

Physiochemical characterization and energy contents of novel corn ethanol co-product streams, with and without inclusion of a multi-carbohydrase enzyme blend, for growing pigs

Melanie Boucher, Cuilan Zhu, Sheena Holt, and Lee-Anne Huber

Abstract: The physiochemical properties and digestible, metabolizable, and predicted net energy contents in high-protein dried distillers' grain (HiPro) were determined to assess the nutritive value for growing pigs. Twelve Yorkshire × Landrace barrows (initial body weight 25 ± 0.5 kg) were used in a partially replicated Latin square design over three periods ($n = 7$ or 8) and assigned to one of five experimental diets. In each period, pigs were adapted to diets for 7 d, followed by 5 d of total urine collection and fecal grab sampling. The experimental diets included a corn- and soybean-meal-based diet (CON) or diets containing dried distillers' grains with solubles (DDGS) or HiPro to partially replace corn and soybean meal, without or with (i.e., DDGS+ and HiPro+) a multi-carbohydrase enzyme blend (0.05% inclusion). The HiPro ingredient contained half as much starch (2.6% vs. 5.2%; DM-basis), 20% more protein (32.5% vs. 27.1%), and had 14% greater water binding capacity versus DDGS. The digestible, metabolizable, and predicted net energy contents of the HiPro co-product were greater than DDGS for growing pigs ($P < 0.05$), but fibre-degrading enzymes were ineffective at improving energy values. The greater (available) energy and protein contents of HiPro make it a promising feed ingredient for inclusion in swine diets.

Key words: corn ethanol co-products, energy content, physiochemical properties, swine.

Résumé : Les propriétés physicochimiques et la teneur en énergie digérable, métabolisable, et nette prévue de la drêche sèche de distillerie à forte teneur en protéines (HiPro) ont été déterminées afin d'évaluer la valeur nutritive pour les porcs en croissance. Douze castrats Yorkshire × Landrace (poids initial [BW — « body weight »] $25 \pm 0,5$ kg) ont été utilisés dans un design expérimental de carré latin partiellement répliqué sur 3 périodes ($n = 7$ ou 8) et assignés à l'une de 5 diètes expérimentales. Dans chaque période, les porcs ont pu s'adapter à la diète pendant 7 jours, suivi de 5 jours de collecte totale d'urine et d'échantillonnage fécal instantané. Les diètes expérimentales comprenaient une diète à base de tourteau de maïs et soja (CON — « control » ou témoin) ou des diètes contenant de la drêche de distillerie avec solubles (DDGS — « dried distillers' grains with solubles ») ou HiPro afin de partiellement remplacer le tourteau de maïs et de soja, sans ou avec (c.-à-d. DDGS + et HiPro+) un mélange de multiples enzymes carbohydrase (inclusion de 0,05%). L'ingrédient HiPro contenait la moitié moins d'amidon (2,6 c. 5,2%; sur une base des matières sèches), 20% plus de protéines (32,5 c. 27,1%), et avait une capacité de liaison d'eau 14% plus élevée par rapport aux DDGS. Les teneurs en énergie digérable, métabolisable, et nette prévue du coproduit HiPro étaient plus élevées que les DDGS pour les porcs en croissance ($P < 0,05$), mais les enzymes de dégradation des fibres étaient inefficaces pour l'amélioration des valeurs d'énergie. La plus grande énergie (disponible) et la plus forte teneur en protéines du HiPro font de lui un ingrédient prometteur pour l'inclusion dans les diètes des porcs. [Traduit par la Rédaction]

Mots-clés : coproduits d'éthanol de maïs, teneur en énergie, propriétés physicochimiques, porcs.

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Introduction

During (corn) ethanol production, after fermentation and distillation, the centrifuge cake is combined with condensed distillers' solubles (CDS) and dried to generate the co-product dried distillers' grains with solubles (DDGS). The DDGS are commonly used in swine diets and have relatively high concentrations of both fibre and protein (Stein and Shurson 2009; Woyengo et al. 2014). Recently, pre-fermentation fractionation technologies have been implemented in some ethanol plants to improve the efficiency of ethanol extraction from corn starch (Sekhon et al. 2015). One fractionation method uses successive separation and wash steps to remove a portion of the ground corn kernel that is considered "unfermentable" (i.e., large, non-starch particles, or fibre) prior to the fermentation process using mechanical sieving technology (IGPC Ethanol Inc., Aylmer, ON, Canada; ICM Inc., Colwich, KS, USA; Rho et al. 2017). Because of these new pre-fermentation technologies, novel co-product streams are now available for inclusion in livestock diets, including, high-protein dried distillers' grain (HiPro; i.e., by drying the centrifuge cake after fractionation and fermentation) and fibre with syrup (FWS; i.e., the combination of the removed unfermentable fraction with CDS). Alternatively, (re-) combining the removed unfermentable fraction, centrifuge cake, and CDS can also generate conventional DDGS.

