Apparent total tract digestibility of nutrients and the digestible and metabolizable energy values of five unconventional feedstuffs fed to growing pigs

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ABSTRACT
This study was conducted to determine the nutrient profiles, the apparent total tract digestibility (ATTD) of nutrients and the digestible and metabolizable energy (DE and ME) values of five unconventional feedstuffs: highland barley (HB), buckwheat (BKW), glutinous broomcorn millet (GBM), non-glutinous broomcorn millet (NBM) and Chinese naked oat (CNO) fed to growing pigs. Thirty-six crossbred barrows were allotted to six dietary treatments in a completely randomized design including a corn-soybean meal basal diet and five test diets containing unconventional ingredients. The ATTD of nutrients and energy as well as the DE and ME values of the five ingredients were calculated using the difference method. Among the five unconventional feedstuffs, GBM had the greatest ATTD of dry matter (DM) and CP, and NBM had the greatest ATTD of organic matter (OM), ether extract (EE), and acid detergent fibre (ADF), while HB had the lowest ATTD of OM, DM, CP, and ADF. On DM basis, the DE and ME values for HB, BKW, GBM, NBM and CNO were 15.97–17.87 MJ/kg and 15.38–17.34 MJ/kg, respectively. From the nutritional point of view, those five unconventional feedstuffs especially the broomcorn millets could be potential replacements of corn in growing pig diets.

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Introduction
Cereal grains are the primary source of energy in both human and animal diets. However, considering the reduced yield of traditional ingredients and the contradiction between food and feed, it is imperative to search for alternative ingredients and to evaluate their utilization in animal diets. Studies have been conducted in our research group on unconventional protein ingredients such as peanut meal, sunflower meal in growing pigs and Chinese corn gluten feed in finishing pigs. Thirty-six crossbred barrows were allotted to six dietary treatments in a completely randomized design including a corn-soybean meal basal diet and five test diets containing unconventional ingredients. The ATTD of nutrients and energy as well as the DE and ME values of the five ingredients were calculated using the difference method. Among the five unconventional feedstuffs, GBM had the greatest ATTD of dry matter (DM) and CP, and NBM had the greatest ATTD of organic matter (OM), ether extract (EE), and acid detergent fibre (ADF), while HB had the lowest ATTD of OM, DM, CP, and ADF. On DM basis, the DE and ME values for HB, BKW, GBM, NBM and CNO were 15.97–17.87 MJ/kg and 15.38–17.34 MJ/kg, respectively. From the nutritional point of view, those five unconventional feedstuffs especially the broomcorn millets could be potential replacements of corn in growing pig diets.

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Proso or common millet, is one of the world’s oldest cultivated cereals. It has the lowest water and nutrient requirement and the shortest growing season among all the cereals, thus it can be cultivated in marginal lands with harsh environment (Ellis et al. 1996). Broomcorn millet is an important cereal in Eurasia for hundreds of years, and is introduced into North America in the 1700s for cultivation. It is now mainly grown for fodder in the semiarid regions of Russia, northern China and Central Asia (Gallaher et al. 1999). However, little information is reported when it is fed to pigs. Oat (Avena sativa) has higher capacity in tolerating wet weather and acidic soils than other cereals, and less agro-chemical and fertilizer input are required when oat is grown (Givens et al. 2014). The nutritive value of oat grains as food has been reported widely for its high amount of soluble fibre, particularly β-glucan (Hsueh et al. 2011). However, low β-glucan concentration is desirable for pig diets (Huang et al. 2014). The Chinese naked oat (Avena chinensis, CNO) evaluated in this experiment is a Chinese variety of oat.

Considering the easy cultivation in harsh conditions and the functional effects of these cereal grains in human food, these cereals have great potential to be utilized in swine diets, so it is necessary to determine the nutrient profiles and the energy values of these unconventional ingredients when fed to pigs. Therefore, the objective of this study was to evaluate the nutrient profiles, the apparent total tract digestibility (ATTD) of nutrients, the digestible energy (DE) and the metabolizable energy (ME) values of HB, BKW, glutinous broomcorn millet (GBM),...
non-glutinous broomcorn millet (NBM), and CNO in growing pigs.

