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# Greenhouse gas emissions, net energy, and nitrogen balance are not impacted by inclusion of hybrid rye in diets for growing pigs, but ileal digestibility of amino acids and acid-hydrolyzed ether extract is reduced if hybrid rye replaces corn

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ABSTRACT

Two experiments were conducted to test the hypothesis that greenhouse gas emissions, nitrogen balance, net energy (NE), and ileal digestibility of amino acids (AA) and acid-hydrolyzed ether extract (AEE) are not affected by inclusion of hybrid rye in diets fed to growing pigs. Three diets were prepared and fed to pigs in both Exp. 1 and 2. The control diet contained corn and soybean meal as energy sources and 2 additional diets were formulated by replacing half or all of the corn in the control diet with hybrid rye. In Exp. 1, 24 pigs (initial body weight: 52.38 ± 2.52 kg) were assigned to 6 calorimeter chambers with 4 pigs per chamber. Chambers were allotted to a replicated 3 × 3 Latin square design with the 3 diets and three 15-day periods for 6 replicates per diet. After a 7-day adaptation period, oxygen consumption and carbon dioxide and methane production were measured for 6 days to determine total heat production, and feces and urine were also collected. In Exp. 2, twelve ileal cannulated pigs (average body weight = 47.78 ± 4.40 kg) were allotted to a 2-period switchback design with 3 diets and 2 periods for a total of 8 replicates per diet. Results from Exp. 1 indicated that consumption of oxygen and production of carbon dioxide and methane, NE, and nitrogen balance were not affected by dietary treatment. However, the respiratory quotient of pigs in the fed state was reduced (linear; $P = 0.047$) by increasing hybrid rye in diets. Results from Exp. 2 indicated that the ileal digestibility of AEE and indispensable AA was reduced ($P < 0.05$) by increasing hybrid rye in diets. In conclusion, replacing corn with hybrid rye in the diets for growing pigs did not impact greenhouse gas emissions, NE, or nitrogen balance, but the respiratory quotient and the ileal digestibility of AEE and AA were reduced. Therefore, hybrid rye can be used as an alternative to corn without negatively impacting the environmental footprint of pig production systems.

*Abbreviations:* AA, amino acids; AEE, acid-hydrolyzed ether extract; AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; $CH_4$, methane; $CO_2$, carbon dioxide; DE, digestible energy; FHP, fasting heat production; ME, metabolizable energy; NE, net energy; $O_2$, oxygen; RQ, respiratory quotient; SID, standardized ileal digestibility; THP, total heat production.

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## 1. Introduction

Rye (*Secale cereale* L.) is a cereal crop that has high winter hardiness and high drought and stress tolerance, suitable for infertile, acidic, or sandy soils, but rye has historically not been widely used in diets for pigs due to its susceptibility to ergot contamination (Miedaner and Laidig, 2019; Wegulo and Carlson, 2011). However, rye can be cross-pollinated to produce hybrid varieties, that can increase disease resistance, as well as increase yield and adaptability to various agronomic conditions (Geiger and Miedaner, 2009). Hybrid rye contains more dietary fiber than wheat and corn (McGhee and Stein, 2018; Acosta and Stein, 2025), and less acid-hydrolyzed ether extract (AEE) than most other cereal grains (Rodehutscord et al., 2016; McGhee and Stein, 2018). The standardized ileal digestibility (SID) of crude protein and most amino acids (AA) in hybrid rye is less than in corn (Brestenský et al., 2013; Strang et al., 2016; McGhee and Stein, 2018), but hybrid rye has greater concentration of AA than corn, and concentrations of standardized ileal digestible crude protein and most AA in hybrid rye are, therefore, not different from corn (McGhee and Stein, 2018). Digestible energy (DE), metabolizable energy (ME), and net energy (NE) of hybrid rye fed to growing pigs have been reported as 15.62, 14.72, and 11.54 MJ/kg, which is less than in corn and wheat (NRC, 2012; Acosta and Stein, 2025).

The environmental footprint of livestock production is influenced by the emission of greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$), and these gases also contribute to climate change (Philippe and Nicks, 2015). Emission of greenhouse gases by pigs can be influenced by composition of the diet, and greater dietary fiber inclusion has been associated with increased $CH_4$ production (Le Goff et al., 2002; Jarret et al., 2012). Likewise, greater fiber inclusion in diets for pigs increased nutrient excretion (Moeser and van Kempen, 2002), and reduced NE and the digestibility of AA and AEE digestibility (Zhang et al., 2013; Acosta et al., 2020). The impact of corn-soybean meal diets on greenhouse gas emissions by pigs has been reported (Trabue and Kerr, 2014), but there is no information about how hybrid rye influences greenhouse gas production when included in diets fed to growing pigs, or if a change from using corn to using hybrid rye will result in a change in nitrogen retention, diet NE, or ileal digestibility of AA and AEE. Therefore, two experiments were conducted to test the null hypothesis that greenhouse gas emissions, nitrogen balance, NE, and ileal digestibility of AA and AEE are not affected by inclusion of hybrid rye in diets fed to growing pigs.

