18] The DE and ME of the diets and ingredients were calculated as described by Adeola.[22]

For viscosity data analysis, the constant and the exponent values of each of the ileal digesta samples obtained from NLREG were analyzed by the MIXED procedure of SAS with period as the random effect and diet as the fixed effect. The LSMEANS statement was used to detect differences in viscosity among cereal grains. For the other measurements, data were tested for outliers and normal distribution using the UNIVARIATE procedure of SAS. Observations that were more than 3 SD away from the treatment mean were considered outliers. An outlier was removed from each of the eight dietary treatments for energy digestibility data analysis except for yellow dent corn, Nutridense corn, and sorghum diets, and an outlier was removed from each of the eight dietary treatments for AID, ATTD and HGD data analysis except for Nutridense corn, dehulled barley, and sorghum diets. Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC, USA) with diet as the fixed effect and period as the random effect. Means were calculated using the LSMEANS statement of SAS and the PDIFF option of SAS was used to separate treatment means. Correlation coefficients among chemical components, water binding capacity, particle size, ileal viscosity, ileal and fecal pH, concentration of SCFA, and the digestibility of TDF in cereal grains were determined using PROC CORR of SAS. The pig was the experimental unit for all analyses except that treatment was the experimental unit for correlation analysis. An alpha value of 0.05 was used to denote statistical significance and an alpha value between 0.05 and 0.10 was used to assess tendencies among treatment means.

RESULTS

The capacity of the dehulled barley diet to bind water was greater ($P < 0.05$), whereas the capacity of the rice diet to bind water was less ($P < 0.05$) than for all the other diets (Table 3). Mean particle size in the dehulled barley diet was the greatest ($P < 0.05$) and

Table 3. Water binding capacity (g g^{-1} dry pellet weight) and mean particle size (µm) of cereal grains

	Diet									
Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat	SEM	*P*-value
Water binding capacity	1.06^{c}	1.20^{b}	1.36^{a}	1.25^{b}	0.86^{d}	1.19^{b}	1.17^{bc}	1.19^{b}	0.037	0.001
Mean particle size	510^{f}	589^{e}	1057^{a}	774^{bc}	684^{d}	830^{b}	700^{d}	767^{cd}	19.98	0.001

$^{a-f}$ Within a row, means without a common superscript differ ($P < 0.05$).

Table 4. Daily balance of gross energy (GE) in growing pigs fed diets based on cereal grains and the concentration of digestible energy (DE) and metabolizable energy (ME) in each cereal grain[†]

	Diet									
Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat	SEM	*P*-value
GE intake (kcal)	3296^{b}	3388^{b}	3302^{b}	3529^{ab}	3244^{b}	3722^{a}	3441^{ab}	3411^{b}	150.42	0.080
GE in feces (kcal)	286^{c}	259^{c}	233^{c}	275^{c}	68^{d}	403^{a}	370^{ab}	299^{bc}	24.76	0.001
GE in urine (kcal)	72^{e}	94^{bcd}	89^{cde}	113^{ab}	89^{cde}	106^{abc}	80^{de}	116^{a}	9.35	0.001
DE in diet (kcal kg^{-1})	3441^{c}	3521^{b}	3507^{b}	3695^{a}	3520^{b}	3330^{d}	3390^{cd}	3509^{b}	29.19	0.001
ME in diet (kcal kg^{-1})	3354^{bc}	3416^{b}	3413^{b}	3566^{a}	3421^{b}	3241^{d}	3300^{cd}	3380^{b}	30.01	0.001
DE in ingredient (kcal kg^{-1})	3533^{c}	3616^{b}	3601^{b}	3792^{a}	3613^{b}	3418^{d}	3481^{cd}	3603^{b}	30.38	0.001
ME in ingredient (kcal kg^{-1})	3443^{bc}	3507^{b}	3504^{b}	3661^{a}	3513^{b}	3327^{d}	3388^{cd}	3471^{b}	30.82	0.001
DE in ingredient (kcal kg^{-1} DM^{2})	4036^{c}	4155^{b}	4167^{b}	4330^{a}	4188^{b}	3875^{d}	3985^{c}	4126^{c}	34.80	0.001
ME in ingredient (kcal kg^{-1} DM^{2})	3934^{de}	4030^{bc}	4055^{bc}	4180^{a}	4063^{b}	3772^{f}	3878^{e}	3975^{cd}	35.30	0.001