**Materials and methods**

All protocols used in this experiment were reviewed and approved by the Institutional Animal Care and Use Committee of China Agricultural University (Beijing, China). Animal trials were conducted at the Metabolism Laboratory of the Ministry of Agriculture Feed Industry Centre (Chengde, China).

**Animals, diets and experimental design**

Thirty-six crossbred growing barrows (Duroc × Large White × Landrace, with initial body weight of 32.1 ± 4.2 kg) were individually housed in stainless-steel metabolism crates (1.4 × 0.7 × 0.6 m). All metabolic crates were equipped with a nipple drinker and a feeder and placed in an environmental controlled room with the temperature maintained at 22 ± 2°C. The animal trial lasted 19 days, including 7 days for metabolism crates adaption using fully balanced commercial diet for growing pigs, 7 days for experimental diet adaption, and 5 days for total urine and faeces collection. Daily feed allowance was equivalent to 4% of body weight determined at the beginning of the trial, and was divided into two equal sized meals provided at 08:00 and 16:00, respectively. Water was provided *ad libitum* via the nipple drinker.

Pigs were assigned to one of six treatment diets in a completely randomized design with six replicate barrows per treatment. The six experimental diets included a corn-soybean meal basal diet and five test diets. The test diets were formulated by replacing part of the corn and soybean meal with unconventional ingredients to make the final proportion of the ingredients in test diets as 50% (HB, BKW, or GBM) or 40% (NBM, CNO). The amount of vitamin and mineral premix was kept constant in all diets and adjusted to meet or exceed the animals’ nutrient requirements according to NRC (Koehler 2002). Chemical analysis of the five ingredients and formulation of the diets used in this experiment were shown in Tables 1 and 2, respectively.

The body weight of each pig was determined at the beginning and at the end of the experiment. The amount of feed provided was recorded daily and the feed refusals and spillages were collected twice daily, then dried and weighed during the five-day urine and faeces collection period.

**Sample collection**

All the samples of diets, ingredients, urine and faeces were collected and stored in the freezer with the temperature maintained at −20°C until used for analysis. Faeces were collected into plastic bags (one bag per pig) as soon as they appeared in the metabolism crates and stored at −20°C immediately. At the end of the collection period, the total five-day faecal productions from each pig were pooled and weighed respectively. Approximate 300 g sub-samples of faeces were weighted and dried in a forced-draft oven at 65°C for 72 h after thawing and mixing. Sub-samples were stored at −20°C for further analysis after drying. Total urine was collected and stored in the freezer with the temperature main-
collected into plastic buckets (one bucket per pig) containing 50 mL of 6 N hydrochloric acid (HCl) and placed under the metabolism crates. The HCl was added to reduce the nitrogen loss and limit the proliferation of bacteria. The volume of collected urine was measured every day and 10% of the daily urinary collection was stored at −20°C after filtered through cotton gauze and transferred into a screw-capped bottle. Urine samples were pooled for each pig after the collection period. Approximately 45 mL sub-samples were saved for further chemical analysis and 4 mL samples were dried at 65°C for 8 h with quantitative filter paper in crucibles for energy determination. The faecal and feed samples were ground through different size screens prior to chemical analysis.