## 2. Materials and methods

Protocols for two experiments were submitted to the Institutional Animal Care and Use Committee at the University of Illinois (Urbana, IL, USA) and both protocols were approved before initiation of the experiments. Pigs were the offspring of Line 800 boars and Camborough females (Pig Improvement Company, Hendersonville, TN, USA). The same batches of corn, soybean meal, and hybrid rye were used to prepare all experimental diets (Table 1).

**Table 1**
Analyzed nutrient composition of ingredients, (as-fed basis).

| Item | Corn | Soybean meal[a] | Hybrid rye |
|---|---|---|---|
| Gross energy, MJ/kg | 16.36 | 17.87 | 16.18 |
| Dry matter, g/kg | 883.0 | 902.7 | 900.9 |
| Ash, g/kg | 12.9 | 63.3 | 16.8 |
| Crude protein, g/kg | 74.6 | 452.5 | 82.0 |
| Acid-hydrolyzed ether extract, g/kg | 30.6 | 23.7 | 7.0 |
| Starch, g/kg | 638.7 | 19.4 | 577.1 |
| Total dietary fiber, g/kg | 99.0 | 186.0 | 178.0 |
| Insoluble dietary fiber, g/kg | 87.0 | 153.0 | 130.0 |
| Soluble dietary fiber, g/kg | 12.0 | 33.0 | 48.0 |
| Indispensable amino acids, g/kg | | | |
| Arg | 3.3 | 33.5 | 4.7 |
| His | 2.3 | 13.1 | 2.3 |
| Ile | 2.9 | 22.8 | 3.2 |
| Leu | 9.3 | 36.7 | 5.8 |
| Lys | 2.6 | 30.5 | 4.3 |
| Met | 1.7 | 6.6 | 1.4 |
| Phe | 3.8 | 24.5 | 3.9 |
| Thr | 2.8 | 18.4 | 3.1 |
| Trp | 0.5 | 6.0 | 0.9 |
| Val | 3.9 | 24.7 | 4.4 |
| Dispensable amino acids, g/kg | | | |
| Ala | 5.8 | 20.4 | 3.9 |
| Asp | 5.3 | 54.0 | 7.4 |
| Cys | 1.7 | 6.5 | 1.9 |
| Glu | 3.0 | 19.6 | 3.9 |
| Gly | 14.6 | 86.9 | 17.8 |
| Pro | 7.0 | 24.5 | 6.7 |
| Ser | 3.4 | 19.7 | 3.6 |
| Tyr | 2.1 | 17.0 | 1.9 |

[a] Low molecular weight carbohydrates (g/kg): glucose, $< 0.5$; sucrose, 75; maltose, 3.2; fructose, 0.8; stachyose, 57.2; and raffinose, 10.2.

### 2.1. Experiment 1

A control diet was formulated to contain corn and soybean meal as energy sources and two additional diets were formulated by replacing 500 or 1000 g/kg of the corn in the control diet with hybrid rye (Tables 2 and 3). Crystalline AA, minerals, and vitamins were included in all diets to meet or exceed requirements for growing pigs (NRC, 2012). A sample of each diet was collected at the time of diet mixing.

Twenty-four pigs (initial body weight: 52.38 ± 2.52 kg) were housed in a calorimeter unit with 6 chambers and 4 pigs per chamber (Muñoz Alfonso et al., 2026). Chambers were allotted to a replicated 3 × 3 Latin square design with 3 diets, 6 chambers, and 3 periods. Therefore, there were a total of 6 replicate chambers per diet. Each chamber was equipped with a stainless steel wet-dry feeder, an auxiliary nipple waterer, slatted floors, 4 stainless steel fecal screens, and 2 urine pans for total, but separate, collection of fecal and urine materials. The temperature and relative humidity inside the chambers were controlled using temperature and humidity control units (Model 9241–2220-B1D0000; Parameter, Black Mountain, NC, USA), and air velocity was controlled using an airflow meter (AccuValve; Accutrol, LLC, Danbury, CT, USA). Throughout the experiment, pigs were allowed *ad libitum* access to feed, and all diets were fed as a meal. Diets were fed for 13 days, where the initial 7 days were considered the adaptation period to the diet. From the morning of day 8 to the morning of day 13, the gas analyzers (Classic Line, Sable System International, North Las Vegas, NV, USA) started measuring oxygen ($O_2$) consumption and $CO_2$ and $CH_4$ productions for determination of total heat production (THP). Fecal and urine samples were also collected from day 8 to day 13. During the collection period, 100 mL of 6 *N* HCl was added to each urine pan every day, to avoid nitrogen loss in urine (Adeola, 2001). Chambers were open for approximately 1 h every day to check feeders, and for collection of feces and urine. Data from the gas analyzers obtained during the period that the chambers were open and until they reached the condition set by the temperature and humidity control unit were disregarded for the final calculation of THP. Fecal samples and 50 g/kg of the urine were stored at −20 °C immediately after collection. On day 14, the fasting period started. The initial 36 h of the fasting period were considered the time the animals digested and metabolized the remaining feed in the intestinal tract, whereas the following 12 h were considered the period when the animals mobilized endogenous nutrients to produce energy (de Lange et al., 2006). Therefore, gas exchange was measured and urine was collected for the last 12 h of fasting.