Of the novel co-products, HiPro is a promising ingredient for inclusion into swine diets as a portion of the fibre may be removed during the pre-fermentation fractionation process, consequently increasing the energy value of HiPro versus conventional DDGS. Information on the nutritive value of HiPro versus DDGS for feeding swine is limited with respect to energy, though HiPro has higher standardized ileal digestibility of amino acid (AA) versus conventional DDGS (Rho et al. 2017). Moreover, the addition of fibre-degrading enzymes to diets containing DDGS can improve the feeding value (Rho et al. 2018). The removal of fibre during the pre-fermentation fractionation process, may hinder the effectiveness of fibre-degrading enzymes due to reduced substrate availability. Therefore, the objectives of the current study were to assess the physiochemical properties of corn ethanol co-product streams resulting from pre-fermentation fractionation technologies, calculate the digestible (DE), metabolizable (ME), and net energy (NE) contents of HiPro and DDGS, and evaluate the effectiveness of a fibre-degrading enzyme blend for improving energy availability in growing pigs.

Materials and Methods

Ingredient sampling

Subsamples of the parent corn, HiPro, DDGS, fibre (i.e., "unfermentable" fraction), and FWS were obtained from IGPC Ethanol Inc., Aylmer, ON, Canada; corn and

fibre samples were collected on four subsequent days, and DDGS, HiPro, and FWS were collected on two subsequent days to capture representative samples of two fermentation batches.

Animals and dietary treatments

The experimental protocol was approved by the University of Guelph Animal Care Committee and followed the Canadian Council of Animal Care guidelines for the care and use of farm animals (CCAC 2009). Twelve Yorkshire × Landrace barrows [initial body weight (BW) 25 ± 0.5 kg (mean \pm standard deviation)] were used for the study. Pigs were housed individually and were offered ad libitum access to a conventional diet for 5 d prior to initiating the study. At the beginning of each experimental period, pigs were weighed to determine feed allowance ($2.8 \times$ estimated maintenance ME requirements; NRC 2012). During the experimental periods, feed was offered once per day at 0900. Pigs had ad libitum access to water via a nipple drinker.

Five experimental diets were created including (1) a corn- and soybean-meal-based diet (CON) or (2 and 3) diets containing DDGS or HiPro to replace 30% of corn and soybean meal with the test ingredient, whereas the corn:soybean meal ratio was kept constant (Velayudhan et al. 2015). One hundred grams of a multi-carbohydrase enzyme blend (1713 units xylanase, 363 units glucanase, 1339 units cellulose, 11546 units amylase, 818 units invertase, and 5922 units protease; analyzed activities per gram of enzyme blend; Canadian Bio-Systems Inc., Calgary, AB, Canada) was added per 200 kg of complete diet during diet manufacturing to create (4) DDGS+ and (5) HiPro+ (Table 2). Titanium dioxide (0.1% inclusion) was added as an indigestible marker for determination of apparent total tract digestibility (ATTD).

Experimental design and procedures

The experiment was conducted in three consecutive periods (12 pigs per period) with pigs assigned to one of five experimental diets following an incomplete repeated Latin square design (i.e., two or three replicates per experimental diet per period; $n = 7$ or 8). Pigs were housed individually and fed the experimental diets for 16 d in each period. Fecal grab sampling and complete urine collection were conducted between days 10 and 15 of each period using metabolic crates and collection buckets containing H_2SO_4 (as described by Huber et al. 2013). Briefly, for each 24 h collection period, urine was weighed, and a 5% representative sample was collected and stored at 4 °C; daily urine samples were pooled within pig and period prior to analysis. Fresh feces were collected daily, pooled within pig and period, and frozen at -20 °C until further analysis.

