JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Article

pubs.acs.org/JAFC

Evaluation of the Feed Value for Ruminants of Blends of Corn and Wheat Distillers Dried Grains

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ABSTRACT: Recently, biofuel processing has produced a large amount of biofuel coproducts. However, to date, there is little information on the metabolic characteristics of proteins and energy in biofuel coproduct-based rations. The objective of this study was to study the metabolic characteristics of proteins and energy in biofuel coproduct-based rations in terms of (1) chemical and nutrient profiles, (2) protein and carbohydrate subfraction associated with various degradation rate, (3) rumen and intestinal degradation and digestion kinetics, and (4) metabolic characteristics of proteins. Two sources of grain corn were mixed with two sources of biofuel coproducts (wheat-based dried distillers grains with solubles, wDDGS) in ratios of 100:0, 75:25, 50:50, and 25:75%. The study revealed that increasing the biofuel coproduct inclusion level increased most of the nutritional components linearly ($P < 0.05$) except starch, which linearly decreased. With increasing biofuel coproduct inclusion level, the rumen degradation rate and the effective degradability of organic matter were not affected ($P > 0.05$), but the effective degradability of starch was decreased ($P < 0.05$). Effective degradation of crude protein and neutral detergent fiber as well as predicted truly absorbed protein supply in the small intestine and degraded protein balance were increased ($P < 0.05$). In conclusion, the inclusion of the biofuel coproduct up to 25−50% in rations improved potential nitrogen and energy synchronization for microbial growth and improved truly absorbable protein supply to the small intestine, without altering energy value.

KEYWORDS: *metabolic characteristics of proteins, nutrient variation and availability, bioethanol coproducts, modeling nutrient supply*

INTRODUCTION

Corn grain (*Zea mays* L.) is used by the western Canadian feedlot industry as an alternative grain source when the cost of barley grain is high.[1] Traditionally, most Canadian feedlot producers have used little or no protein supplementation for barley-based diets fed to cattle weighing >350 kg.[1] There are important nutritional differences between barley and corn that must be considered when in the formulation of diets for feedlot cattle. Corn contains more starch than barley, and consequently metabolizable energy (ME) is ∼7% higher in corn than in barley,[2] although the difference in energy content will depend on the manner in which the grains are processed.[3] However, corn is considerably lower in crude protein (CP; 9.8 vs 13.2% of dry matter (DM)) and degradable intake protein (DIP; 4.4 vs 8.8% of DM) than barley.[2] Therefore, corn-based diets fed to finishing cattle in the United States are supplemented to contain >12.5% CP (DM basis).[4] The amount and source of crude protein (CP) supplementation required in corn-based diets in western Canada are not clear. Koenig and Beauchemin[5] reported similar growth rates for finishing feedlot cattle fed barley or corn grain/silage in iso-nitrogenous diets (13% CP). However, feeding corn grain and silage without protein supplements (diet 10% CP) substantially lowered the growth rate of feedlot cattle due to reduced dry matter intake (DMI).[5] Ruminal N limitation reduces microbial growth, which leads to a reduction in feed intake[6] as a result of reduced ruminal digestion of feed and reduced rate of passage.[7]

Others studies[5] found that supplementing corn diets with either urea or a combination of canola meal and urea resulted in similar growth rates in feedlot cattle, but the feed/gain ratio was only improved using canola meal. Recently, wheat-based dried distillers grains with solubles (wDDGS) is readily available in western Canada due to the expansion of bioethanol production.[8] Wheat DDGS is generated by drying whole stillage that remains after ethanol has been distilled off.[9] Wheat is the primary cereal grain grown in western Canada and therefore used as the main feedstock for bioethanol production.[8] Depending on the type of DDGS and processing, crude protein (CP) content can range from 28 to 44% DM[8−10] with high rumen undegraded protein (RUP).[8,11,12] Energy values in wDDGS are similar to those in wheat and corn.[8] We hypothesized that feeding corn in combination with wDDGS will improve availability of nutrients to the animal (i.e.,

Received: December 18, 2012
Revised: April 14, 2013
Accepted: April 14, 2013
Published: April 14, 2013

metabolizable protein) and synchronize protein to energy fermentation in the rumen. The objective of this study was to determine effects of substituting corn grain at graded levels by wDDGS in the diet on the metabolic characteristics of proteins and various nutritive value for ruminants in terms of detailed (1) nutritional profiles, (2) energy values, (3) protein and carbohydrate subfractions, (4) in situ rumen degradation kinetics, (5) protein to energy degradation ratios, and (6) absorbable protein supply to the intestine.

■ MATERIALS AND METHODS

Sampling. Two sources of corn samples were used for this experiment and mixed with two wDDGS batch samples collected from two bioethanol plants located in Saskatchewan, Canada. Approximately 6 kg of wDDGS per bioethanol plant was obtained and stored in paper bags under dry and cool conditions (~ −4 °C) prior to analysis. One corn sample was mixed with one batch wDDGS and the other corn sample with the other wDDGS batch in ratios of 100:0, 75:25, 50:50, and 25:75 (%DM basis; denoted C0, C25, C50, and C75, respectively; n = 2 for each mixture). For chemical analysis, samples were milled to pass through a 1 mm screen in a Retsch ZM-1 (Brinkmann Instruments Ltd., Ontario, Canada), and a subsample (~10 g) was further milled to pass through a 0.5 mm screen for starch analysis. Before in situ rumen incubations, to reflect commercial feeding practices the corn samples were coarsely rolled through a 0.203 mm gap Seven Grain Mill (Apollo Machine and Products Ltd., Saskatoon, SK, Canada), and wDDGS samples remained unprocessed as received from the ethanol plant where they had been processed through a 6 mm screen before ethanol fermentation. Samples were stored in airtight vials at room temperature prior to subsequent analysis.