At the conclusion of the experiment, urine samples were thawed and mixed within chamber and diet, and a sub-sample was prepared for gross energy analysis following the procedure described by Kim et al. (2009). In short, 10 mL of urine was dripped on a cotton ball that was placed in a plastic bag and then lyophilized. Gross energy was subsequently measured in the lyophilized samples as well as in plastic bags and cotton balls and the gross energy contribution from the urine was calculated by difference (Kim et al., 2009). All urine samples were analyzed in quadruplicates. A second sub-sample of urine was collected for nitrogen analysis. Fecal samples were thawed and mixed within pig and diet and then dried in a 50 °C forced air drying oven prior to analysis (Heratherm OMH750, Thermo Fisher Scientific, Pittsburgh, PA, USA). Fecal samples were ground through a 1-mm screen using a hammermill (Model: MM4; Schutte Buffalo, NY, USA). Ingredients and diets were also ground before analysis. Ingredients, diets, and fecal samples were analyzed for dry matter by oven drying at 135 ºC for 2 h (method 930.15; AOAC Int.., 2019), and for gross energy determined by bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA) using benzoic acid as the standard for calibration. Diets and ingredients

**Table 2**
Ingredient composition of experimental diets, as-fed basis.

| Ingredient, g/kg | Corn replacement rate, g/kg | | | Nitrogen-free diet[a] |
|---|---|---|---|---|
| | 0 | 500 | 1000 | |
| Corn | 770.8 | 385.7 | - | - |
| Hybrid rye | - | 385.8 | 772.5 | - |
| Soybean meal | 200.0 | 200.0 | 200.0 | - |
| Corn starch | - | - | - | 674.8 |
| Sucrose | - | - | - | 200.0 |
| Soybean oil | - | - | - | 50.0 |
| Solka floc[b] | - | - | - | 40.0 |
| L-Lys·HCl, 78 % Lys | 2.6 | 2.2 | 1.7 | - |
| DL-Met, 99 % Met | 0.3 | 0.3 | 0.3 | - |
| L-Thr, 99 % Thr | 0.5 | 0.5 | 0.6 | - |
| Limestone | 7.7 | 8.8 | 9.7 | 3.6 |
| Dicalcium phosphate | 9.1 | 7.7 | 6.2 | 17.6 |
| Magnesium oxide | - | - | - | 1.0 |
| Potassium carbonate | - | - | - | 4.0 |
| Salt | 4.0 | 4.0 | 4.0 | 4.0 |
| Vitamin-mineral premix[c] | 5.0 | 5.0 | 5.0 | 5.0 |

[a] The nitrogen-free diet was used only in experiment 2.
[b] Fiber Sales and Development Corp., Urbana, OH, USA.
[c] The vitamin-mineral premix provided the following quantities of vitamins and micro-minerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin $D_3$ as cholecalciferol, 2208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylpyrimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin $B_{12}$, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

**Table 3**
Analyzed composition of experimental diets, as-fed basis.

| Item | Corn replacement rate, g/kg | | |
|---|---|---|---|
| | 0 | 500 | 1000 |
| Gross energy, MJ/kg | 16.26 | 16.22 | 16.21 |
| Dry matter, g/kg | 885.3 | 898.0 | 904.1 |
| Ash, g/kg | 36.5 | 40.0 | 44.1 |
| Crude protein, g/kg | 153.2 | 156.5 | 172.0 |
| Acid hydrolyzed ether extract, g/kg | 27.8 | 21.2 | 15.8 |
| Total dietary fiber, g/kg | 114.0 | 144.0 | 189.0 |
| Soluble dietary fiber, g/kg | 19.0 | 36.0 | 69.0 |
| Insoluble dietary fiber, g/kg | 95.0 | 108.0 | 120.0 |
| Indispensable amino acids, g/kg | | | |
| Arg | 8.6 | 9.7 | 10.9 |
| His | 4.3 | 4.3 | 4.8 |
| Ile | 6.3 | 6.6 | 7.4 |
| Leu | 14.6 | 13.3 | 12.8 |
| Lys | 9.4 | 10.2 | 11.5 |
| Met | 3.0 | 2.7 | 2.7 |
| Phe | 7.6 | 7.9 | 8.6 |
| Thr | 6.2 | 6.5 | 7.5 |
| Trp | 1.7 | 1.7 | 2.0 |
| Val | 7.4 | 7.7 | 8.5 |
| Dispensable amino acids, g/kg | | | |
| Ala | 8.5 | 7.9 | 7.8 |
| Asp | 14.3 | 15.7 | 18.0 |
| Cys | 2.5 | 2.8 | 3.1 |
| Glu | 28.5 | 30.3 | 34.0 |
| Gly | 6.0 | 6.6 | 7.6 |
| Pro | 10.2 | 10.2 | 10.9 |
| Ser | 6.9 | 7.1 | 7.8 |
| Tyr | 4.9 | 5.0 | 4.7 |
| Total amino acids | 153.6 | 158.8 | 172.9 |