Sample preparation and chemical and physiochemical analyses

The co-products, diets, and fecal samples were freeze-dried [wet co-products (fibre and FWS) and feces only]

and finely ground prior to analyses. The co-products were analysed for starch (Megazyme total starch assay kit; Megazyme International Ltd., Bray, Ireland), ether extract (ANKOM XT 20 Extractor; Ankom Technology, Fairport, NY, USA), total dietary fibre [Association of Official Analytical Chemists (AOAC) 1991; method 991.43; Intertek, Saskatoon, SK, Canada], and acid detergent fiber (ADF) and neutral detergent fiber (NDF) (Ankom 200 Fiber Analyzer; Ankom Technology, Fairport, NY, USA; Van Soest et al. 1991). The co-products, diets, and fecal samples were analyzed for dry matter (DM) (AOAC 2005; method 930.15), ash (AOAC 1990; method 942.05), crude protein (CP) (also for urine; $N \times 6.25$; Foss Kjeltex 8200 Auto Distillation Unit, Fisher Scientific, Ottawa, ON, Canada; AOAC 2005; method 968.06), and gross energy (GE; using a bomb calorimeter; IKA Calorimeter System C5000; IKA Works, Inc., Wilmington, NC, USA). For urine GE, approximately 1 g of liquid urine was added to approximately 0.5 g of cellulose and freeze-dried. The urine–cellulose mixture was then analyzed using the bomb calorimeter, and GE of urine was determined by subtracting the GE contribution from a cellulose blank. The experimental diets were also analyzed for calcium and phosphorus using inductively coupled plasma mass spectrophotometry (AOAC 2005; method 985.01). Experimental diets and fecal samples were analyzed for titanium according to Myers et al. (2004) with minor adaptations (digestion for 24 h at 120 °C in 10 mL tubes and addition of H₂O₂ after precipitate settled in 100 mL volumetric flasks) and measured using a UV spectrophotometer.

The physiochemical characteristics of each co-product and corn were also measured using procedures adapted from Navarro et al. (2018a). Bulk density was determined by weighing 10 mL of each co-product. Swelling was measured by weighing 0.3 g of each co-product into a tube and then adding 10 mL of 0.9% NaCl and 0.02% NaN₃ to the sample. The tubes were then mixed and placed in a shaking water bath at 37 °C for 20 h. After allowing the sample to settle for 1 h, swelling capacity was measured by reading the volume the sample occupied. The water-binding capacity was measured by hydrating 1 g of the sample in 10 mL of distilled water for 18 h at room temperature. The sample was then centrifuged (2000g for 20 min at room temperature), the supernatant was drained, and the weights of the pellets were recorded.

Calculations

The ATTD of DM, ash, and energy in the ingredients were calculated as described by Woyengo et al. (2010). The ME contents of the ingredients were calculated by subtracting urinary energy loss from the DE contents of the ingredients. The NE of the ingredients were calculated according to the equations established by Noblet et al. (1994):

$$NE = 0.843 \times DE - 463,$$

$$NE = 0.700 \times DE + 1.61 \times \%EE + 0.48 \times \%starch \\ - 0.91 \times \%CP - 0.87 \times \%ADF,$$

$$NE = 0.870 \times ME - 442, \text{ and}$$

$$NE = 0.726 \times ME + 1.33 \times \%EE + 0.39 \times \%starch \\ - 0.62 \times \%CP - 0.83 \times \%ADF$$

where NE, DE, and ME are in kilocalories per kilogram DM, EE is ether extract in percent DM, and starch, ADF, and NDF are also in percent DM. The average of the four prediction equations was used to predict NE of DDGS and HiPro (Kim and Nyachoti 2017).

Statistical analysis

All statistical analyses were conducted using the Proc Mixed function of SAS (SAS Inst. Inc., Cary, NC, USA) with pig as the experimental unit. Dietary treatment was the fixed effect, pig within treatment was the random effect, and initial BW was used as a covariate. When appropriate, differences among individual means were assessed using the Tukey–Kramer post-hoc test. For ingredient energy values (DDGS and HiPro only), a 2 × 2 factorial analysis was completed using the Mixed procedure in SAS, with the main effects of ingredient, enzyme, and the interaction between ingredient and enzyme, pig within treatment as the random effect, and initial BW as a covariate. The interaction between ingredient and enzyme nor the main effect of enzyme were significant and, therefore, were not presented. A probability of $P < 0.05$ was considered significant, whereas $0.05 \leq P \leq 0.10$ was considered a tendency.