$^{a-f}$ Within a row, means without a common superscript differ ($P < 0.05$).
[†]Data are means of eight observations per treatment except for yellow dent corn, Nutridense corn, and sorghum diets, where data are means of nine observations per treatment.
DM, dry matter.

the mean particle size of the yellow dent corn diet was the least ($P < 0.05$) among all diets. Mean particle size of the dehulled oats and rye diets was greater ($P < 0.05$) than the particle size of rice, sorghum, yellow dent corn, and Nutridense corn diets, but the particle size of rice and sorghum diets was greater ($P < 0.05$) than the particle size of the Nutridense corn diet.

Diets containing Nutridense corn, dehulled barley, rice or wheat had greater ($P < 0.05$) DE and ME than diets containing yellow dent corn, rye, or sorghum, but had less ($P < 0.05$) DE and ME than the diet containing dehulled oats (Table 4). The DE and ME (kcal kg^{-1} DM) for Nutridense corn, dehulled barley, and rice were less ($P < 0.05$) than for dehulled oats, but greater ($P < 0.05$) than for other cereals except the ME for wheat. The DE and ME for yellow dent corn, sorghum, and wheat were greater ($P < 0.05$) than for rye.

The AID of GE, OM, and carbohydrates was greatest ($P < 0.05$) in rice, but least ($P < 0.05$) in rye and/or dehulled barley among all cereal grains (Table 5). The ATTD of GE, OM, and carbohydrates in rice was the greatest ($P < 0.05$), but the ATTD of GE and OM in rye and sorghum was the least ($P < 0.05$) and the ATTD of carbohydrates in rye and wheat was the least ($P < 0.05$) among all cereal grains. Dehulled barley and rye had the greatest ($P < 0.05$) HGD of GE, OM and carbohydrates, but rice had the least ($P < 0.05$) HGD of GE, OM and carbohydrates among the cereals.

The AID of CP was greatest ($P < 0.05$) in dehulled oats and rice, but least ($P < 0.05$) in yellow dent corn. The ATTD of CP was greatest ($P < 0.05$) in rice, but least ($P < 0.05$) in sorghum. As a consequence, sorghum had the greatest ($P < 0.05$) HGD of CP, but dehulled oats had the least ($P < 0.05$) HGD of CP among the cereals. The AID of AEE in dehulled oats and sorghum were greater ($P < 0.05$), but the AID of AEE in rye was less ($P < 0.05$), than in all other cereals. The ATTD of AEE in Nutridense corn and sorghum was greater ($P < 0.05$), but the ATTD of AEE in rye was less ($P < 0.05$), than in other cereals. Therefore, the HGD of AEE in rye was greater ($P < 0.05$), but the HGD of AEE in Nutridense corn, dehulled oats, rice, and sorghum was less ($P < 0.05$), than in other cereals.

The AID of starch in Nutridense corn, rice, and wheat was greater ($P < 0.05$), and the AID of starch in dehulled barley was less ($P < 0.05$), than in other cereals. The ATTD of starch in rice was greater ($P < 0.05$), but the ATTD of starch in sorghum was less ($P < 0.05$) than in other cereals. As a result, dehulled barley had the greatest ($P < 0.05$) HGD of starch while Nutridense corn, rice, and wheat had the least ($P < 0.05$) HGD of starch among all cereal grains. The AID of TDF in sorghum was greater ($P < 0.05$), but the AID of TDF in rice was less ($P < 0.05$), than in other cereals. The ATTD of TDF in sorghum was greater ($P < 0.05$), but the ATTD of TDF in dehulled oats was less ($P < 0.05$) than in other cereals. Therefore, dehulled barley had the greatest ($P < 0.05$) HGD of TDF, but sorghum had the least ($P < 0.05$) HGD of TDF, among all cereal grains.