were also analyzed for ash (method 942.05; AOAC Int.., 2019), and AEE by acid-hydrolysis using 3 *N* HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (method Am 5–04; AOCS, 2013) using petroleum ether (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA). Nitrogen in ingredients, diets, and fecal samples were analyzed using the combustion procedure (method 990.03; AOAC Int.., 2019) on a LECO FP628 (LECO Corp., Saint Joseph, MI, USA). However, nitrogen in urine samples was analyzed using the Kjeldahl method (method 984.13; AOAC Int.., 2019) on a Kjeltec 8400 (FOSS Inc., Eden Prairie, MN, USA). Crude protein was calculated as analyzed nitrogen × 6.25. Diets and ingredients were analyzed for AA on a Hitachi Amino Acid Analyzer (Model No. l8800; Hitachi High Technologies America, Inc., Pleasanton, CA, USA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard [Method 982.30 E (a, b, c); AOAC Int.., 2019]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int.., 2019]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C [method 982.30 E(c); AOAC Int.., 2019]. Diet and ingredient samples were also analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int.., 2019) using the Ankom$^{TDF}$ Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of insoluble dietary fiber and soluble dietary fiber. Ingredients were also analyzed for total starch using the glucoamylase procedure (method 979.10; AOAC Int.., 2019), and low molecular weight carbohydrates (i.e., glucose, sucrose, maltose, fructose, stachyose, and raffinose) were analyzed in soybean meal using high-performance liquid chromatography (method 977.2, AOAC Int.., 2019).

Concentrations of $O_2$, $CO_2$, and $CH_4$ were averaged within collection period and for the last 12 h of the fasting period. Daily consumption of $O_2$ and productions of $CO_2$, and $CH_4$ were expressed as L/pig, L/kg body weight, L/kg metabolic body weight, L/g of nitrogen intake, and L/kg body weight gain. Respiratory quotient (RQ) was calculated by dividing $CO_2$ produced by $O_2$ consumed. The THP from pigs during the collection period was calculated using the following equation (Brouwer, 1965):

$$THP_{MJ} = [(0.01617 \times O_2) + (0.00502 \times CO_2) - (0.00217 \times CH_4) - (0.00598 \times \text{Urine nitrogen})]$$

where $O_2$, $CO_2$, and $CH_4$ are expressed in L, and urine nitrogen is expressed in g. Fasting heat production (FHP) was calculated using urine nitrogen and measured $O_2$ consumption and $CO_2$ and $CH_4$ production during the fasting period. The apparent total tract digestibility (ATTD) of dry matter, gross energy, and nitrogen was calculated for each diet (Adeola, 2001), and concentrations of DE and ME in the 3 diets were calculated (NRC, 2012). The concentration of NE was calculated using the following equation (modified from NRC, 2012):

$$NE_{MJ/kg} = \frac{ME - (THP - FHP)}{\text{feed intake}}$$

where ME is in MJ/kg, THP and FHP are in MJ, and feed intake is in kg during the collection period. Nitrogen excretion and nitrogen balance were also calculated using weights of feces and urine and analyzed nitrogen in diets, feces, and urine.

Homogeneity of the variances and normality were confirmed using the UNIVARIATE procedure, and data were analyzed using the MIXED procedure (SAS Institute Inc.., 2016). The statistical model included diet as fixed effect and chamber and period as random effects. Mean values were calculated using the LSMeans statement. Linear effects of increasing hybrid rye were analyzed using contrast coefficients. Calorimeter chamber was the experimental unit. Results were considered significant at $P < 0.05$ and considered a trend at $P \leq 0.10$.

### 2.2. Experiment 2

The diets used in experiment 1 were also used in experiment 2, but 4 g/kg of chromic oxide was mixed into each diet. A nitrogen-free diet was also used in experiment 2 to determine the basal endogenous losses of AA. A sample of each diet was collected at the time of diet mixing.

Twelve pigs (initial body weight: 47.78 ± 4.40 kg) that had a T-cannula installed in the distal ileum were used (Stein et al., 1998). Pigs were allotted to a 2-period switchback design with 3 diets. There were four pigs per diet in each period for a total of 8 replicate pigs per treatment. The nitrogen-free diet was fed to all pigs during an additional period. Pigs were placed in individual pens that had a feeder, a drinking nipple, and fully slatted floors. Daily feed intake was calculated as 3.2 times the maintenance requirement for ME (i.e., 197 kcal ME per kg body weight$^{0.60}$; NRC, 2012), and feed was provided every morning at 0700 h. Water was available at all times. Experimental diets were fed for 7 days. The initial 5 days of each period were considered an adaptation period to the diets and ileal digesta were collected on days 6 and 7 for 9 h per day using standard procedures (Lee et al., 2021). Cannulas were opened at the beginning of collection and a 225-mL plastic bag was attached to the cannula barrel using a cable tie. Digesta flowing into the bag were collected and bags were replaced whenever they were full or at least once every 30 min. Digesta samples were stored at −20 °C immediately after collection (Lee et al., 2021). At the conclusion of the experiment, ileal digesta samples were thawed and mixed within pig and diet, and a subsample was collected for chemical analysis.

Digesta samples were lyophilized in a freeze dryer (Model Gamma 1–16 LCSplus, Ima Life, Tonawanda, NY, USA) and ground using a coffee grinder. Lyophilized ileal digesta samples were analyzed for dry matter, crude protein, AA, and AEE as explained for experiment 1. The chromium concentration in diets and ileal digesta samples were determined using an inductive coupled plasma atomic emission spectrometric method (method 990.08; AOAC Int.., 2019). Samples were prepared for analysis using nitric acid-perchloric acid (method 968.08D(b); AOAC Int.., 2019).