Results

Dry matter was comparable among corn, DDGS, and HiPro (Table 1). Gross energy was 22% and 31% greater for DDGS and HiPro, respectively, versus corn, whereas the gross energy was within 10% between DDGS and HiPro. Crude protein was 317% and 400% greater for DDGS and HiPro, respectively, versus corn, and 20% greater for HiPro versus DDGS. Ether extract was 95% and 113% greater for DDGS and HiPro, respectively, versus corn, and 23% greater for HiPro versus DDGS. Starch was 93% and 97% less for DDGS and HiPro, respectively, versus corn, and 49% less for HiPro versus DDGS. Total dietary fiber was 228% and 255% greater for DDGS and HiPro, respectively, versus corn, and within 1% between DDGS and HiPro. Neutral detergent fiber was 150% and 236% greater for DDGS and HiPro, respectively, versus corn, and 35% greater for HiPro versus DDGS. Acid detergent fiber was 122% and 372% greater for DDGS and HiPro, respectively, versus corn and 113% greater for HiPro versus DDGS. Bulk density was within 10% for corn, DDGS, and HiPro. Swelling was 46% and 50% greater for DDGS and HiPro, respectively, versus corn, but within 3% for HiPro and DDGS. Water-binding capacity was 38% and 57% greater for DDGS and HiPro,

Table 1. Analyzed chemical composition and physiochemical characterization of corn ethanol co-products (as-fed).

	Ingredient ^a					Percent difference ^b		
	Corn	DDGS	HiPro	Fibre ^c	FWS ^c	Corn vs DDGS	Corn vs HiPro	DDGS vs HiPro
Chemical composition								
Dry matter (%) ^d	86.1 ^(0.2)	89.3 ^(0.7)	88.9 ^(0.2)	100.1 ^(0.2)	94.96 ^(0.1)	3.7	3.2	0.4
Gross energy (kcal.kg ⁻¹)	3769 ^(0.4)	4600 ^(0.9)	4950 ^(2.1)	5043 ^(1.4)	4629 ^(0.2)	22.0	31.3	7.6
Crude protein (%)	6.5 ^(3.6)	27.1 ^(5.9)	32.5 ^(14.2)	18.8 ^(4.6)	19.4 ^(4.7)	316.9	400.0	19.9
Ether extract (%)	2.7 ^(25.6)	7.6 ^(2.6)	9.6 ^(7.3)	9.2 ^(4.2)	6.8 ^(6.8)	95.3	112.7	23.8
Starch (%)	67.1 ^(6.1)	4.5 ^(13.7)	2.3 ^(4.3)	10.7 ^(7.8)	7.4 ^(4.9)	93.3	96.5	48.9
Total dietary fiber (%)	11.2	36.7	39.7	55.6	37.0	227.7	254.5	0.8
NDF (%)	12.3 ^(33.9)	30.5 ^(6.5)	41.3 ^(4.0)	60.0 ^(4.1)	33.5 ^(4.3)	150.0	235.8	35.4
ADF (%)	3.2 ^(59.3)	7.1 ^(21.2)	15.1 ^(12.6)	16.0 ^(12.9)	7.6 ^(34.1)	121.9	371.9	112.7
Physiochemical attributes								
Bulk density (g.L ⁻¹)	522 ^(4.2)	507 ^(1.4)	478 ^(1.4)	288 ^(2.0)	386 ^(3.5)	2.9	8.4	5.7
Swelling (L.kg ⁻¹)	2.4 ^(4.9)	3.5 ^(0.0)	3.6 ^(2.6)	4.8 ^(5.6)	4.4 ^(1.3)	45.8	50.0	2.9
Water-binding capacity (g.g ⁻¹)	2.1 ^(2.9)	2.9 ^(2.6)	3.3 ^(0.3)	4.3 ^(0.3)	2.9 ^(3.7)	38.1	57.1	13.8

Note: DDGS, dried distillers' grains with solubles; HiPro, high-protein dried distillers' grains; FWS, fibre with syrup.

^aCorn ($n = 4$) and its ethanol co-products: DDGS ($n = 2$), HiPro ($n = 2$), fibre ($n = 4$; freeze-dried), and FWS ($n = 2$; freeze-dried).

^bPercent difference (%) between select ingredients.

^cChemical composition and physiochemical characterization of the freeze-dried product.

^dCoefficient of variation (%) among subsamples of the same ingredient collected from different batches are presented in parentheses.

respectively, versus corn, and 14% greater for HiPro versus DDGS. The variation among batches, within ingredient, was minimal (<10%) for DM, GE, and the physiochemical attributes. The variability for CP among batches of HiPro was 14%, but among all other co-products and corn was less than 10%. The variability for ether extract among batches of corn was 26% but less than 10% for all co-products. The variability for starch among batches of DDGS was 14% but less than 10% for HiPro and for corn. The fiber analyses were more variable than other chemical components. For NDF, the variability among batches of corn was 34% but less than 10% for DDGS and HiPro. The variability for ADF among batches of corn was 59%, among batches of DDGS was 21%, and among batches of HiPro was 13%. The chemical composition, physiochemical attributes, and variability of these analyses among batches for the fibre and FWS fractions are also presented in Table 1.