Chemical Analysis. Dry matter (DM; AOAC method 930.15), ash (AOAC method 942.05), crude fat (AOAC method 920.02), and crude protein (CP; AOAC method 984.13) contents were analyzed according to established procedures.[13] Crude protein was determined using a Leco FP-2000 nitrogen analyzer (Leco Corp., St. Joseph, MI, USA). Acid detergent fiber (ADF), neutral detergent fiber with heat-stable α-amylase (NDF), and acid detergent lignin (ADL) were analyzed according to the procedures of Van Soest et al.[14] using a fiber analyzer (ANKOM Technology Corp., Fairport, NY, USA). Samples were analyzed for total starch using the Total Starch Assay Kit (Megazyme International Ltd., Wicklow, Ireland).[15] Total soluble carbohydrate (sugar) was determined after extraction in 80% ethanol for 4 h followed by measurement of the absorbance at 490 nm in a Ultrospec III spectrophotometer (Pharmacia LKB, Cambridge, UK) using the phenol−sulfuric acid assay according to Hall.[16] Nonprotein nitrogen (NPN) was determined after precipitation of true protein in the filtrate with sodium tungstate ($Na_2WO_4{\cdot}2H_2O$; final concentration = 10%) and determined as the difference between total N and the Kjeldahl-N content of the residue after filtration.[17] The amount of CP associated with NDF (NDICP) and ADF (ADICP) was determined by analyzing the Kjeldahl-N contents of NDF and ADF.[17] The reported NDF and ADF values were adjusted for NDICP and ADICP, respectively, but not for ash. Total soluble crude protein (SCP) was determined by incubating the sample with bicarbonate−phosphate buffer and filtration through Whatman no. 54 filter paper followed by Kjeldahl-N analysis as described by Roe et al.[18] Total carbohydrates (CHO), true protein, hemicelluloses, cellulose, and nonstructural carbohydrate (NSC) were calculated according to NRC.[19] All samples were analyzed in duplicates and repeated if the error exceeded 5%. Total digestible nutrient ($TDN_{1\times}$), net energy for maintenance (NE_m), and net energy for growth (NE_g) were calculated according to NRC beef,[2] and net energy for lactation was calculated according to NRC dairy.[19]

Fractionation of Protein and Carbohydrates. Crude protein and carbohydrates were partitioned according to the Cornell Net Carbohydrate Protein System.[20] The CP fractions in this system are characterized into a directly available (soluble) protein (PA; i.e., NPN), a true potentially degradable protein (PB; i.e., CP-NPN-ADICP), and an unavailable (undegradable) protein (PC; i.e., ADICP). The PB fraction was further divided into rapidly degradable (PB1; i.e., SCP-NPN), intermediately (medium) degradable (PB2; i.e., PB-PB1-PB3), and slowly degradable (PB3; i.e., NDICP-ADICP) true protein. The relative rumen degradation rates of the five protein fractions were described by Sniffen et al.[20] as infinity for PA, 1.20−4.00/h for PB1, 0.03−0.16/h for PB2, and 0.0006−0.0055/h for PB3. The PC fraction was considered to be undegradable. Carbohydrates were fractioned into a soluble fraction (CA; composed of soluble sugars with a rapid degradation rate of 3.00/h), a rapidly degradable fraction (CB1; composed of starch and pectin with an intermediate degradation rate of 0.20−0.50/h), a slowly degradable fraction (CB2; composed of available cell walls with a slow degradation rate of 0.02−0.10/h), and an undegradable fraction (CC; composed of unavailable cell walls).[20,21]

In Situ Rumen Incubation Technique. Rumen degradation characteristics were determined using the in situ method as described previously.[22,23] Two dry Holstein Friesian cows, fitted with a flexible rumen cannula with an internal diameter of 10 cm, were used for measuring rumen degradation characteristics. The cows were housed in pens of approximately 6 m × 9 m in the Livestock Research Building at the University of Saskatchewan (Saskatoon, Canada) during in situ rumen incubations.[21] The cows were fed a 50:50 barley silage (26.8% DM) to concentrate diet (containing barley, wheat, oats, dairy supplement pellets, and molasses) according to the NRC maintenance requirements.[19] The cows were fed half of the ration at 8:00 a.m. and the other half at 4:00 p.m. Water was available ad libitum. The animal trial was approved by the Animal Care Committee of the University of Saskatchewan (Animal Use Protocol 19910012), and animals were cared for according to the guidelines of the Canadian Council on Animal Care.[24] Before incubations, 7 g of an individual sample was weighed into a preweighed and numbered 10 × 20 cm Nitex 03-41/31 monofilament open mesh fabric nylon bags (Screentec Corp., Mississagua, ON, Canada) with a pore size of approximately 40 μm. These bags were tied about 2 cm below the top, allowing a ratio of sample size to bag surface area of 28 mg/cm^2. Samples were incubated in the rumen for 0, 2, 4, 8, 12, 36, and 72 h according to the "gradual addition/all out" schedule.[21,25] The numbers of bags for each treatment time and each incubation time were 4, 4, 4, 6, 6, 8, and 8 bags for 0, 2, 4, 8, 12, 36, and 72 h, respectively. Bags were held in the ventral sac by placing them in a polyester mesh lingerie bag, which was anchored by a plastic bottle filled with sand. All treatments for each incubation time were randomly allocated to the rumen of either cow. The maximum number of bags in the rumen at any given time was 30. After incubation, the bags were removed from the rumen and rinsed under a cold stream of tap water to remove excess ruminal contents. The bags were then washed with tap water and subsequently dried at 55 °C for 48 h. The 0 h samples were not placed in the rumen but were treated to the same soaking and rinsing procedure as described for rumen-incubated samples.[21] Dry samples were stored in a refrigerated room (4 °C) until analysis. The residues were pooled according to feed combination, incubation time, and run and analyzed for DM, organic matter, CP, neutral detergent fiber, and starch, as described previously.[21] Dry matter, organic matter, CP, neutral detergent fiber, and starch disappearances were calculated by the difference between original and residue amounts after ruminal incubation. In vitro intestinal digestibility of the rumen undegraded protein fraction of each sample was determined by incubation of 16 h in situ residues with pepsin and pancreatin as described by Calsamiglia and Stern.[26]