Apparent ileal digestibility (AID) of dry matter and AEE, basal ileal endogenous losses of AA, and SID of nitrogen and AA in each diet were calculated (Stein et al., 2007). Model assumptions were confirmed and data were analyzed using the MIXED procedure (SAS Institute Inc.., 2016) as in experiment 1. The model included diet as the fixed effect, whereas period and square were random effects. Least squares means were calculated as in experiment 1. Pig was the experimental unit and results were considered significant at $P < 0.05$, and a tendency for a difference was considered at $5 > P < 0.10$.

**Table 4**
Oxygen ($O_2$) consumption and greenhouse gas emissions as carbon dioxide ($CO_2$) and methane ($CH_4$) from growing pigs fed experimental diets[a].

| Item | Corn replacement rate, g/kg | | | SEM | Linearity[b] |
|---|---|---|---|---|---|
| | 0 | 500 | 1000 | | |
| Respiratory quotient, fasted | 0.69 | 0.68 | 0.68 | 0.02 | 0.957 |
| Respiratory quotient, fed | 1.11 | 1.07 | 1.08 | 0.04 | 0.047 |
| Gas exchanges, L | | | | | |
| $O_2$ consumption | 871.24 | 878.38 | 875.49 | 38.89 | 0.860 |
| $CO_2$ production | 960.87 | 945.06 | 940.50 | 65.16 | 0.432 |
| $CH_4$ production | -0.07 | 0.36 | 0.26 | 1.10 | 0.414 |
| Gas exchanges, L/kg body weight | | | | | |
| $O_2$ consumption | 12.18 | 12.16 | 12.14 | 0.97 | 0.925 |
| $CO_2$ production | 13.38 | 13.00 | 12.97 | 0.81 | 0.261 |
| $CH_4$ production | -0.001 | 0.005 | 0.003 | 0.02 | 0.442 |
| Gas exchanges, L/kg body weight$^{0.60}$ | | | | | |
| $O_2$ consumption | 66.98 | 67.14 | 67.00 | 2.50 | 0.991 |
| $CO_2$ production | 73.70 | 71.96 | 71.73 | 2.47 | 0.313 |
| $CH_4$ production | -0.01 | 0.03 | 0.02 | 0.08 | 0.466 |
| Daily gas exchanges, L/kg body weight gain | | | | | |
| $O_2$ consumption | 891.66 | 897.40 | 909.37 | 53.10 | 0.817 |
| $CO_2$ production | 984.45 | 956.10 | 976.79 | 59.78 | 0.929 |
| $CH_4$ production | 0.58 | 1.19 | 0.36 | 1.54 | 0.765 |
| Gas exchanges, L/g nitrogen intake | | | | | |
| $O_2$ consumption | 8.89 | 8.35 | 8.52 | 0.63 | 0.605 |
| $CO_2$ production | 9.79 | 8.92 | 9.11 | 0.57 | 0.349 |
| $CH_4$ production | -0.0002 | 0.0033 | 0.0031 | 0.0104 | 0.469 |

[a] Least mean squares represent 6 replicates per dietary treatment except for $CH_4$ production data ($n = 5$).
[b] Linear effects (P-value) of increasing hybrid rye in diets.

## 3. Results

Analyzed concentrations of energy and nutrients in diets were in agreement with calculated values. Results from experiment 1 indicated that $O_2$ consumption, and $CO_2$ and $CH_4$ production per day were not affected by dietary treatment (Table 4). The RQ of pigs during the fasted period was also not different among treatments; however, the RQ of pigs during the fed period was reduced (linear; $P = 0.047$) by increasing hybrid rye in diets.

There were no differences among diets in the ATTD of dry matter, gross energy, and nitrogen or in THP and FHP, concentrations of DE, ME, and NE, nitrogen intake, fecal nitrogen excretion, excretion of nitrogen in urine, or retention of nitrogen (Tables 5 and 6). However, the gross energy fecal output was reduced (linear; $P = 0.020$) and the concentration of nitrogen in feces increased (linear; $P = 0.020$) when corn was replaced by hybrid rye.

The AID of dry matter and AEE in experiment 2 were reduced (linear; $P < 0.001$) as hybrid rye replaced corn in the diets (Table 7). Likewise, the SID of nitrogen and all AA was reduced (linear; $P < 0.05$) by increasing hybrid rye in diets, with the exception that the SID of Cys tended (linear; $P < 0.10$) to be reduced, and Pro tended (linear; $P < 0.10$) to increase as hybrid rye increased in the diet.

## 4. Discussion

Concentrations of nutrients and gross energy in corn, hybrid rye, and soybean meal were in agreement with reported values (NRC, 2012; McGhee and Stein, 2018; Song et al., 2024). Corn is the most extensively cultivated and consumed cereal grain in the world due to its high yield capacity, and corn is mainly used as a feed ingredient in animal diets, for bioethanol production, or for other industrial purposes (Loy and Lurdy, 2019). In pig production, the corn-soybean meal diet is the most widely used diet in the United States because this combination meets the nutritional requirements of pigs, and combined with vitamins and minerals, results in a balanced diet (NRC, 2012). However, in countries where corn is not produced, pigs may be fed diets based on barley, wheat, or other cereal grains (Rodehutscord et al., 2016) because pigs have requirements for nutrients and energy and not for specific ingredients, and the energy can be provided by cereal grains other than corn (Rodehutscord et al., 2016; Stas et al., 2024).