Chemical analysis and calculations

Dry matter (DM, method 930.15; AOAC 2007), ash (method 942.15; AOAC 2007), crude protein (CP, method 990.03; AOAC 2007), ether extract (EE, method 920.39; AOAC 2007) and crude fibre (CF, method 978.10 AOAC 2007) of all ingredients, experimental diets and faecal samples were determined following the procedure of AOAC (2007). Filter bags (Model F57; Ankom Technology, Macedon, NY, USA) and fibre analyzer equipment (NAKOM200 Fiber Analyzer, Ankom Technology, Macedon, NY, USA) were applied to determine the neutral detergent fibre (NDF) and acid detergent fibre (ADF) contents of all ingredients, experimental diets and faecal samples according to a modified procedure described by van Soest et al. (van Soest et al. 1991). All ingredients were analysed for calcium (Ca, method 978.02; AOAC 2007) and phosphorus (P, method 946.06; AOAC 2007). Total starch of all ingredients, experimental diets and faecal samples according to Huang et al. (Huang et al. 2014). Fifteen AAAs were determined after hydrolysis with 6 N HCl at 110°C for 24 h using an Amino Acid Analyzer (Hitachi L-8900; Tokyo, Japan). Methionine and cysteine were determined as methionine sulphone and cysteic acid using an AA analyzer (Hitachi L-8900; Tokyo, Japan) after cold performic acid oxidation overnight and hydrolysing with 7.5 N HCl at 110°C for 24 h. Tryptophan was determined using high performance liquid chromatography (Agilent 1200 Series, Santa Clara, CA, USA) after LiOH hydrolysis for 22 h at 110°C. All chemical analysis was conducted in duplicate.

Minerals and vitamins were considered insignificant to the DE and ME values of diets as well as the digestibility of nutrients and energy considering their small inclusion proportion (2.2%) in the experimental diets. The DE and ME values of the diets and the ATTD of GE, DM, CP, EE, and organic matter (OM) in each diet was calculated using the equations described by Adeola (Metzler-Zebeli and Zebeli 2013) as follows:

\[
DE_d = \frac{(GE_f - GE_f)}{DM_i} \quad (1)
\]

\[
DE_{dc} = \frac{DE_d}{0.978} \quad (2)
\]

\[
DE_f = (DE_d - (97.8\% - X\%) \times ME_{dc})/X\% \quad (3)
\]

\[
ME_d = \frac{(GE_f - GE_f - GE_d)}{DM_i} \quad (4)
\]

\[
ME_{dc} = ME_d/0.978 \quad (5)
\]

\[
ME_f = \frac{(ME_d - (97.8\% - X\%) \times ME_{dc})}{X\%} \quad (6)
\]

\[
ATTD = \frac{(IN_m - N_{out})}{IN_m} \times 100\% \quad (7)
\]

\[
ATTD_N = \frac{(A - B)}{F\% \times 100\% + B} \quad (8)
\]

The apparent digestible energy (DE_d) and metabolizable energy (ME_d) content in each diet (MJ/kg of DM) can be calculated by Equations (1) and (4), where the total GE intake (GE_i) of each pig (MJ/kg of DM) can be calculated as the result of the GE content of the diet multiplied by DM_i. The DM_i is the actual total DM intake during the collection period; GE_f and GE_d are the GE content of faeces and urine (MJ/kg of DM) and can be calculated by the product of GE content of the faeces or urine multiplied by the dry weight of total faeces or the volume of urine recorded over the collection period, respectively. As is shown in Equations (2) and (5), DE_{dc} and ME_{dc} are the corrected apparent DE and ME in the basal diet (MJ/kg of DM); 0.978 is the percentage of the energy-yielding ingredients in this diet. The DE and ME values of the tested ingredients can be obtained using the difference method from Equations (3) and (6), respectively; DE_f and ME_f are the DE and ME values of the tested ingredients, respectively; X is the percentage of the tested ingredients in the corresponding diets (50% or 40%). The ATTD of nutrients in diets can be calculated by Equation (7), where N_m represents the total intake of a certain nutrient in feed, and N_{out} represents the total faecal output of the homologous nutrient. The ATTD of nutrients in ingredients can be calculated by Equation (8), where A represents the ATTD of a certain nutrient in the tested diet, and B represents the ATTD of the corresponding nutrient in the basal diet; F% is the percentage of the target nutrients supplied by the ingredients in the test diets.

Statistical analysis

Data were checked for normality using the UNIVERiate procedure of SAS (SAS Inst. Inc., Cary, NC, USA). No outliers were identified. Then data were analysed by one-way ANOVA using the GLM procedure of SAS. The ingredient source was the only factor included in the model and the individual pig was included in the equation. In all analyses, the differences were considered significant if p < .05.