Rumen Degradation Kinetics. The first-order kinetic degradation model described the rumen degradation characteristics of DM, CP, neutral detergent fiber, and starch, calculated using the NLIN procedure of SAS with iterative least-squares regression (Gauss−Newton method). The first-order kinetics equations used were[27,28]

$$R(t) = U + D \times \exp(-K_d \times (t - T_0)) \text{ for OM, NDF, and CP}$$

$$R(t) = D \times \exp(-K_d \times t) \text{ for starch}$$

dx.doi.org/10.1021/jf400595n | J. Agric. Food Chem. 2013, 61, 4387−4395

Table 1. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Chemical Profiles and Energy Values

	biofuel coproduct-based feed[a]					P value[b]
item	C0	C25	C50	C75	SEM	linear
basic chemical profile (g/kg DM)						
ash	14.0d	23.8c	34.8b	47.0a	0.76	0.001
crude fat	32.8b	38.3ab	41.8ab	46.3a	2.45	0.002
structural carbohydrate profile (g/kg DM)						
neutral detergent fiber	138.3d	182.8c	219.5b	256.0a	6.18	0.001
acid detergent fiber	52.8d	85.8c	129.0b	168.5a	2.79	0.001
acid detergent lignin	8.5d	18.3c	27.5b	43.0a	1.33	0.001
hemicellulose	110.3c	161.3b	199.3ab	246.5a	12.10	0.001
cellulose	44.3d	67.5c	101.5b	125.5a	2.31	0.001
nonstructural carbohydrate profile (g/kg DM)						
starch	750.5a	564.8b	379.8c	186.5d	11.15	0.001
sugar	11.8d	23.0c	37.0b	62.5a	2.46	0.001
crude protein profile (g/kg CP)						
CP (g/kg DM)	89.0d	166.0c	244.0b	331.8a	6.73	0.001
soluble CP (SCP)	306.3	343.0	361.0	385.0	23.42	0.032
non-protein N (NPN; g/kg SCP)	591.5	788.5	820.5	840.8	90.06	0.126
neutral detergent insoluble CP	272.3	388.8	450.0	485.5	53.27	0.012
acid detergent insoluble CP	91.8b	130.3ab	170.3a	177.3a	13.45	0.001
total digestible nutrient at maintenance level (g/kg DM)						
total digestible nutrients$_{1X}$	889.1a	848.3b	805.8c	755.8d	4.88	0.001
energy values for dairy cattle (Mcal/kg DM)[19]						
digestible energy for production	3.5a	3.5a	3.4b	3.3c	0.02	0.001
metabolizable energy for production	3.1a	3.1ab	3.0b	2.9c	0.02	0.001
net energy for lactation	2.0a	2.0ab	1.9b	1.9c	0.01	0.001
energy values for beef cattle[b] (Mcal/kg DM)						
net energy for maintenance	2.2a	2.1a	2.1b	2.0c	0.01	0.001
net energy for gain	1.5a	1.4a	1.4b	1.3c	0.01	0.001

[a]Corn and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]There was no quadratic or cubic effect ($P > 0.05$).

where $R(t)$ stands for residue of the incubated material after t h of the rumen incubation (g/kg), U and D stand for the undegradable and potentially degradable fractions, respectively (g/k), T_0 is lag time (h), and K_d is the degradation rate of D (/h).

The effective degradability (ED) values were calculated as

$$\text{EDCP (or EDOM, EDNDF or EDST) (g/kg)} = S + D \times K_d/(K_p + K_d)$$

where soluble fractions (S) are in g/kg and a passage rate (K_p) of 0.06/h was assumed.[28] The rumen undegradable feed protein (RUP) value was calculated as

$$\text{RUP (g/kg DM)} = 1.11 \times (\text{CP (g/kg DM)} \times \text{EDCP (g/kg)})$$

The rumen undegradable feed starch (RUST) values were calculated as

$$\text{RUST (g/kg)} = D \times K_p/(K_p + K_d) + 0.1 \times S$$

where K_p of 0.06/h was adapted and the factor 0.1 denotes the assumption that for starch 100 g/kg of soluble fraction (S) escapes rumen fermentation.[28]

Ratio of Rumen Available Protein to Organic Matter and Carbohydrates. The ratios of rumen available protein to energy should be balanced and synchronized for optimal microbial synthesis.[28] On the basis of measured characteristics, we calculated (a) hourly and (b) total rumen degradation ratios of N and energy (CHO, OM). The effective degradation of N, OM, and CHO was calculated hourly as outlined by Sinclair et al.[29] as

$$\text{hourly ED (g/kg)} = S + [(D \times K_d)/(K_p + K_d)] \times [1 - e^{-t \times (K_d + K_p)}]$$

The difference in cumulative amounts degraded between successive hours was regarded as the quantity degraded per hour, and hourly ratios between N and OM (or CHO) were calculated.