The analyzed values for CP in the experimental diets were generally comparable to the calculated values (Table 2). For the CON and HiPro+ diets only, analyzed CP was ~10% less than calculated. The ATTD for DM and GE were less for diets containing DDGS or HiPro versus the CON diet ($P < 0.05$; Table 3). There was no treatment effect on the ATTD for ash, but the ATTD of N was less for pigs fed the DDGS diets versus the CON diet ($P < 0.05$), whereas intermediate ATTD N values were observed for pigs fed diets containing HiPro. Nitrogen intake was greater for pigs fed diets containing HiPro versus those fed diets containing DDGS or the

CON diet ($P < 0.05$) and greater for pigs fed diets containing DDGS versus the CON diet ($P < 0.05$). Nitrogen excretion in feces was greater for pigs fed diets containing DDGS or HiPro versus the CON diet ($P < 0.05$). Nitrogen excretion in urine was greater for pigs fed the HiPro+ diet versus the DDGS-containing diets and the CON diet ($P < 0.05$) and greater for pigs fed diets containing DDGS versus the CON diet ($P < 0.05$); pigs fed the HiPro diet had intermediate N excretion in urine versus those fed the HiPro+ diet and those fed the DDGS diets. Nitrogen retention was greater for pigs fed the HiPro versus the DDGS+ diet ($P < 0.05$) and intermediate for pigs fed all other dietary treatments. The apparent efficiency of N retention was less for pigs fed the DDGS+, HiPro, and HiPro+ diets versus pigs fed the CON diet ($P < 0.05$); intermediate N retention efficiency was observed for pigs fed the DDGS diet.

The DE content for the DDGS+ diet was less than for the HiPro, HiPro+, or CON diets ($P < 0.05$) and was less for the DDGS diet than for the HiPro diet ($P < 0.05$); intermediate DE contents were determined for the HiPro+ and CON diets (Table 4). The ME contents for the DDGS diets were less than for the CON diet ($P < 0.05$); intermediate ME contents were determined for the HiPro diets. The predicted NE content for the DDGS+ diet was less than for the CON or HiPro diets ($P < 0.05$); an intermediate predicted NE content was determined for the DDGS diet. The efficiencies for the conversion of ME to NE and DE to NE were not affected by dietary treatment.

Table 2. Ingredient and nutrient composition of a conventional corn- and soybean-meal-based diet or diets containing corn ethanol co-products, with or without a multi-carbohydrase enzyme blend (as-fed).

Item	Dietary treatment ^a				
	CON	DDGS	DDGS+	HiPro	HiPro+
Ingredient composition (%)					
Corn	65.47	44.89	44.87	44.89	44.87
Soybean meal	29.96	20.54	20.53	20.54	20.53
DDGS	—	30.00	29.98	—	—
HiPro	—	—	—	30.00	29.98
Enzyme blend ^b	—	—	0.05	—	0.05
Fat, animal-vegetable blend	0.92	0.92	0.92	0.92	0.92
Vitamin and mineral premix ^c	0.60	0.60	0.60	0.60	0.60
L-Lys-HCl	0.24	0.24	0.24	0.24	0.24
Limestone	1.06	1.06	1.06	1.06	1.06
Monocalcium phosphate	1.15	1.15	1.15	1.15	1.15
Sodium chloride	0.50	0.50	0.50	0.50	0.50
Titanium dioxide	0.10	0.10	0.10	0.10	0.10
Calculated nutrient composition					
Crude protein (%)	20.0	22.0	22.0	27.4	27.4
ME (kcal·kg ⁻¹)	3300	3310	3310	3411	3411
Standardized ileal digestible Lys (%)	1.10	0.98	0.98	1.07	1.07
Analyzed nutrient composition					
Dry matter (%)	87.4	88.1	88.1	87.8	87.8
Crude protein (%)	18.0	20.9	21.5	25.3	24.2
Ca (%)	0.74	0.71	0.74	0.76	0.64
P (%)	0.55	0.75	0.72	0.68	0.60
Xylanase (units·kg ⁻¹)	81	65	1094	34	1020

Note: DDGS, dried distillers' grains with solubles; HiPro, high-protein dried distillers' grains; FWS, fibre with syrup.