Results

All pigs remained healthy and adapted well to the diets and metabolism crates. Both faeces and urine were collected from the animals successfully.
The ATTD of nutrients and energy utilization

The ATTD of nutrients and energy in the experimental diets are shown in Table 3. There was no difference (p = .58) in the ATTD of GE among all the diets. The ATTD of OM in the two broomcorn millet diets were greater (p < .01) than that in the other diets, while the ATTD of OM in the HB and the basal diet were lower (p < .01) than that in the other diets. The ATTD of DM in the GBM diet was the greatest (p < .01) among all the diets, and the ATTD of DM in the NBM diet was greater (p < .01) than that in the basal, HB and CNO diet. The HB diet had lower (p < .01) ATTD of CP compared with the BKW, GBM and NBM diets. The CNO diet had the lowest (p < .01) ATTD of EE but the greatest ATTD of NDF among all the diets. The BKW diet showed the lowest (p < .01) ATTD of NDF and ADF among all the diets, while the NBM diet showed the greatest (p < .01) ATTD of ADF among all the diets.

The ATTD of nutrients and energy in the five unconventional cereal ingredients are shown in Table 4. There was no difference (p = .54) in the ATTD of GE among all the five ingredients. The NBM had greater (p < .01) ATTD of OM and ADF than the HB, BKW, and CNO, while the GBM had greater (p < .01) ATTD of OM than the HB and CNO, and greater (p < .01) ATTD of ADF than the HB and BKW. The ATTD of DM for the GBM and NBM diets were greater (p < .01) than that for the other ingredients. Moreover, the HB, CNO, and BKW had the lowest (p < .01) ATTD of CP, EE, and NDF among all the five ingredients, respectively. The NBM had greater (p < .01) ATTD of EE, and the HB and CNO had greater (p < .01) ATTD of NDF compared with the other ingredients.

Energy value in ingredients

The energy balance and the DE and ME concentrations of the experimental diets are shown in Table 5. The DE concentration in the HB diet was the lowest (p < .01) among all the diets. The DE and ME values of the five test ingredients are also shown in Table 5. On DM basis, the DE and ME values for HB, BKW, GBM, NBM and CNO were 15.97 and 15.38 MJ/kg, 16.90 and 15.76 MJ/kg, 17.65 and 16.86 MJ/kg, 17.87 and 17.34 MJ/kg, 17.57 and 16.85 MJ/kg, respectively. HB had the lowest (p < .01) DE value among all the five ingredients. There was no significant difference for the ME content (p = .23) and the ME/DE ratio (p = .94) among the five ingredients.

The correlation coefficients between the chemical characteristics and the energy values of the 5 unconventional feedstuffs are shown in Table 6. The significant correlations include: the ME value was positively correlated (p < .05, r = .96) with the DE value; the ADF level was positively correlated (p < .01, r = .98) with the NDF level; both the Ca and P levels were positively correlated (p < .05, r = .89 and 0.91, respectively) with the ash level; and both the ADF and NDF levels were negatively correlated (p < .05, r = −0.93 and −0.95, respectively) with the starch level. The stepwise regression equations and the best-fit prediction equations for the DE and ME values of the five cereal ingredients are presented in Table 7. The EE and P were the best predictors for the DE values of the five ingredients (R² = 0.93, p = .07), and DE could be used to predict the ME value (R² = 0.92, p = .01). With the addition of Ca, the R² of the prediction equations for the ME value improved from 0.92 to 0.98. On DM basis, the best-fit prediction equations for the DE and ME (MJ/kg) values of these five unconventional feedstuffs were DE = 16.10 + (0.87 × EE) − (7.57 × P), and ME = 2.17 + (0.86 × DE) − (6.57 × Ca) in which chemical compositions are expressed in %.

Discussion

Nutritional profile

The concentrations of CP and EE in HB used in the current study were slightly lower than the CP and EE values in barley and hulless barley reported by NRC (2012) (Koehler 2002), whereas the content of starch in HB in our study was greater than that in barley and hulless barley in NRC (2012) (Koehler 2002). The HB used in this study also demonstrated greater methionine level compared with barley and hulless barley, and much abundant lysine content compared with the traditional cereal grains.