On the basis of measured parameters, the following total rumen degradation characteristics ratios were also calculated:[30] (1) EN/ECHO or EOM (g/kg) = insoluble rumen available N/CHO or OM; (2) SN/SCHO or SOM (g/kg) = soluble rumen N/CHO or OM; and (3) FN/FCHO or FOM (g/kg) = total rumen available (effective degradable) N/CHO or OM. The optimal ratio between the effective degradability of N and energy to achieve maximum microbial synthesis and minimize N loss is ∼25 g N/kg OM truly digested in rumen[30] or ∼32 g N/kg CHO truly digested in rumen,[29,30] which were used as benchmarks to interpret the results of the current study.

Intestinal Protein Supply. The potential protein supply from the feed mixture in terms of truly absorbable rumen synthesized microbial protein in the small intestine (AMCP, g/kg of DM), truly absorbable rumen undegradable feed protein in the small intestine (ARUP, g/kg of DM), total truly absorbable protein in the small intestine (DVE in DVE/OEB system; MP in NRC model), and rumen degradable protein balance (OEB in DVE/OEB system, PBD in NRC model) were calculated according to the DVE/OEB system[28] and the NRC-2001 model.[19] Details of two models including principles, similarity, and differences were described previously.[32]

Statistical Analysis. All data were analyzed using the MIXED procedure of SAS 9.2.[33] The model used for the analysis was $Y_{ij} = \mu + T_i + e_{ij}$, where Y_{ij} is the observation of the dependent variable ij, μ is the population mean for the variable, T_i is the fixed effect of the

Table 2. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Protein and Carbohydrate Subfractions

	biofuel coproduct-based feed[a]					P value[b]
item	C0	C25	C50	C75	SEM	linear
protein subfractions (g/kg CP)[20]						
PA (soluble)	161.8b	271.3a	297.2a	308.1a	22.50	0.001
PB1 (rapidly degradable)	144.4	71.6	63.7	49.5	35.62	0.001
PB2 (medium degradable)	421.4a	268.2ab	189.0ab	129.6b	62.45	0.009
PB3 (slowly degradable)	180.6	258.3	280.0	308.2	42.63	0.049
PC (undegradable)	91.9b	130.6ab	170.2a	177.3a	13.40	0.001
true protein	746.4a	598.1b	532.7c	487.3c	14.45	0.001
carbohydrate subfractions (g/kg CHO)[20]						
total CHO (g/kg DM)	864.4a	771.9b	679.4c	575.7d	5.34	0.001
nonstructural CHO	839.7a	763.4b	676.8c	555.2d	7.32	0.001
CA (soluble)	0.4c	31.4c	117.6b	231.2a	12.19	0.001
CB1 (rapidly degradable)	839.3a	732.0b	559.2c	324.1d	14.29	0.001
CB2 (slowly degradable)	136.6d	179.7c	225.9b	264.6a	5.91	0.001
CC (undegradable)	23.8d	57.0c	97.3b	180.2a	4.40	0.001

[a]Corn and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]There was no quadratic or cubic effect ($P > 0.05$).

Table 3. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) Inclusion on Organic Matter and Protein Rumen Degradation Characteristics

	biofuel coproduct-based feed[a]					P value[b]
item	C0	C25	C50	C75	SEM	linear
rumen degradation kinetics of organic matter (g/kg OM)						
lag time (/h)	0.4a	0.0b	0.0b	0.0b	0.04	0.002
soluble OM (S_{OM})	67.4	118.3	177.8	229.4	56.65	0.098
potentially degradable OM (D_{OM})	841.2	795.0	758.3	655.8	66.16	0.116
undegradable OM (U_{OM})	91.3	86.7	64.0	114.8	19.84	0.620
degradation rate (K_d; /h)	0.063	0.060	0.050	0.061	0.0119	0.781
rumen undegradable-OM (RUP; g/kg DM)	495.4	486.1	465.2	424.8	63.34	0.458
effective degradable-OM (EDOM)	497.7	502.0	518.2	554.8	64.56	0.978
effective degradable-OM (g/kg DM)	490.6	490.0	500.1	529.0	62.10	0.675
rumen degradation kinetics of crude protein (g/kg CP)						
soluble CP (S_{CP})	44.1	203.8	281.2	323.7	87.43	0.079
potentially degradable CP (D_{CP})	845.0	769.7	676.9	626.5	134.80	0.282
undegradable CP (U_{CP})	111.0	26.5	41.9	49.8	58.10	0.553
degradation rate (K_d; /h)	0.039	0.041	0.051	0.058	0.0157	0.393
rumen undegradable CP (RUP: g/kg DM)	49.8	78.5	100.8	128.5	16.54	0.025
effective degradable-CP	380.1	492.3	579.5	605.9	89.71	0.130
effective degradable-CP (g/kg DM)	30.6b	78.0ab	141.5ab	202.9a	29.37	0.012

[a]Corn and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]There was no quadratic or cubic effect ($P > 0.05$).

inclusion of the wDDGS in feed mixtures, and e_{ij} is the random error associated with the observation *ij*. When a significant difference was detected ($P < 0.05$), means were separated using the Tukey–Kramer post hoc test. Orthogonal polynomial contrasts were used to examine the linear, quadratic, and cubic effects of wDDGS inclusion level (0, 25, 50, and 75% of the mixture). To discuss the relationship between the feed chemical profile and rumen degradation kinetics or protein supply values, correlation analyses were performed using the CORR procedure of SAS.[33]

■ RESULTS

Chemical and Nutrient Profiles. With increasing inclusion level of wDDGS, ash, crude fat, neutral detergent fiber, acid detergent fiber, acid detergent lignin, hemicelluloses, sugars, CP, soluble crude protein, nonprotein nitrogen, neutral detergent insoluble crude protein, and acid detergent insoluble crude protein increased linearly ($P < 0.05$) while at the same time starch decreased linearly ($P < 0.05$) (Table 1). All energy values decreased linearly ($P < 0.05$) with increasing inclusion level of wDDGS. However, energy values were not different ($P > 0.05$) between C0 and C25 diets.