Hybrid rye is a cereal grain that has been introduced in Europe and North America. Hybrid rye has greater yield per hectare than conventional rye and also has increased tolerance for cold temperatures and reduced rainfall than corn and wheat (Miedaner and Laidig, 2019; Zhang et al., 2024). These characteristics make hybrid rye a less expensive crop to produce because it requires less water and fertilizers than corn and wheat, which may result in lower carbon footprint compared with other cereal grain crops (Miedaner et al., 2025). As a feed ingredient, hybrid rye is characterized by greater concentration of fiber, slightly greater concentration of crude protein, and lower concentration of fat and starch compared with corn and wheat (Rodehutscord et al., 2016; McGhee and Stein, 2018; Acosta and Stein, 2025). In addition, hybrid rye has reduced susceptibility to ergot contamination and reduced presence of anti-nutritional factors compared with conventional population rye (Schwarz et al., 2015; Miedaner et al., 2021). Therefore, hybrid rye is a potential feed ingredient in animal diets.

Animal respiration is a source of greenhouse gas emissions associated with livestock farming production and agriculture (Johnson et al., 2007; Cai et al., 2022). The environmental impact of pigs fed diets containing coproducts such as distillers dried grains with solubles, wheat shorts, bakery meal, sugar beet pulp, or rapeseed meal indicated that using coproducts may reduce the environmental impact of pig production by reducing ammonia emission or global warming potential (Jarret et al., 2011; 2012; van Zanten et al., 2015; Mackenzie et al., 2016) although that is not always the case (Pepple et al., 2011; Montalvo et al., 2013). However, to our knowledge, the production of greenhouse gases by pigs fed diets containing hybrid rye has not been reported and the current research was conducted to fill this gap. The observation that replacing 500 or 1000 g/kg of corn with hybrid rye did not impact $O_2$ consumption and $CO_2$ production indicates that pigs fed diets containing SBM and hybrid rye will have the same carbon footprint per day compared with

**Table 5**
Apparent total tract digestibility (ATTD) of dry matter and gross energy, and concentrations of digestible energy (DE), metabolizable energy (ME) and net energy (NE) in diets fed to growing pigs[a].

| Item | Corn replacement rate, g/kg | | | SEM | Linearity[b] |
|---|---|---|---|---|---|
| | 0 | 500 | 1000 | | |
| Dry matter intake, kg/d | 2.41 | 2.69 | 2.49 | 0.24 | 0.677 |
| Fecal dry matter output, kg/d | 0.27 | 0.28 | 0.25 | 0.01 | 0.045 |
| ATTD of dry matter | 0.89 | 0.89 | 0.90 | 0.01 | 0.163 |
| Gross energy intake, MJ/d | 44.20 | 48.40 | 44.35 | 4.27 | 0.965 |
| Gross energy fecal output, MJ/d | 5.66 | 5.80 | 5.13 | 0.26 | 0.020 |
| ATTD of gross energy | 0.87 | 0.88 | 0.88 | 0.01 | 0.218 |
| DE, MJ/kg | 14.13 | 14.15 | 14.24 | 0.15 | 0.554 |
| Gross energy urine output, MJ/d | 1.08 | 1.16 | 1.10 | 0.13 | 0.853 |
| ME, MJ/kg | 13.73 | 13.75 | 13.84 | 0.16 | 0.643 |
| Total heat production, MJ/d | 18.92 | 18.95 | 18.88 | 0.94 | 0.948 |
| Fasting heat production, MJ/d | 9.73 | 9.84 | 10.12 | 2.18 | 0.826 |
| NE, MJ/kg | 10.29 | 10.28 | 10.56 | 1.08 | 0.807 |

[a] Least mean squares represent 6 replicates per dietary treatment.
[b] Linear effects (P-value) of increasing hybrid rye in diets.

**Table 6**
Nitrogen excretion and nitrogen balance in diets fed to growing pigs[a].

| Item (per one pig) | Corn replacement rate, g/kg | | | SEM | Linearity[b] |
|---|---|---|---|---|---|
| | 0 | 500 | 1000 | | |
| Nitrogen intake, g/day | 98.80 | 110.46 | 103.27 | 9.75 | 0.574 |
| Nitrogen in feces, g/kg | 40.87 | 37.79 | 42.55 | 1.15 | 0.020 |
| Fecal nitrogen excretion, g/day | 17.63 | 16.86 | 16.80 | 0.89 | 0.164 |
| ATTD[c] of nitrogen | 0.82 | 0.84 | 0.84 | 0.02 | 0.312 |
| Absorbed nitrogen, g/day | 81.17 | 93.59 | 86.46 | 9.61 | 0.511 |
| Nitrogen in urine, g/kg | 2.50 | 2.51 | 2.48 | 0.47 | 0.951 |
| Urine nitrogen excretion, g/day | 21.90 | 24.07 | 23.87 | 4.27 | 0.366 |
| Retained nitrogen, g/day | 59.27 | 69.52 | 62.59 | 6.56 | 0.683 |
| Retention of nitrogen, g/g intake | 0.60 | 0.62 | 0.61 | 0.03 | 0.845 |
| Retention of nitrogen, g/g absorbed | 0.73 | 0.74 | 0.73 | 0.03 | 0.881 |

[a] Least mean squares represent 6 replicates per dietary treatment.
[b] Linear effects (P-value) of increasing hybrid rye in diets.
[c] ATTD = apparent total tract digestibility.