^aConventional corn- and soybean-meal-based diet (CON) or diets containing the corn ethanol co-products DDGS or HiPro to partially replace corn and soybean meal, with (+) or without a multi-carbohydrase enzyme blend.

^bAbout 100 g of multi-carbohydrase enzyme blend was added per 200 kg of complete diet during manufacturing. Blend of xylanase, glucanase, cellulase, amylase, invertase, and protease; analyzed activities units per gram enzyme blend: 1713 (1680; analyzed), 363, 1339, 11546, 818, and 5922, respectively.

^cSupplied per kilogram of complete diet: vitamin A, 10 000 IU as retinyl acetate (2.5 mg) and retinylpalmitate (1.7 mg); vitamin D₃, 1000 IU as cholecalciferol; vitamin E, 56 IU as DL- α -tocopherol acetate (44 mg); vitamin K, 2.5 mg as menadione; choline, 500 mg; pantothenic acid, 15 mg; riboflavin, 5 mg; folic acid, 2 mg; niacin, 25 mg; thiamine, 1.5 mg; vitamin B₆, 1.5 mg; biotin, 0.2 mg; vitamin B₁₂, 0.025 mg; Se, 0.3 mg from Na₂SeO₃; Cu, 15 mg from CuSO₄·5H₂O; Zn, 104 mg from ZnO; Fe, 100 mg from FeSO₄; Mn, 19 mg from MnO₂; and I, 0.3 mg from KI (DSM Nutritional Products Canada Inc., Ayr, ON, Canada).

The energy digestibility for the HiPro ingredient tended to be greater than for the DDGS ingredient ($P = 0.058$; Table 5) and the DE content for the HiPro ingredient was greater than for the DDGS ingredient ($P < 0.01$). The estimated energy lost in urine tended to be greater for pigs fed the HiPro ingredient than for those fed the DDGS ingredient ($P = 0.095$), but the ME content was greater for HiPro than DDGS ($P < 0.05$). The predicted NE for the HiPro ingredient was greater than for the DDGS ingredient and the efficiency of converting ME into NE tended to be greater for the HiPro versus the

DDGS ingredient ($P = 0.059$); the efficiency of converting DE into NE was not affected by ingredient.

Discussion

The aims of the current study were to assess the physiochemical properties of corn ethanol co-product streams resulting from pre-fermentation fractionation technologies and to determine the energy availability of HiPro and DDGS for growing pigs, with and without the addition of feed-grade fibre-degrading enzymes. It was found that the fractionation process improved the

Table 3. Apparent total tract nutrient digestibility (ATTD) and nitrogen balance for growing pigs fed a conventional corn- and soybean-meal-based diet or diets containing corn ethanol co-products, with or without a multi-carbohydrase enzyme blend.

Item	Dietary treatment ^a					SEM	P value
	CON	DDGS	DDGS+	HiPro	HiPro+		
No.	7	7	8	7	7	—	—
ATTD (%)							
DM	87.4a	80.4b	80.3b	82.5b	82.1b	1.0	<0.0001
Ash	62.4	63.4	63.6	62.0	62.7	2.1	0.911
GE	86.2a	79.7b	79.2b	81.6b	80.8b	1.1	<0.0001
N	84.1a	80.2b	80.7b	82.1ab	81.5ab	1.4	0.048
Nitrogen balance							
N intake (g·d ⁻¹)	34.2c	37.2b	36.8b	41.9a	41.4a	0.5	<0.001
N output in feces (g·d ⁻¹)	5.2b	6.9a	7.2a	7.4a	7.3a	0.5	0.002
N excretion in urine (g·d ⁻¹)	8.5c	10.7b	11.0b	12.6ab	13.3a	0.7	<0.001
N retained (g·d ⁻¹)	20.5ab	19.6ab	18.5b	21.9a	20.7ab	0.9	0.007
N retained (%)	59.5a	52.9ab	50.4b	52.3b	50.1b	2.2	0.001

Note: DDGS, dried distillers' grains with solubles; HiPro, high-protein dried distillers' grains; SEM, standard error of the means. Means within a row with different lowercase letters differ ($P < 0.05$).

^aConventional corn- and soybean meal-based diet (CON) or diets containing the corn ethanol co-products DDGS or HiPro to partially replace corn and soybean meal, with (+) or without a multi-carbohydrase enzyme blend.