Protein and Carbohydrate Subfractions. Soluble, slowly degradable, and undegradable fractions of protein and carbohydrate increased linearly ($P < 0.05$) with increasing inclusion level of wDDGS, whereas medium degradable fraction of CP and true protein and nonstructural carbohydrate and rapidly degradable fraction of carbohydrate linearly decreased ($P < 0.05$) with increasing inclusion level of wDDGS (Table 2).

Rumen Degradation Kinetics. Effects of substituting corn grain by wheat-based dried distillers' grains with solubles on rumen degradation kinetics are presented in Tables 3 and 4. Lag time of organic matter degradation was relevant only for

Table 4. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Starch and Neutral Detergent Fiber Rumen Degradation Characteristics

	biofuel coproduct-based feed[a]					*P* value[b]
item	C0	C25	C50	C75	SEM	linear
rumen degradation kinetics of starch (ST; g/kg starch)						
soluble ST (S_{ST})	276.3	139.1	130.2	109.5	72.83	0.227
potentially degradable ST (D_{ST})	723.7	860.9	869.8	890.5	72.83	0.227
degradation rate (K_D; /h)	0.079	0.094	0.067	0.074	0.0113	0.446
rumen undegradable ST (RUST; g/kg DM)	256.6a	200.5a	155.2ab	76.3b	20.39	0.003
effective degradable ST (EDST)	658.7	643.8	589.6	587.9	47.70	0.286
effective degradable ST (g/kg DM)	493.8a	364.4ab	224.4bc	110.0c	27.86	0.001
rumen degradation kinetics of NDF (g/kg NDF)						
potentially degradable NDF (D_{NDF})	560.1	692.2	715.0	722.1	141.15	0.289
undegradable NDF (U_{NDF})	439.1	307.8	285.0	277.9	92.56	0.165
degradation rate (K_D; /h)	0.062	0.029	0.027	0.038	0.0106	0.194
rumen undegradable-NDF (RUNDF; g/kg DM)	99.8c	142.5bc	173.0ab	185.0a	7.60	0.002
effective degradable-NDF (EDNDF)	278.9	216.8	213.7	277.8	49.10	0.811
effective degradable-NDF (g/kg DM)	38.0	40.3	46.7	71.1	11.05	0.049

[a]Corn and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$) according to the Tukey−Kramer method. [b]There was no quadratic and cubic effect ($P > 0.05$).

the corn sample. As wDDGS increased in the mixture, the soluble fraction of organic matter tended to increase linearly ($P < 0.10$), whereas the degradable fraction of organic matter tended to decline linearly ($P < 0.10$) (Table 3). Degradation rates of organic matter (0.059/h), rumen undegradable organic matter (467.9 g/kg DM), and effective degradable organic matter (502.4 g/kg DM) were similar ($P > 0.05$) among corn/wDDGS feeds.

Soluble CP fraction and CP degradation rate numerically increased ($P > 0.05$) and potentially degradable CP fraction numerically decreased with increasing inclusion of wDDGS in the mixture (Table 3). Both effective degradable CP and rumen undegradable CP increased (in g/kg DM) (Table 3) linearly ($P < 0.05$) with increasing inclusion of wDDGS in the mixture. The portion of rumen degradable fraction in total CP also numerically increased. As expected, both rumen undegradable and effective degradable starch decreased linearly ($P < 0.05$) as the wDDGS inclusion increased in the mixture (in g/kg DM). Other starch degradation parameters were similar among feed mixtures.

In situ neutral detergent fiber degradable fraction numerically increased (from 560 to 722 g/kg neutral detergent fiber), whereas the undegradable fraction decreased (from 439.1 to 277.9 g/kg neutral detergent fiber) with wDDGS inclusion in the mixture (Table 4). Overall, when neutral detergent fiber was expressed in grams per kilogram DM, effective degradable neutral detergent fiber, as well as rumen undegradable neutral detergent fiber, increased linearly ($P < 0.05$) with inclusion of wDDGS in the mixture (in g/kg DM).

Ratio of Rumen Available Protein to Carbohydrates and Organic Matter. The ratio of rumen available protein to carbohydrates and organic matter is presented in Figure 1. C0 exhibited lower and C50 and C75 exhibited higher than optimal rumen fermentation ratio at all incubation times, whereas C25 (75% corn and 25% wDDGS mixture) exhibited a greater high ratio (∼1.5-fold greater than optimal level) at 0 h, then dramatically fell to suboptimal level from 1 to 18 h of incubation time, then gradually increased and reached approximately optimal level. In general, from the point of view of microbial synthesis efficiency, C25 showed a relatively optimal hourly effective degradation ratio of nitrogen and energy (N/OM; Figure 1A; N/CHO; Figure 1B). Also, insoluble rumen available N to organic matter and carbohydrate ratio and total rumen available N to organic matter and carbohydrate, as well as soluble N to organic matter and carbohydrate, increased linearly ($P < 0.05$) as wDDGS inclusion increased (Table 5).