The viscosity constant for the ileal digesta of pigs fed the Nutridense corn and rye diets was greater ($P < 0.05$) than that for the ileal digesta of pigs fed the other grains except that pigs fed

Table 5. Apparent ileal digestibility (AID), apparent total tract digestibility (ATTD), and hindgut disappearance (HGD) of gross energy, organic matter, crude protein, acid hydrolyzed ether extract, total starch, total carbohydrates, and total dietary fiber in pigs fed diets based on cereal grains[†]

	Diet									
Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat	SEM	*P*-value
Gross energy (g kg^{-1})										
AID	730^{c}	793^{b}	667^{d}	808^{b}	914^{a}	623^{e}	720^{c}	712^{c}	13.4	0.001
ATTD	913^{cd}	923^{b}	932^{b}	919^{bc}	979^{a}	896de	893de	919^{bc}	8.1	0.001
HGD	164^{cd}	131de	267^{a}	112^{e}	62^{f}	275^{a}	171^{bc}	208^{b}	12.3	0.001
Organic matter (g kg^{-1})										
AID	767^{c}	827^{b}	698^{d}	835^{b}	931^{a}	669^{d}	739^{c}	754^{c}	11.6	0.001
ATTD	935^{cd}	943^{bc}	951^{b}	945^{bc}	987^{a}	924^{d}	923^{d}	934^{cd}	6.0	0.001
HGD	152^{bc}	124^{cd}	255^{a}	108^{d}	53^{e}	257^{a}	183^{b}	180^{b}	11.6	0.001
Crude protein (g kg^{-1})										
AID	498^{d}	584^{b}	613^{b}	724^{a}	707^{a}	565^{bc}	500^{cd}	622^{b}	26.3	0.001
ATTD	837^{c}	884^{b}	873^{bc}	889^{b}	945^{a}	850^{bc}	778^{d}	893^{b}	18.7	0.001
HGD	298^{ab}	289^{ab}	284^{ab}	162^{d}	192^{cd}	279^{ab}	323^{a}	250^{bc}	23.0	0.001
Acid-hydrolyzed ether extract (g kg^{-1})										
AID	355^{c}	543^{ab}	277^{cd}	598^{a}	496^{b}	−133^{e}	600^{a}	242^{d}	33.4	0.001
ATTD	582^{b}	698^{a}	560^{b}	663^{ab}	616^{ab}	318^{c}	699^{a}	647^{ab}	53.7	0.001
HGD	173^{cd}	155^{d}	302^{bc}	64^{d}	124^{d}	458^{a}	98^{d}	394^{ab}	47.7	0.001
Total starch (g kg^{-1})										
AID	951^{b}	985^{a}	849^{e}	968^{ab}	986^{a}	923^{c}	890^{d}	980^{a}	7.0	0.001
ATTD	997^{bcd}	999^{ab}	999^{ab}	998^{abc}	999^{a}	996^{cd}	994^{e}	996de	0.8	0.001
HGD	45^{d}	15^{e}	148^{a}	34de	14^{e}	74^{c}	98^{b}	21^{e}	7.2	0.001
Total carbohydrates (g kg^{-1})										
AID	814^{c}	874^{b}	723^{d}	887^{b}	963^{a}	711^{d}	790^{c}	799^{c}	10.8	0.001
ATTD	963^{c}	967^{c}	978^{b}	983^{b}	996^{a}	954^{d}	966^{c}	953^{d}	3.8	0.001
HGD	150^{b}	93^{c}	256^{a}	94^{c}	33^{d}	242^{a}	173^{b}	153^{b}	11.3	0.001
Total dietary fiber (g kg^{-1})										
AID	126^{b}	46^{bc}	−74^{cd}	−156^{d}	−298^{e}	−72^{cd}	406^{a}	9^{bc}	47.5	0.001
ATTD	650^{ab}	662^{ab}	709^{ab}	532^{c}	600^{bc}	679^{ab}	760^{a}	620^{bc}	257.3	0.020
HGD	506^{cd}	610^{bc}	796^{a}	683^{ab}	697^{ab}	705^{ab}	354^{d}	591^{bc}	79.2	0.001