Table 3. ATTD of nutrients and energy of the experimental diets (% as-fed basis)*.

| Treatments | Items | Basal diet | HB diet | BKW diet | GBM diet | NBM diet | CNO diet | SEM | p-Value |
|------------|-------|------------|---------|----------|----------|----------|----------|-----|---------|
| GE         | 88.52 | 88.49      | 90.47   | 92.14    | 92.22    | 88.69    | 5.94     | .58 |
| OM         | 90.86 | 90.63      | 92.69   | 93.63    | 93.67    | 92.37    | 0.39     | <.01|
| DM         | 88.45 | 88.57      | 89.97   | 91.81    | 91.38    | 89.24    | 0.51     | <.01|
| CP         | 85.84 | 84.23      | 87.69   | 88.42    | 87.12    | 85.81    | 0.86     | <.01|
| EE         | 56.36 | 57.21      | 58.32   | 59.15    | 65.32    | 36.26    | 2.34     | <.01|
| NDF        | 53.39 | 64.80      | 36.17   | 54.31    | 52.74    | 75.24    | 2.64     | <.01|
| ADF        | 45.09 | 39.88      | 34.73   | 50.26    | 52.27    | 45.21    | 2.25     | <.01|

Note: HB, highland barley; BKW, buckwheat; GBM, glutinous broomcorn millet; NBM, non-glutinous broomcorn millet; CNO, Chinese naked oat; SEM, standard error of the mean; GE, gross energy; OM, organic matter; DM, dry matter; CP, crude protein; EE, ether extract; NDF, neutral detergent fibre; ADF, acid detergent fibre; SEM, standard error of the mean. Within a row means, different superscripts indicate a significant difference (p < .05).

Table 4. ATTD of nutrients and energy of the five unconventional cereal ingredients (% as-fed basis)*.

| Treatments | Items | HB | BKW | GBM | NBM | CNO | SEM | p-Value |
|------------|-------|----|-----|-----|-----|-----|-----|---------|
| GE         | 88.63 | 88.63 | 91.96 | 90.53 | 86.14 | 6.51 | .54    |
| OM         | 90.31 | 94.55 | 96.32 | 93.76 | 93.31 | 0.77 | <.01  |
| DM         | 87.14 | 89.93 | 93.60 | 93.44 | 88.73 | 1.01 | .01    |
| CP         | 82.01 | 88.93 | 90.39 | 88.13 | 85.37 | 1.77 | <.05  |
| EE         | 56.99 | 59.22 | 60.88 | 77.15 | 25.92 | 4.83 | <.01  |
| NDF        | 54.72 | 37.86 | 59.17 | 57.67 | 88.68 | 5.96 | <.01  |
| ADF        | 32.49 | 34.58 | 53.26 | 57.84 | 43.84 | 4.24 | <.01  |

Note: HB, highland barley; BKW, buckwheat; GBM, glutinous broomcorn millet; NBM, non-glutinous broomcorn millet; CNO, Chinese naked oat; SEM, standard error of the mean; GE, gross energy; OM, organic matter; DM, dry matter; CP, crude protein; EE, ether extract; NDF, neutral detergent fibre; ADF, acid detergent fibre; SEM, standard error of the mean. Within a row means, different superscripts indicate a significant difference (p < .05).

*Data are means of six observations per treatment (n = 6).
such as corn and wheat (Koehler 2002). The concentrations of CP and lysine in BKW were comparable with those in triticale and wheat reported by NRC (2012) (Koehler 2002). However, greater starch content was observed in BKW compared with those in triticale and wheat. The CP and EE contents in GBM and NBM were lower than those in millet reported by NRC (2012) (Koehler 2002). From the perspective of energy sources, those five unconventional feedstuffs especially the BKW and the broomcorn millet could be potential replacements of the traditional energy feedstuffs such as corn and barley fed to growing pigs owing to their greater starch content compared with those traditional feedstuffs.