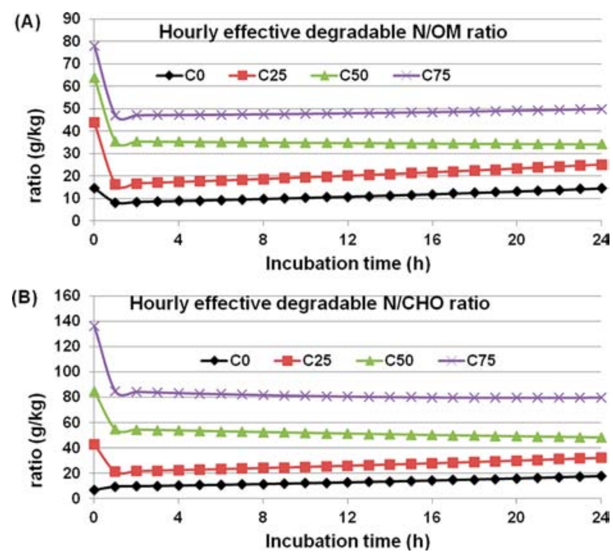

Figure 1. Effect of replacing corn with biofuel coproduct of wheat-based dried distillers' grains with solubles (wDDGS) on hourly effective degradability ratios between N and organic matter (OM) (A) or carbohydrate (CHO) (B).

Protein Supply. Using the DVE/OEB system,[28] absorbable microbial protein was similar among feeds (54.5 g/kg DM), whereas all three corn−wDDGS mixtures had greater absorbable microbial protein ($P < 0.05$) than corn (18.4 vs av 54.7 g/kg DM) when calculated according to NRC[19] (Table 6). The absorbable rumen undegradable feed protein tended to increase linearly ($P < 0.10$) as the wDDGS inclusion increased when calculated with either of two models. Metabolizable protein (MP and DVE) and rumen degraded protein balance (OEB and DPB) increased linearly ($P < 0.05$) as the wDDGS inclusion increased.

Table 5. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Ruminal Degradation Ratios between N and OM or CHO

	biofuel coproduct-based feed[a]					P value[b]
item[c]	C0	C25	C50	C75	SEM	linear
FN/FOM	10.0	25.0	44.8	60.6	4.82	0.001
FN/FCHO	10.6b	30.2b	64.6ab	105.9a	11.72	0.004
EN/EOM	10.2b	19.2b	35.2a	48.3a	2.34	0.001
EN/ECHO	12.0c	24.9bc	52.3b	82.9a	4.87	0.001
SN/SOM	5.0c	44.0b	63.9ab	77.9a	4.67	0.001
SN/SCHO	7.0b	56.9ab	84.8ab	136.2a	16.74	0.005

[a]Corn and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$). Mean separation was done using the Tukey−Kramer method. [b]The quadratic and cubic effect was not detected ($P > 0.05$). [c]FN/FOM of FCHO, total rumen available N/organic matter (OM) or carbohydrate (CHO); EN/EOM or ECHO, insoluble rumen available N/OM or CHO; SN/SOM or CHO, soluble rumen N/OM or CHO. The ratios were calculated according to the method of Tamminga et al.[31]

■ DISCUSSION

Chemical and Energy Profiles and Rumen Degradation Kinetics. The wheat-based DDGS utilized in this study (data not shown) averaged 908 ± 38 g DM, 401 ± 17 g CP, 56 ± 2 g crude fat, 315 ± 8 g neutral detergent fiber, 208 ± 4 g acid detergent fiber, 52 ± 1 g acid detergent lignin, 186 ± 7 g acid detergent insoluble crude protein (/kg CP), 944 ± 1 g organic matter, 15 ± 1 g starch, 71 ± 3 g sugar, 717 ± 3 g total digestible nutrients ($TDN_{1\times}$), 3.24 ± 0.02 Mcal digestible energy ($DE_{3\times}$), 1.94 ± 0.01 Mcal net energy for maintenance (NE_m), and 1.29 ± 0.01 Mcal net energy for growth (NE_g) (mean ± SE, /kg DM), which were within the ranges of previous findings.[8,12,34−36] Differences in chemical content of the mixtures in this study were reflected by the nutrient content of the corn grain and wDDGS. Corn in this study had typical nutritional characteristics.[2,5,8] Corn in our current study had greater energy and lower CP than barley used in our previous study to mix with wDDGS.[37] Energy values decreased linearly with increasing inclusion of wDDGS the mixture, which reflects the slightly lower energy value of wDDGS than of corn.

Previously, ruminal degradation kinetics was reported for corn and wDDGS by Nuez Ortín and Yu,[38] but not for corn−wDDGS mixtures. Rumen degradation kinetics of corn and wDDGS in this study were in agreement with result of Nuez-Ortín and Yu,[38] who found organic matter degradation rates of 0.068 and 0.061/h and effective degradability 483 and 507 g/kg DM for the corn and wDDGS, respectively. The similar degradation rate for corn (C0) with the corn−wDDGS mixtures was consistent with previous findings.[39] The soluble protein fraction increased ∼7-fold as wDDGS inclusion increased in the mixture, which augmented the extent of degradability. The increased rumen undegradable feed CP content (in total g/kg DM) with increased inclusion of wDDGS in the mixture was largely attributed to the higher CP content of wDDGS (402 g/kg DM) relative to corn (89 g/kg DM). In the current study, rumen undegradable feed CP of wDDGS averaged 357 g/kg CP (data not shown), which is at the lower end of the range of 300−600 g/kg CP for rumen undegradable feed CP values found before for wDDGS.[10,19] The ratios of effective degradable feed protein to rumen undegradable feed protein were 0.61, 0.99, 1.42, and 1.58 for C0, C25, C50, and C75, respectively.