**Table 7**
Apparent ileal digestibility (AID) of dry matter and acid-hydrolyzed ether extract (AEE) and standardized ileal digestibility (SID) of amino acids (AA) in diets fed to growing pigs[a].

| Item, % | Corn replacement rate, g/kg | | | SEM | Linearity[c] |
|---|---|---|---|---|---|
| | 0 | 500 | 1000 | | |
| AID of dry matter | 0.72 | 0.66 | 0.61 | 0.01 | < 0.001 |
| AID of AEE | 0.61 | 0.44 | 0.29 | 0.03 | < 0.001 |
| SID[b] of nitrogen | 0.84 | 0.81 | 0.79 | 0.02 | 0.038 |
| SID[b] of indispensable AA | | | | | |
| Arg | 0.89 | 0.90 | 0.86 | 0.01 | 0.032 |
| His | 0.84 | 0.81 | 0.77 | 0.01 | 0.003 |
| Ile | 0.82 | 0.77 | 0.75 | 0.01 | 0.003 |
| Leu | 0.83 | 0.79 | 0.74 | 0.01 | < 0.001 |
| Lys | 0.83 | 0.80 | 0.78 | 0.01 | 0.010 |
| Met | 0.87 | 0.82 | 0.78 | 0.01 | < 0.001 |
| Phe | 0.83 | 0.78 | 0.75 | 0.01 | 0.002 |
| Thr | 0.80 | 0.75 | 0.74 | 0.02 | 0.018 |
| Trp | 0.87 | 0.81 | 0.80 | 0.01 | 0.001 |
| Val | 0.80 | 0.74 | 0.71 | 0.01 | 0.001 |
| Total | 0.83 | 0.80 | 0.77 | 0.01 | 0.002 |
| SID[b] of dispensable AA | | | | | |
| Ala | 0.80 | 0.74 | 0.69 | 0.02 | < 0.001 |
| Asp | 0.78 | 0.75 | 0.73 | 0.01 | 0.014 |
| Cys | 0.75 | 0.73 | 0.71 | 0.02 | 0.096 |
| Glu | 0.85 | 0.82 | 0.78 | 0.01 | 0.001 |
| Gly | 0.83 | 0.8 | 0.7 | 0.05 | 0.034 |
| Pro | 0.95 | 1.15 | 1.18 | 0.1 | 0.076 |
| Ser | 0.84 | 0.81 | 0.8 | 0.01 | 0.013 |
| Tyr | 0.85 | 0.82 | 0.76 | 0.01 | < 0.001 |
| Total | 0.84 | 0.84 | 0.8 | 0.02 | 0.145 |
| Total AA | 0.83 | 0.82 | 0.78 | 0.02 | 0.021 |

[a] Least mean squares represent 8 replicates per dietary treatment except for the AID of AEE in the diet where corn was replaced with 1000 g/kg hybrid rye ($n = 5$).
[b] Values for the SID were calculated by correcting the AID for basal ileal endogenous losses. Basal ileal endogenous losses (g/kg of dry matter intake) were determined as: nitrogen, 3.98; Arg, 0.88; His, 0.33; Ile, 0.58; Leu, 0.91; Lys, 0.73; Met, 0.16; Phe, 0.55; Thr, 0.94; Trp, 0.14; Val, 0.72.
[c] Linear effects (P-value) of increasing hybrid rye in diets.

pigs fed a corn-SBM diet. The reduced RQ that was calculated for pigs fed diets with hybrid rye instead of corn may be a result of reduced carbohydrate utilization as an energy source (Richardson, 1929), which likely is due to the lower starch in hybrid rye compared with corn (McGhee and Stein, 2018; 2020; Schmitz et al., 2024; Song et al., 2024). This indicates that pigs fed hybrid rye potentially shifted some of their metabolic substrate to products of fiber fermentation (Rijnen et al., 2001; Gondret et al., 2014).

Methane is produced via microbial fermentation in the hindgut of pigs and in the manure during storage (Petersen et al., 2016). However, in this experiment, urine and feces were collected and removed from the chambers daily and the contribution of $CH_4$ production from the manure, therefore, was assumed to be insignificant and the measured $CH_4$ was, therefore, assumed to be a result of fiber fermentation. Greater inclusion of dietary fiber in diets for pigs results in increased $CH_4$ emissions (Jarret et al., 2012; Montalvo et al., 2013; Philippe et al., 2015; Sattarova et al., 2024). Hybrid rye contains slightly more insoluble dietary fiber and more soluble dietary fiber than corn (McGhee and Stein, 2020; McGhee et al., 2021), particularly soluble arabinoxylans that can be fermented by microbes in the large intestine of pigs resulting in production of short-chain fatty acids and $CH_4$ (Bach Knudsen, 2015). However, the observation that $CH_4$ emissions did not increase by substituting corn for hybrid rye indicates that the increase in dietary fiber in the diets containing hybrid rye was too small to impact synthesis of $CH_4$. This observation is in agreement with the conclusion that an increase in soluble and fermentable dietary fiber does not always result in increased $CH_4$ emissions from pigs (Pepple et al., 2011; Kerr et al., 2020; Kpogo et al., 2021). Therefore, the hypothesis that replacing corn with hybrid rye did not influence greenhouse gas emissions was confirmed.