**Nutrient digestibility and energy utilization**

Overall, the differences on nutrient digestibility among the experimental diets and the 5 unconventional ingredients could be attributed to the different nutritional profiles of these diets and ingredients. For instance, the greater OM and DM digestibility of GBM and NBM could be attributed to the lower fibre concentrations and greater starch contents in GBM and NBM compared to the other feedstuffs. In addition, the concentration of NDF in HB and CNO was comparable with that in barley and hulless oats (Koehler 2002; National Research Council 2012). Our results showed that the ATTD of nutrients were negatively correlated with the concentration of NDF in diets or ingredients, which is consistent with the results of Noblet and Perez (1993). The CP content of all the 5 ingredients were greater than those of corn, but lower than the other protein supplements such as corn gluten meal and distillers dried grains with solubles (AOAC [Association of Official Analytical Chemists] 2007; Koehler 2002). Therefore, the ATTD of CP of all these unconventional ingredients were greater than that of corn but lower than that of corn gluten meal and distillers dried grains with solubles according to the data from previous literatures (Noblet and van Milgen 2004; Park et al. 2015). The presence of non-starch polysaccharides (NSP) in cereal grains could reduce the nutrient digestibility and alter the gastrointestinal functions, causing reduction in growth performance when fed to growing pigs, which has been widely reported in previous studies such as Metzler-Zebeli and Zebeli (Metzler-Zebeli and Zebeli 2013). Approximately 50% of the fibre in barley and oats are soluble fibre, of which β-glucan is the major component (National Research Council 2012; Rojas et al. 2013). It is reported that β-glucan in diet can limit the interaction between enzymes and nutrients and reduce the nutrient digestion and absorption by increasing the digesta viscosity (Seneviratne et al. 2010; Shen et al. 2016).

### Table 5. Energy balance, DE and ME values in diets and ingredients*

| Items                | Basal diet | HB      | BKW     | GBM     | NBM     | CNO     | SEM     | p-Value |
|----------------------|------------|---------|---------|---------|---------|---------|---------|---------|
| Sd-GE intake, MJ     | 82.90<sup>b</sup> | 79.64<sup>b</sup> | 80.55<sup>b</sup> | 80.27<sup>b</sup> | 79.65<sup>b</sup> | 105.62<sup>a</sup> | 3.03    | <.01    |
| Sd-GE in faeces, MJ  | 9.56<sup>bc</sup> | 9.16<sup>b</sup> | 7.64<sup>bc</sup> | 6.28<sup>c</sup> | 6.23<sup>c</sup> | 11.99<sup>a</sup> | 0.54    | <.01    |
| Sd-GE in urine, MJ   | 2.45       | 2.57    | 3.53    | 3.03    | 2.35    | 3.45    | 1.10    | .96     |
| Energy content in diets |           |         |         |         |         |         |         |         |
| DE, MJ/kg            | 14.20<sup>ab</sup> | 13.90<sup>c</sup> | 14.33<sup>ab</sup> | 14.66<sup>a</sup> | 14.56<sup>ab</sup> | 14.53<sup>ab</sup> | 0.09    | <.01    |
| ME, MJ/kg            | 13.72      | 13.41   | 13.60   | 14.08   | 14.10   | 14.00   | 0.26    | .37     |
| ME/DE, %             | 0.97       | 0.96    | 0.95    | 0.96    | 0.97    | 0.96    | 0.02    | .95     |
| Energy content in ingredients (as-fed basis) |           |         |         |         |         |         |         |         |
| DE, MJ/kg            | –          | 13.92<sup>b</sup> | 14.78<sup>a</sup> | 15.44<sup>a</sup> | 15.42<sup>a</sup> | 15.35<sup>a</sup> | 0.20    | <.01    |
| ME, MJ/kg            | –          | 13.41   | 13.78   | 14.74   | 14.96   | 14.72   | 0.58    | .28     |
| ME/DE, %             | –          | 0.96    | 0.93    | 0.96    | 0.97    | 0.96    | 0.03    | 0.94    |
| Energy content in ingredients (as-dry-matter basis) |           |         |         |         |         |         |         |         |
| DE, MJ/kg            | –          | 15.97<sup>c</sup> | 16.90<sup>bc</sup> | 17.65<sup>ab</sup> | 17.87<sup>a</sup> | 17.57<sup>ab</sup> | 0.23    | <.01    |
| ME, MJ/kg            | –          | 15.38   | 15.76   | 16.86   | 17.34   | 16.85   | 0.67    | 0.23    |
| ME/DE, %             | –          | 0.96    | 0.93    | 0.96    | 0.97    | 0.96    | 0.03    | 0.94    |