[a–f] Within a row, means without a common superscript differ ($P < 0.05$).
[†] Data are means of eight observations per treatment except for Nutridense corn, dehulled barley, and sorghum diets, where data are means of nine observations per treatment.

the rye diet had a viscosity constant that was not different from that of pigs fed the sorghum diet (Table 6). The pH in the ileal digesta from pigs fed wheat was not different from the pH in the ileal digesta from pigs fed Nutridense corn or dehulled oats, but greater ($P < 0.05$) than from pigs fed the other cereal diets. The pH of the ileal digesta of pigs fed dehulled barley or rye was less ($P < 0.05$) than that of pigs fed the other cereal grains. The fecal pH was greatest ($P < 0.05$) in pigs fed wheat and least ($P < 0.05$) in pigs fed yellow dent corn, Nutridense corn, or sorghum.

The concentrations of acetate in feces from pigs fed yellow dent corn or Nutridense corn were not different, but greater ($P < 0.05$) than the concentrations of acetate in feces from pigs fed all other cereal grains, and the concentration of acetate in feces from pigs fed dehulled barley and rye were greater ($P < 0.05$) than from pigs fed dehulled oats, rice, and wheat. The concentration of propionate was greater ($P < 0.05$) in feces from pigs fed dehulled barley or sorghum than in feces from pigs fed all other grains except rye, and the concentration of fecal butyrate was greatest ($P < 0.05$) for pigs fed sorghum and least ($P < 0.05$) for pigs fed Nutridense corn, dehulled oats, wheat, or rice. The concentration of total SCFA was greater ($P < 0.05$) in feces from pigs fed yellow dent corn, Nutridense corn, dehulled barley, rye, or sorghum compared with pigs fed dehulled oats, rice, or wheat.

The water binding capacity was positively correlated ($r = 0.78$; $P < 0.05$) with the concentration of ash, but negatively correlated ($r = -0.73$; $P < 0.05$) with the concentration of total carbohydrates in cereal grains. However, no correlation was observed between chemical components and ileal viscosity. The ileal pH was negatively correlated ($P < 0.05$) with the concentration of propionate and butyrate in feces, and the fecal pH was negatively correlated ($P < 0.05$) with the concentration of resistant starch in cereal grains and the concentration of total SCFA in feces (Table 7). The AID of TDF was positively correlated ($P < 0.05$) with the concentration of resistant starch, and the ATTD of TDF positively correlated

Table 6. Ileal viscosity, ileal and fecal pH and concentrations of short-chain fatty acids (SCFA; μmol g^{-1}, dry matter basis) in the feces of pigs fed diets based on cereal grains

