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.

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 and is beneficial in preventing and managing metabolic diseases. The protective effects of whole cereal grains against metabolic diseases may be a result of the dietary fiber in the cereal grains. However, the presence of dietary fiber in the diet reduces energy and nutrient digestibility, 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.

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. 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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Cereal grains, diets, ileal digesta and fecal samples were analyzed for dry matter (AOAC method 930.15), CP (AOAC method 990.03), ash (AOAC method 942.05) and TDF (AOAC method 985.29). Samples were also analyzed for AEE by boiling the samples in 3 mol L$^{-1}$ HCl followed by ether extraction (AOAC method 2003.06). 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 × 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-I+ 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 Thiven 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 log10 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.$^{17}$
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., 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 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              | 886             | 864             | 860             |
| Total starch (g kg⁻¹)          | 647              | 641             | 642             | 651             | 751              | 744             | 706             | 678             |
| 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 and the concentration of digestible starch. 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) |
|---------------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 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             |

* 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 and the concentration of digestible starch. AEE, acid-hydrolyzed ether extract; TDF, total dietary fiber (determined by AOAC method 985.29).9
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 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†

<table>
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<tr>
<th>Item</th>
<th>Diet</th>
<th>Gross energy (g kg(^{-1}))</th>
<th>Organic matter (g kg(^{-1}))</th>
<th>Crude protein (g kg(^{-1}))</th>
<th>Acid-hydrolyzed ether extract (g kg(^{-1}))</th>
<th>Total starch (g kg(^{-1}))</th>
<th>Total carbohydrates (g kg(^{-1}))</th>
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<td>808(^b)</td>
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<td>923(^b)</td>
<td>932(^b)</td>
<td>919(^b)</td>
<td>979(^a)</td>
<td>896(^d)</td>
<td>893(^d)</td>
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<td>131(^b)</td>
<td>267(^a)</td>
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\(^a–f\) 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...
(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 function 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 other 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, 724 to 880 g kg⁻¹; TDF, 13 to 16 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.24,25 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 and AEE are components 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 CP and the reduced ATTD of 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...
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. However, the nutritional value of sorghum is only 95% of that of corn because CP digestibility and DE of sorghum is less than for yellow dent corn. 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, 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.

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. 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.

Unlike corn, where more than 80% of the TDF is insoluble fiber, soluble fibers, particularly β-glucans and arabinoxylans, are present in wheat, barley and rye. These soluble fibers are believed to have health promoting effects in humans. 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. 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 $^{-1}$). 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. 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, which contributes to the desired properties in bread preparation. 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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REFERENCES

Comparative energy and nutrient digestibility in cereal grains