*Note: HB, highland barley; BKW, buckwheat; GBM, glutinous broomcorn millet; NBM, non-glutinous broomcorn millet; CNO, Chinese naked oat; SEM, standard error of the mean. aWithin a row means, different superscripts indicate a significant difference (p < .05).

### Table 6. Correlation coefficients (r) between chemical constituents and energy values of the five unconventional cereal ingredients*

| Item  | DE     | ME     | GE     | CP     | EE     | Starch | NDF    | ADF    | Ash    | Ca     | P     |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------|
| DE    | 1      |        |        |        |        |        |        |        |        |        |      |
| ME    | 0.96*  | 1      |        |        |        |        |        |        |        |        |      |
| GE    | 0.46   | 0.56   | 1      |        |        |        |        |        |        |        |      |
| CP    | 0.04   | −0.01  | 0.64   | 1      |        |        |        |        |        |        |      |
| EE    | 0.78   | 0.62   | 0.50   | 0.46   | 1      |        |        |        |        |        |      |
| Starch| 0.52   | 0.46   | −0.41  | −0.78  | 0.16   | 1      |        |        |        |        |      |
| NDF   | −0.57  | −0.46  | 0.45   | 0.62   | −0.28  | −0.95* | 1      |        |        |        |      |
| ADF   | −0.41  | −0.61  | 0.61   | 0.69   | −0.17  | −0.93* | 0.98** | 1      |        |        |      |
| Ash   | −0.42  | −0.25  | 0.26   | 0.56   | 0.15   | −0.49  | 0.28   | 0.19   | 1      |        |      |
| Ca    | −0.51  | −0.66  | −0.65  | 0.15   | −0.10  | −0.18  | 0.02   | −0.15  | 0.89*  | 1      |      |
| P     | −0.46  | −0.08  | 0.08   | 0.78   | 0.13   | −0.79  | 0.62   | 0.56   | 0.91*  | 0.66  | 1    |

*Analysis based on DM basis.

**Note:** DE, digestible energy; ME, metabolizable energy; GE, gross energy; CP, crude protein; EE, ether extract; NDF, neutral detergent fibre; ADF, acid detergent fibre; Ca, calcium; P, phosphorus.

*Data are means of six observations per treatment (n = 6).
We observed that the ATTD of CP, DM, NDF and ADF in HB were similar to those in CNO, which could be attributed to the similar CF, ADF and NDF amount between those two cereal grains. Although with the greater fibre content, the ATTD of NDF for HB and CNO were greater than that of the broomcorn millet. A possible explanation may be the different NSP compositions especially the β-glucan proportions among these ingredients. Further analysis on carbohydrate components is needed.

The digestibility of nutrients and energy in GBM is similar to those of NBM except for the ATTD of EE. Moreover, CNO showed extremely lower ATTD of EE compared to the other ingredients, even though no outliers were found. This may be attributed to the methods for EE measurement in these ingredients. There were few previous literature that reported the nutrient and energy digestibility of these unconventional feedstuffs, especially in growing pigs. The only report focused on the effect of millet on broilers, and showed that the ATTD of CP, EE, and starch of millet-based broiler diet was significantly higher than the sorghum-based broiler diets, and diets containing broomcorn millet had greater EE and OM digestibility than the basal diet (Stein et al. 2016). We also observed similar pattern on OM, DM and EE digestibility between the basal diet and the broomcorn millet-containing diets in growing pigs.