	Diet									
Item	Yellow dent corn	Nutridense corn	Dehulled barley	Dehulled oats	Polished white rice	Rye	Sorghum	Wheat	SEM	*P*-value
Ileal viscosity										
Constant (cP)	488^{c}	1429^{a}	416^{c}	545^{c}	652^{c}	1224^{ab}	664^{bc}	413^{c}	197.74	0.001
Exponent	−1.0	−1.2	−0.9	−0.9	−1.1	−0.9	−1.0	−1.0	0.08	0.084
R^2	0.99	0.99	0.98	0.99	0.98	0.98	0.99	0.99	—	—
Ileal pH	6.62^{b}	6.76^{ab}	6.40^{d}	6.71^{ab}	6.60^{b}	6.39^{d}	6.45^{cd}	6.83^{a}	0.068	0.001
Fecal pH	5.89^{c}	5.97^{c}	6.36^{b}	6.33^{b}	6.43^{b}	6.47^{b}	5.75^{c}	6.90^{a}	0.113	0.001
Fecal SCFA										
Acetate	104^{a}	103^{a}	88^{b}	63^{cd}	70^{cd}	85^{b}	76^{bc}	60^{d}	5.31	0.001
Propionate	22^{bc}	21^{bc}	34^{a}	16^{cd}	12^{d}	26^{ab}	34^{a}	16^{cd}	3.26	0.001
Butyrate	13^{bc}	10^{cde}	12^{bcd}	9^{de}	11^{bcde}	14^{b}	20^{a}	8^{e}	1.63	0.001
Total SCFA	143^{a}	137^{a}	134^{a}	88^{b}	92^{b}	128^{a}	128^{a}	83^{b}	9.18	0.001

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

($P < 0.05$) with the concentration of propionate and butyrate in feces.

DISCUSSION

Although starch is the major carbohydrate in cereal grains, the non-starch carbohydrate components of cereal grains vary considerably and a proportion of cereal starch is usually resistant to digestion. The presence of non-starch polysaccharides and resistant starch in cereal grains may alter gastrointestinal functions[23] and may reduce nutrient digestibility in these grains, which may be of benefit in promoting health of humans, but may cause reduction in feed conversion efficiency when fed to pigs.

The concentration of AEE in the rice used in this experiment was approximately 60% less than the concentration of ether extract in rice used in other experiments and this may be the reason for the low GE obtained in the rice used in this experiment compared with data from other experiments.[24,25] However, the concentrations of total starch, resistant starch, and TDF were within the ranges previously reported (total starch, 724 to 880 g kg^{-1}; resistant starch, 13 to 16 g kg^{-1}; TDF, 10 to 50 g kg^{-1}).[24,25] The high digestibility of GE, OM, starch and total carbohydrates in rice supports the results of studies indicating that energy and nutrients from rice are better digested and absorbed than energy and nutrients from corn when fed to young pigs.[24,26] The low concentration of TDF and resistant starch in rice may contribute to this effect, which results in less fermentable substrates in the hindgut of pigs fed rice than pigs fed corn. This is likely the reason the concentration of total SCFA in the feces of pigs fed the rice diet was relatively low. However, the high AID of starch and total carbohydrates in rice also indicates that white rice may be a high glycemic grain,[27] which may be a concern in diabetic management for humans. The high GE digestibility of rice results in a caloric value of rice that is second only to dehulled oats, which further indicates that rice may not be the cereal of choice in weight loss management or glycemic control.

The concentration of TDF in dehulled oats used in this experiment is within the typical range for oat grouts.[28] Approximately 50% of the TDF in oats is soluble fiber, of which β-glucans is the major component.[28] The presence of soluble TDF and β-glucans in the diet increases digesta viscosity,[29] and increased viscosity in the digesta can limit the interaction between nutrients and enzymes and reduce nutrient digestion and absorption.[30] In this experiment, total starch in dehulled oats was as digestible as the starch in rice, but there was also no difference in digesta viscosity between pigs fed dehulled oats and rice. However, a reduction in the AID of GE, OM and total carbohydrates in dehulled oats compared with rice was observed and this was probably because of the increased concentration of TDF in dehulled oats. The negative value for the AID of TDF in dehulled oats and rice is likely a result of endogenous secretions, such as glycoproteins in the mucus, that are analyzed as TDF.[31] However, because total carbohydrates were calculated and TDF is a component of total carbohydrates, and because there was no difference in the AID of starch between dehulled oats and rice, the reduced AID of total carbohydrates in dehulled oats is likely a result of a reduced disappearance of TDF and resistant starch in dehulled oats compared with rice. The greater caloric value of dehulled oats compared with rice was likely a result of the greater concentration of AEE and the greater digestibility of AEE in dehulled oats than in rice.