Table 4. Energy values for growing pigs fed a conventional corn- and soybean-meal-based diet or diets containing corn ethanol co-products, with or without a multi-carbohydrase enzyme blend (dry matter basis).

	Dietary treatment ^a					SEM	P value
	CON	DDGS	DDGS+	HiPro	HiPro+		
No.	7	7	8	7	7	—	—
Energy value (kcal·kg⁻¹)							
DE	3825ab	3700bc	3674c	3856a	3830ab	49	0.001
ME	3562a	3386b	3386b	3519ab	3475ab	64	0.022
NE _{1,3} ^b	2705a	2592ab	2561b	2704a	2674a	43	0.003
Efficiencies of NE							
NE _{1,3} :ME	0.76	0.76	0.76	0.76	0.77	0.004	0.139
NE _{1,3} :DE	0.70	0.70	0.70	0.70	0.70	0.004	0.643

Note: Means within a row with different superscripts differ ($P < 0.05$). DDGS, dried distillers' grains with solubles; HiPro, high-protein dried distillers' grains; SEM, standard error of the means.

^aConventional corn- and soybean meal-based diet (CON) or diets containing the corn ethanol co-products DDGS or HiPro to partially replace corn and soybean meal, with (+) or without a multi-carbohydrase enzyme blend.

^bAverage of NE prediction equations: $NE_1 = 0.843 \times DE - 463$ and $NE_3 = 0.870 \times ME - 442$.

efficacy of starch fermentation for ethanol production because less starch was present in the HiPro versus the DDGS co-product, though it is noted that the removed fibre fraction also contained some starch. As a result, the other chemical components (i.e., CP, ether extract, NDF, and ADF) were more concentrated in the HiPro co-product, which led to greater DE, ME, and predicted NE for growing pigs, as well as a higher standardized ileal digestibility of AA versus DDGS (Rho et al. 2017).

Therefore, in terms of both energy and AA, HiPro has a higher feeding value than DDGS for growing pigs, but the fibre-degrading enzyme blend used in the current study was not effective at improving DE, ME, or predicted NE of either HiPro or DDGS. Moreover, due to the high moisture contents of the remaining co-products (i.e., fibre and FWS), it is unlikely that these co-products will be routinely incorporated into swine feeding programs due to the logistics of transport and high

Table 5. Energy values for growing pigs fed dried distillers' grains with solubles (DDGS) or high-protein dried distillers' grains (HiPro) (dry matter basis).

	Ingredient ^a			P value ^b
	DDGS	HiPro	SEM	
Digestible energy				
Digestibility (%)	65.3	70.6	2.5	0.058
DE (kcal·kg ⁻¹)	3896	4405	123.2	0.001
Metabolizable energy				
Energy lost in urine (kcal·kg ⁻¹)	358	485	70.0	0.095
ME (kcal·kg ⁻¹)	3494	3872	153.8	0.030
Predicted net energy^c				
NE ₁₋₄	2663	3010	105.8	0.007
NE ₁₋₄ :ME ratio	0.76	0.78	0.01	0.059
NE ₁₋₄ :DE ratio	0.68	0.68	0.01	0.994

Note: SEM, standard error of the means.

^aCorn ethanol co-products DDGS or HiPro to partially replace corn and soybean meal.

^bP value for the main effect of ingredient; the P values for the main effect of enzyme addition and the interactive effect of ingredient and enzyme addition were not significant and are not presented.

^cNE₁ = 0.843 × DE – 463

NE₂ = 0.700 × DE + 1.61 × % ether extract + 0.48 × % starch – 0.91 × % CP – 0.87 × % ADF

NE₃ = 0.870 × ME – 442

NE₄ = 0.726 × ME + 1.33 × % ether extract + 0.39 × % starch – 0.62 × % CP – 0.83 × % ADF

NE₁₋₄ = average of NE₁ to NE₄.

potential for spoilage. The exception could be for those producers located near corn-ethanol plants with liquid feeding systems. Due to the high-fibre contents in the (freeze-dried) fibre and FWS co-product streams, it is unlikely these would have a high feeding value for young pigs but could be used for pigs with more mature gastrointestinal tracts (e.g., gestating sows or finishing pigs).