The ratio between effective degradable feed protein and rumen undegradable feed protein in wDDGS is mainly influenced by the amount of soluble added back during drying and to a smaller degree by the temperature used during the drying process[40] in wDDGS. The high effective degradable feed protein to rumen undegradable feed protein ratio of wDDGS in this study will result in a relatively high ruminal protein degradation of dietary protein and decreases the delivery of dietary protein (in % of total CP) (absorbable rumen undegradable feed protein) to the small intestine. The NRC model[2] predicts that effective degradable CP required for feedlot finishing cattle fed a diet based on dry-rolled, cracked or ground corn is about 68 g/kg DM. The effective degradable CP

Table 6. Effect of Replacing Corn Grain with Biofuel Coproduct of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Calculated Protein Supply (Grams per Kilogram DM) in Cattle According to NRC[19] Model and DVE/OEB[27] Systems

	biofuel coproduct-based feed[a]					P value[b]
item[c]	C0	C25	C50	C75	SEM	linear
truly absorbed rumen synthesized microbial protein in the small intestine (AMCP)						
AMCP (DVE/OEB)	52.1	53.5	56.8	55.4	3.89	0.499
AMCP (NRC)	18.4b	44.8ab	61.6a	57.8a	5.97	0.007
truly absorbed rumen undegraded feed protein in the small intestine (ARUP)						
ARUP (DVE/OEB)	49.7	71.8	89.6	108.0	19.50	0.092
ARUP (NRC)	44.7	64.7	80.7	97.3	17.56	0.092
total truly absorbed protein in the small intestine or total metabolizable protein supply (DVE or MP)						
DVE (= AMCP + ARUP − ENDP)	94.7	118.4	140.8	153.9	18.43	0.072
MP (= AMCP + ARUP + AECP)	67.4	113.7	146.6	159.3	16.30	0.013
degraded protein balance (OEB or PDB)						
OEB (DVE/OEB)	−54.0	−10.9	42.1	101.9	27.44	0.013
DPB (NRC)	−91.4b	−37.2ab	28.8ab	96.4a	29.00	0.008

[a]Corn and and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted C0, C25, C50, and C75, respectively). Means within a row with different letters differ ($P < 0.05$). Mean separation was done using the Tukey-Kramer method. [b]The quadratic and cubic effect was not detected ($P > 0.05$). [c]ENDP, endogenous protein losses in the digestive tract;[29] AECP, truly absorbable endogenous protein in the small intestine.[20]

dx.doi.org/10.1021/jf400595n | J. Agric. Food Chem. 2013, 61, 4387−4395

of the C25 mixture was close (78.5 g/kg DM) to this requirement. Furthermore, when 25% of corn was substituted by wDDGS, the effective degradable CP concentration of the mixture was similar to that of 100% barley grain.[37,41]

The relationship between the rate of starch degradability and wDDGS inclusion in feed mixture was not significant. Consequently, the magnitude of elevation of rumen undegradable feed starch was lower (from 412 to 341g/kg starch) as wDDGS inclusion increased. It is well documented that barley grain is more rapidly fermented in the rumen than corn grain, which can increase the acidity of the rumen and reduce the activity and numbers of fiber-digesting bacteria to ferment forage fiber.[41−43] In contrast, the current study indicated corn or corn−wDDGS mixtures had lower and slower starch degradation in the rumen, which is an important positive characteristic for ruminants over barley-based feeds.

Rates of neutral detergent fiber degradation were comparable to previous findings.[12,44] Effective degradable neutral detergent fiber averaged 247 g/kg neutral detergent fiber, which was not influenced by the inclusion of wDDGS in the mixture, and this was lower than results of others,[38] who found effective degradable neutral detergent fiber of 418 and 356 g/kg neutral detergent fiber for corn and wDDGS, respectively. The readily digestible fiber in DDGS is an important factor contributing to the energy content of DDGS.[45] The current study further indicates that increased inclusion of wDDGS in the mixture increases neutral detergent fiber rumen availability up to ∼1.9-folds (expressed in g/kg DM) of neutral detergent fiber, which can provide a significant amount of energy for microbial growth in the rumen. The greater amount of rumen available neutral detergent fiber of wDDGS can substitute partially corn starch as ruminal energy source. The magnitude of effective degradable neutral detergent fiber from wDDGS results mainly from the higher neutral detergent fiber content in wDDGS rather than from changes in effective degradable neutral detergent fiber to rumen undegradable neutral detergent fiber ratio with wDDGS inclusion in the mixture.

In DDGS, the high temperature (100−600 °C) applied during the drying process usually results in acid detergent insoluble crude protein formation due to Maillard reactions.[46] Whereas some studies have established a negative correlation between acid detergent insoluble crude protein and CP digestibility in forages[47−49] and nonforages,[22,49] it is not clear whether acid detergent insoluble crude protein behavior in DDGS is similar to that in conventional feeds.[12,37,38] In the current study, acid detergent insoluble crude protein was not correlated with the protein degradation rate (r = 0.07, P = 0.87), soluble fraction (r = 0.56; P = 0.15), potential degradable fraction (r = 0.48, P = 0.23), undegradable fraction (r = 0.02, P = 0.95), and undegradable feed CP (r = −0.33, P = 0.41), suggesting that acid detergent insoluble crude protein may not affect protein utilization and availability of corn and wDDGS in the rumen.