The digestibility of nutrients in Nutridense corn is relatively similar to that of dehulled oats, but the reduced caloric value of Nutridense corn compared with dehulled oats can be attributed to the reduced AID of CP and the reduced ATTD of total carbohydrates as well as the reduced concentration of AEE in Nutridense corn compared with dehulled oats. The potential use of Nutridense corn for human consumption has not been investigated, but results of this experiment support results of several studies with pigs and poultry that indicate that Nutridense corn contains more DE and ME than yellow dent corn.[8,32] The increased DE and ME in Nutridense corn compared with yellow dent corn is attributed to the greater AID of OM, CP, AEE and starch, and total carbohydrates, as well as the greater concentrations of CP and AEE in Nutridense corn than in yellow dent corn. The viscous nature of the ileal digesta of pigs fed Nutridense corn is not a characteristic of conventional corn varieties because the concentration of soluble fiber in corn is low.[33] The reason for the high viscosity of digesta in pigs fed

Table 7. Correlation coefficients between the concentration of resistant starch (RS), total dietary fiber (TDF), short-chain fatty acids (SCFA), and the digestibility of TDF in eight cereal grains

	Correlation coefficient									
Item	RS	TDF	Ileal pH	Fecal pH	Acetate	Propionate	Butyrate	SCFA	AID of TDF	ATTD of TDF
RS	1	0.22	−0.17	−0.90***	0.38	0.57	0.68*	0.55	0.83**	0.57
TDF	—	1	−0.05	−0.13	0.35	0.42	0.22	0.23	0.60	0.41
Ileal pH	—	—	1	0.26	−0.22	−0.75**	−0.72**	−0.60	−0.15	−0.64*
Fecal pH	—	—	—	1	−0.62	−0.45	−0.65*	−0.78**	−0.63*	−0.45
Acetate	—	—	—	—	1	0.37	0.22	0.85***	0.28	0.43
Propionate	—	—	—	—	—	1	0.73**	0.62*	0.62*	0.88***
Butyrate	—	—	—	—	—	—	1	0.56	0.70*	0.78**
SCFA	—	—	—	—	—	—	—	1	0.34	0.57
AID of TDF	—	—	—	—	—	—	—	—	1	0.70*
ATTD of TDF	—	—	—	—	—	—	—	—	—	1

*$P < 0.10$ **$P < 0.05$ ***$P < 0.01$. AID, apparent ileal digestibility; ATTD, apparent total tract digestibility.

Nutridense corn is unknown, but together with the greater water binding capacity of Nutridense corn than of yellow dent corn, this observation indicates that the types of fiber in Nutridense corn are different from those in yellow dent corn. We are not aware of any reports in which the types of fiber in Nutridense corn were investigated.

The digestibility of nutrients in sorghum and wheat is relatively similar to that of corn, but in terms of grain structure and nutrient composition, sorghum is more similar to corn than to wheat.[34] However, the nutritional value of sorghum is only 95% of that of corn[35] because CP digestibility and DE of sorghum is less than for yellow dent corn.[7,8] The reduced digestibility of CP in sorghum is attributed to the binding of tannins to the protein in sorghum, which makes the protein resistant to proteolysis,[36] whereas the reduced caloric value of sorghum is attributed to low starch digestibility resulting from the formation of disulfide crosslinks between the endosperm and the protein in sorghum.[34] In the present experiment, the AID of starch, but not of CP, was less for sorghum than for yellow dent corn, but the reduction in starch digestibility did not reduce the caloric value of sorghum compared with yellow dent corn, which may have been a result of the greater AID of AEE in sorghum than in yellow dent corn. The lack of a difference in the nutritional value between yellow dent corn and sorghum in this experiment is consistent with the results of Lin *et al.*[37] Sorghum contains approximately 80% more resistant starch than corn and this may be the reason for the reduced AID of starch in sorghum compared with corn and wheat. However, the resistant starch appeared to be fermented in the hindgut because the total tract disappearance of starch was close to 1000 g kg^{-1} for sorghum as it was for the other cereal grains. The greater concentration of butyrate in the feces of pigs fed sorghum is likely the result of fermentation of the resistant starch in sorghum. The relatively low AID of starch in sorghum indicates that sorghum is a suitable grain to manage blood sugar levels.[38]