In the current study, HiPro had greater CP contents compared with the conventional DDGS, but it was lower than the CP contents of HiPro collected previously from the same ethanol plant (i.e., Rho et al. 2017) and others (e.g., Jacela et al. 2010; Anderson et al. 2012; Cristobal et al. 2020). Because the starch contents of both HiPro and conventional DDGS were also higher in the current study, it is postulated that the starch fermentation was not as efficient as during previous sampling periods at the same plant, despite little variation in the chemical profile of co-products from two or four subsequent fermentation batches. Regardless, improvement in CP contents of HiPro versus DDGS make it a promising protein source for swine diets. Indeed, HiPro has been used as a partial replacement for soybean meal (Widmer et al. 2008), though supplementation with crystalline AA (i.e., specifically Lys, Thr, and Trp) or a complementary protein source is required to ensure a sufficient supply of essential AA if completely replacing soybean meal with HiPro (Kim et al. 2009).

In the current study, the HiPro co-product had slightly greater GE, but also greater DE, ME, and predicted NE

than DDGS when fed to growing pigs, which is consistent with observations for HiPro and DDGS co-products from ethanol plants in the United States (Anderson et al. 2012; Cristobal et al. 2020). As indicated above, this could, in part, be due to the greater concentration of ether extract because fat is easily digestible and has a low-heat increment of feeding (Stahly 1984). An improvement in fibre solubility and fermentability may, however, also contribute to improved energy availability for HiPro versus DDGS for growing pigs (Robinson et al. 2008). Indeed, increased solubility of fibres can be achieved via the processing of corn during ethanol production. Specifically, grinding, heating, and fermentation may modify the structure of dietary fibre making it more easily fermentable in the hindgut of the pig versus the fibre present in the parent corn, which is typically highly insoluble and resistant to fermentation (Urriola et al. 2010). The HiPro co-product had greater NDF and ADF contents, slightly lower bulk density, and a higher water-binding capacity compared with DDGS and lower bulk density compared HiPro from other ethanol plants in the United States (i.e., Anderson et al. 2012). A lower bulk density implies greater fibre content, which matches with the NDF and ADF values; however, it does not specify the accessibility or fermentability of the fibre fraction (Navarro et al. 2018b). The water-binding capacity indicates the proportion of the fibre fraction that may be solubilized and fermented by the pig because it correlates to the ATTD of total dietary fibre and non-starch polysaccharides (Navarro et al. 2018b). Greater

swelling and water-binding capacities, as observed for the HiPro co-product, suggest a greater abundance of soluble fibres, which could yield additional energy in the form of volatile fatty acids during fermentation in the hindgut of the pig (as reviewed by [Agyekum and Nyachoti 2017](#)). Therefore, in addition to the greater ether extract, the fibre fraction may be more fermentable in the HiPro co-product, which could explain improved energy availability for growing pigs.

Another method commonly implemented to further improve fibre digestibility is that of exogenous feed-grade enzymes, which help degrade compounds inaccessible by the pig's endogenous enzymes (as reviewed by [Kerr and Shurson 2013](#)). In previous studies, the supplementation of multi-carbohydrase and protease enzymes improved the energy and AA digestibilities of various high-fibre ingredients (e.g., [Kim et al. 2003](#); [Jha and Berrococo 2015](#)). In the current study, however, the enzymes included in the diets were not efficacious at improving the digestible energy of either the HiPro or DDGS co-products. It is possible that the multi-carbohydrase enzyme used in the current study either (a) did not target the appropriate fibre components, (b) the target fibre components of this enzyme blend were not present in great enough concentrations in either the HiPro or DDGS co-products to detect differences in energy digestibility, or (c) the enzyme blend was not included at a high enough level to be effective ([Pedersen et al. 2016](#)). Furthermore, the pigs used in the current study were from a high-health research herd with, assumedly, healthy gastrointestinal tracts that were effective at fermenting dietary fibres. Thus, it is possible that the added benefit of including an exogenous fibre-degrading enzyme blend was undetectable.

In conclusion, the pre-fraction process resulted in a HiPro co-product with less starch and, consequently, greater concentrations of protein, ether extract, and fibre versus DDGS. Therefore, the pre-fractionation process improved the fermentation efficiency of starch to produce ethanol, though it is noted that the removed fibre fraction also contained some starch. As a result, when fed to growing pigs, the HiPro co-product had improved DE, ME, and predicted NE values versus DDGS, making it a higher value feed ingredient compared with DDGS. However, the addition of multi-carbohydrase enzymes to either HiPro- or DDGS-containing diets was ineffective at improving energy digestibility. Therefore, HiPro could be used to supply both energy and AA in practical swine diets, though the optimal inclusion level should be determined based on economic and feed efficiency outcomes in individual commercial settings.

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