Substituting Barley by Corn−wDDGS Mixtures. One might ask if it is possible to prepare a corn−wDDGs mixture with a nutritive value similar to that of conventional western Canadian feed lot grain−barley diets. As the current study revealed, when corn was replaced 25% by wDDGS, the mixture was similar (P > 0.05) to that previously reported barley grain[37] as to organic matter (976.3 vs 978.8 g/kg DM), starch (564.8 vs 609.3 g/kg DM), sugar (23.0 vs 25.5 g/kg DM), CP (16.6 vs 13.8 g/kg DM), total digestible nutrients (848.3 vs 859.2 g/kg DM), digestible energy ($DE_{3\times}$) (3.47 vs 3.48 Mcal/kg DM), metabolizable energy ($ME_{3\times}$) (3.06 vs 3.06 Mcal/kg DM), net energy for lactation (NE_L) (1.96 vs 1.95 Mcal/kg DM), net energy for maintenance (2.11 vs 2.12 Mcal/kg DM), net energy for growth (1.44 vs 1.45 Mcal/kg DM), effective degradable CP (78.7 vs 78.0 g/kg DM), and degradable protein balance (DPB; −37.2 vs −42.3 g/kg DM). Total truly absorbable protein in the small intestine (DVE = 118.4 vs 100.1 g/kg DM; MP = 113.7 vs 94.5 g/kg DM) and truly absorbable rumen undegradable protein in the small intestine (ARUP; 64.7 vs 47.4 g/kg DM) were greater in C25 than in barley grain, respectively.

Ratio of Rumen Available Protein to Energy and Intestinal Protein Supply. Ruminal available dietary CP and energy (carbohydrate or organic matter) are needed for microbial protein synthesis with an optimum ratio of around 25 g N/kg organic matter truly digested in rumen[31] or 32 g N/kg carbohydrate truly digested in rumen[29,30] and OEB of 0.[28] In the current study, both the hourly effective degradable ratio of N to energy (Figure 1) and the total effective degradable ratio of N to energy data (Table 5) and OEB/DPB (Table 6) indicate that corn was below optimal rumen N to energy fermentation ratios, whereas especially C75 exhibited higher than optimal rumen N to energy fermentation ratios. The lower N to energy ratio for corn will result in decreased microbial growth (protein synthesis) because of ruminal N shortage, whereas the higher N to energy ratio of C75 will result in deamination of excess CP into energy and NH_3.[50] Overall, C25 and C50 showed a relatively optimal effective degradable ratio of N/organic matter and of N/carbohydrate for the microbial synthesis in the rumen.

The protein supply to the rumen and intestine for corn in the current study was in agreement with previously reported values.[38] Published information on nutrient supply from corn−wDDGS mixture is not available. Increasing wDDGS inclusion in the feed mixture increased predicted protein supply to the intestine of cattle (Table 6) without greatly altering energy values. When DDGS replaces up to 25−50% of corn-based diet, the corn−wDDGS mixture becomes a unique feed source that serves as a good source of both protein and energy for feedlot production. However, these results obtained using the NRC model and DVE/OEB system should be confirmed in feedlot trials before firm conclusions are drawn.

In conclusion, this study showed that increasing the inclusion of DDGS in corn−wDDGS mixtures linearly increased their major nutritional components while decreasing their starch and energy values. However, replacing corn with wDDGS up to 25% increased protein content and other nutrients without altering the energy value compared with 100% corn-based diets. The study further revealed that the degradation rate and the ratio of effective degradable to undegradable feed components did not differ among corn and corn−wDDGS mixtures. This suggests that degradation kinetics of corn grain-based diets will not change dramatically due to substitution by wDDGS in a feed. However, the inclusion of wDDGS in corn-based diets changed the ratio between nitrogen and energy supply in the rumen and the small intestine. Inclusion of wDDGS up to ∼50% of DM created desirable nitrogen to energy ratios for microbial growth in the rumen. Overall, this study suggests that corn and wheat DDGS combinations are viable alternatives for replacing feed barley grain for the beef industry in western Canada.

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Funding

Funding provided by the Beef Cattle Research Council (BCRC) and Canadian Cattlemen's Association and Agriculture and Agri-Food of Canada (AAFC) and Ministry of Agriculture Feed Strategic Research Chair Program (Saskatchewan, Canada) is greatly acknowledged (Project FED.02.09).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank Zhiyuan Niu (Department of Animal and Poultry Science, University of Saskatchewan, Saskatoon, Canada) for his support with laboratory analysis.

ABBREVIATIONS USED

ADF, acid detergent fiber; ADICP, acid detergent insoluble crude protein; ADL, acid detergent lignin; AMCP, absorbable microbial protein; ARUP, absorbable rumen undegradable feed protein; CA, soluble carbohydrate fraction; CB1, rapidly degradable carbohydrate fraction; CB2, slowly degradable carbohydrate fraction; CC, undegradable cell walls fraction; CHO, total carbohydrates; CNCPS, Cornell Net Carbohydrate and Protein System; *D*, insoluble potentially degradable in situ fraction; DM, dry matter; DMI, dry matter intake; DPB, degradable protein balance; DVE, total truly absorbable protein in the small intestine; EDDM, EDN, EDCP, EDOM, EDST, and EDNDF, effective degradation of feed DM, N, CP, OM, starch, and NDF, respectively; EN, insoluble rumen available protein; EOM, insoluble rumen available OM; K_d, rate of degradation of D fraction; K_p, passage rate; MP, metabolizable protein supply; NDF, neutral detergent fiber; NDICP, neutral detergent insoluble crude protein; NE_g, net energy for growth; NE_m, net energy for maintenance; NPN, nonprotein nitrogen; OEB, degradable protein balance; OM, organic matter; PA, soluble protein fraction; PB1, rapidly degradable protein fraction; PB2, intermediately degradable protein fraction; PB3, slowly degradable protein fraction; PC, undegradable protein fraction; RUOM, RUP, RUST, and RUNDF, rumen undegradable feed OM, CP, starch, or NDF, respectively; S, soluble in situ fraction; SCHO, carbohydrates soluble in rumen; SCP, soluble crude protein; SN, N soluble in rumen; TDN, total digestible nutrients; *U*, undegradable in situ fraction; wDDGS, wheat-based dried distillers grains with solubles

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