The DE and ME in the corn–soybean meal diet that were calculated in this experiment were in agreement with previous values (NRC, 2012; Ibagon et al., 2024). The observation that values of DE, ME, and NE in the diets containing 500 or 1000 g/kg hybrid rye were not different from the DE, ME, and NE in the corn–soybean meal diet demonstrates that hybrid rye may be included in corn–soybean meal diets for pigs without changing the energy concentrations of the diets because the fiber from hybrid rye is fermentable and contributes to the energy status of pigs, as observed by less gross energy excreted in feces as hybrid rye increased in the diet. These data are in agreement with data demonstrating that hybrid rye can replace corn in diets for growing pigs without impacting growth or feed efficiency (McGhee et al., 2021, 2023). Hybrid rye may contain less ME than corn (McGhee and Stein, 2020), but the fact that this was not observed in the present experiment may be a result of the pigs used in this experiment being between 52 and 88 kg, whereas pigs used by McGhee and Stein (2020) were only 28 kg. Therefore, the hypothesis that replacing corn with hybrid rye did not influence NE in the diet was confirmed.

It was hypothesized that replacing corn with hybrid rye would not impact nitrogen balance. This hypothesis was confirmed because neither fecal or urine nitrogen excretion, nor nitrogen retention, was affected by increasing hybrid rye in diets. These observations agree with data demonstrating that nitrogen retention was not impacted by using distillers dried grains with solubles, sugar beet pulp, or rapeseed meal in balanced diets with added crystalline AA for pigs (Jarret et al., 2011; Trabue and Kerr, 2014). However, the observation that fecal nitrogen concentration linearly increased with increasing hybrid rye in diets indicates that pigs had reduced nitrogen digestibility, resulting in more nitrogen in the feces. This is in agreement with data showing lower digestibility of protein and AA in pigs fed hybrid rye (Jondreville et al., 2001; McGhee and Stein, 2018). A reduced digestibility of protein in diets with hybrid rye was also observed in experiment 2. Reduced AID of dry matter and SID of nitrogen and AA in diets with hybrid rye may be due to the soluble fiber in hybrid rye, which can increase viscosity of digesta, increase endogenous losses of AA, and reduce absorption efficiency of AA in the small intestine (Jürgens et al., 2012; Zuber et al., 2016). Indeed, the endogenous losses of AA determined in the present experiment were slightly greater than average values for pigs of similar body weight (Park et al., 2024). Nevertheless, regardless of diet, the daily nitrogen excretion obtained in the present experiment was greater than recent estimates for nitrogen excretion from growing pigs (Lee et al., 2026). The reason for this observation is primarily that fecal nitrogen excretion was greater than estimated by Lee al. (2026), which is likely due to the greater concentration of fiber in the diets used in the present experiment and a subsequent lower ATTD of nitrogen. Fiber may also interfere with micelle formation and thereby reduce the digestibility of lipids (Agyekum and Nyachoti, 2017; Acosta et al., 2020; Hu et al., 2023), which is in agreement with the reduced AID of AEE that was observed in experiment 2 when hybrid rye replaced corn. Reduced digestibility of AA may be overcome with greater inclusion of crude protein and AA in the diet and the fact that hybrid rye contains approximately the same amounts of standardized ileal digestible AA as corn indicates that the provision of digestible AA will not be compromised if hybrid rye is used in diets for pigs instead of corn (McGhee and Stein, 2018; Acosta and Stein, 2025). The observation that nitrogen retention was not impacted by replacing corn with hybrid rye further indicates that hybrid rye provides sufficient digestible AA to maximize protein synthesis.

The AID of AEE for the corn-soybean meal based diet was in agreement with values reported for corn and soybean oil (Kim et al., 2013). The reduced AID of AEE that was observed in experiment 2 as hybrid rye was included in the diets may be a result of the very low concentrations of AEE in the diets because low AEE in diets results in increased impact of endogenous fat on AID of AEE (Kil et al., 2010). The low AID of AEE, therefore, does not necessarily mean that the digestibility of fat in hybrid rye is less than in corn. Nevertheless, the hypothesis that changing from using corn to using hybrid rye will not affect the digestibility of AA and lipids was rejected, but the reduced digestibility of AA in diets containing hybrid rye was compensated for greater concentration of AA in hybrid rye compared with corn.

## 5. Conclusions

Hybrid rye can replace all corn in diets for growing pigs without increasing greenhouse gas emissions from pigs or reducing energy or nitrogen utilization. Although the digestibility of amino acids and acid hydrolyzed ether extract was reduced as hybrid rye replaced corn, net energy and nitrogen utilization by pigs were not different among diets. Therefore, if hybrid rye is available at competitive prices, this ingredient may be used in diets for pigs without compromising energy and nitrogen utilization or impacting greenhouse gas production.

## CRediT authorship contribution statement

**Jessica P. Acosta:** Writing – original draft, Formal analysis, Data curation. **Stein Hans H:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Su A Lee:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors have no conflicts of interest.

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