Unlike corn, where more than 80% of the TDF is insoluble fiber,[33] soluble fibers, particularly β-glucans and arabinoxylans, are present in wheat, barley and rye.[39] These soluble fibers are believed to have health promoting effects in humans.[2] However, in this experiment, the AID of starch in wheat was greater than in corn, but the ME of wheat was not different from that of corn. This is likely a result of the low concentration of AEE in wheat and the relatively lower AID of AEE in wheat than in yellow dent corn. There are also differences in the nutritional value among varieties of wheat.[40,41] Results of this experiment indicate that at least some varieties of wheat have a nutritional value that is equal to the nutritional value of yellow dent corn.

The concentration of TDF in dehulled barley was less than what has been reported for hulled barley (190–220 g kg^{-1}) and for hulless barley (110–157 g kg^{-1}).[42] The low AID of OM in dehulled barley is a result of the low AID of starch and total carbohydrates in dehulled barley. The poor AID of starch and total carbohydrates may be a result of the greater particle size of the dehulled barley compared with the other cereal grains. Grains with large particle sizes have less surface area exposed for enzymatic degradation and, therefore, are more likely to have a reduced digestibility of starch.[43] However, the ATTD of GE in dehulled barley was greater than in yellow dent corn, which was the reason the DE in dehulled barley was greater than the DE in yellow dent corn.

Rye contains more arabinoxylans than β-glucans,[33] which contributes to the desired properties in bread preparation.[44] However, these properties likely also are responsible for the relatively high viscosity of digesta from pigs fed the rye diet that was observed in this experiment. The high digesta viscosity in pigs fed the rye diet likely contributed to the reduced digestibility of nutrients and energy in rye compared with the other cereal grains.

Ileal pH, fecal pH, and the concentration of SCFA in the feces were measured as indicators of the degree of fermentation of TDF at the end of the terminal ileum and throughout the total tract. For cereal grains that have a low concentration of resistant starch and TDF such as rice, ileal digesta pH and fecal pH was expected to be more basic than the ileal digesta pH of cereals with greater concentration of resistant starch and TDF. The concentration of SCFA is also expected to be less in feces of pigs fed cereals with low concentrations of resistant starch and TDF than in the feces of pigs fed cereals with more resistant starch and TDF. However, this hypothesis was only confirmed between the concentration of resistant starch and fecal pH. For all cereal grains, no correlation between concentration of TDF and resistant starch and measures of ileal pH and concentration of fecal SCFA was observed. A possible reason for this observation is that because

SCFA are continuously produced and efficiently absorbed along the small and large intestines, changes in fecal pH but not in ileal digesta pH may be reflective of the continuous flux of SCFA in the gut.

CONCLUSIONS

The GE, nutrient digestibility and caloric value of rice were greater and the GE and nutrient digestibility of rye was less than that of the other cereal grains. The AID of starch in yellow dent corn, barley, rye, and sorghum, but not in Nutridense corn, dehulled oats, and wheat, was less compared with the AID of starch in rice, which may be a result of the presence of resistant starch and TDF in yellow dent corn, dehulled barley, rye, and sorghum. The relatively high digestibility of energy and all nutrients in these cereal grains makes them good energy sources in diets for pigs with rice and dehulled oats being superior to yellow dent corn. It is also expected that these cereal grains are excellent sources of energy for humans. If the goal is to feed grains with a high caloric value and absorption of most energy in the form of glucose, rice and dehulled oats are the preferred cereal grains. However, if the goal is to reduce the glycemic index and reduce weight gain, sorghum and rye may be the most ideal cereal grains.

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