**Energy value in ingredients**

The two kinds of broomcorn millet diets showed the greatest DE values, which could be owing to the greater GE and OM digestibility of these two diets. The HB diet demonstrated lower DE value compared with the other diets, and this could be attributed to the high amount of NDF in HB, and concurs with previous studies of Noblet and Perez (Noblet and Perez 1993). However, the relatively lower DE content of the BKW diet was in contradiction to its relatively high EE and CP contents and low NDF content. There may be other nutritional factors containing in HB which could negatively affect its energy value. Although different DE contents were observed among the experimental diets, no discrepancies were observed for the ME contents. This could be explained by the greater deviation of the energy loss in urine.

Chemical characteristics, animals, technological treatments, and interaction between these factors can influence the energy values of ingredients (Wang et al. 2017). In terms of chemical characteristics, previous studies proved that the available energy content of ingredients were positively affected by the EE and CP contents and negatively affected by the dietary fibre content, especially the NDF concentration (van Soest et al. 1991; Wang et al. 2014, 2017).

Although comparable, the DE and ME concentrations of HB determined in this experiment were greater than the DE and ME values of barley and hulless barley suggested by NRC (2012) and a review by Stein et al. (2016), but lower than the values obtained from Wang et al. (2017) and Li (2018) (Xiong et al. 1990; Koehler 2002; National Research Council 2012; Rojas et al. 2013). These inconsistent energy values could be due to the different environment and soil conditions for the barley grown, and the animals used for trial may also matter. Currently, no information is reported regarding the DE and ME contents of BKW. The energy values of BKW obtained from our study are similar to those of the traditional cereal grains such as corn and barley. In addition, the energy values of the two millets used in this study were greater than the previously published values for millet, and lower than the corresponding energy values for dehulled millet (Xiong et al. 1990; Koehler 2002). In NRC (2012), the DE and ME contents of oat, naked oat and groats are 10.99 and 10.67, 15.43 and 15.04 MJ/kg, respectively. The energy content of naked oat reported by Li (2018) was similar to the values of naked oat published in NRC (2012) (Xiong et al. 1990; Koehler 2002). However, these values were greater than the values obtained in the current experiment. An explanation is that the CNO (*A. chinensis*) used in this study differs from the previous cultivated varieties genetically. Nevertheless, the energy value of the current variety of naked oat in the present study is similar to that of the oat groats (Koehler 2002). Further research is required to determine the best inclusion levels of these unconventional feedstuffs in growing pigs through growth trial.

**Table 7. Stepwise regression equations for DE and ME based on the chemical characteristics of the five unconventional grain ingredients*.**

| Equation | Liner regression equations | R² | RMSE | p-Value |
|----------|----------------------------|----|------|---------|
| 1        | DE (MJ/kg DM) = 15.04 + (0.81 × EE) | 0.62 | 0.55 | .1 |
| 2        | DE (MJ/kg DM) = 16.10 + (0.87 × EE)− (7.57 × P) | 0.93 | 0.28 | .07 |
| 3        | ME (MJ/kg DM) = (1.03 × DE)− 1.19 | 0.92 | 0.28 | .01 |
| 4        | ME (MJ/kg DM) = 2.17 + (0.86 × EE)− (6.57 × Ca) | 0.98 | 0.15 | .01 |

Note: EE, ether extract; Ca, calcium; P, phosphorus; RMSE, root mean square error. *Equations based on analysed nutrient content expressed on DM basis, n = 5.

**Conclusion**

In summary, on DM basis, the DE and ME values of HB, BKW, GBM, NBM, naked oat we determined using difference method were 15.97 and 15.38 MJ/kg, 16.90 and 15.76 MJ/kg, 17.65 and 16.86 MJ/kg, 17.87 and 17.34 MJ/kg, 17.57 and 16.85 MJ/kg, respectively. On DM basis, the DE and ME values of these five unconventional feedstuffs could be predicted through the following equations: DE = 16.10 + (0.87 × EE)− (7.57 × P), and ME = 2.17 + (0.86 × DE)− (6.57 × Ca) in which energy values are expressed as MJ/kg and chemical compositions are expressed as %. The ATTD of nutrients and energy and the energy content of the five ingredients were negatively related with the NDF concentration.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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