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# Effect of Wheat-Based Dried Distillers' Grains with Solubles Inclusion on Barley-Based Feed Chemical Profile, Energy Values, Rumen Degradation Kinetics, and Protein Supply

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**ABSTRACT:** The objectives of this study were to determine the effect of replacing the barley grain portion of the diet by wheat-based dried distillers' grains with solubles (wDDGS) at graded levels on feeding value for beef cattle. Two cultivars of barley were mixed with two sources of wDDGS in ratios of 100:0, 75:25, 50:50, and 25:75% (weight DM basis; denoted B0, B25, B50, and B75, respectively). This study revealed that increasing wDDGS inclusion level increased most of the nutritional composition linearly except for starch, which linearly decreased (from 609 to 320 g/kg of DM). Soluble, slowly degradable, and undegradable Cornel Net Carbohydrate and Protein System (CNCPS) protein and carbohydrate fractions linearly increased with increasing wDDGS inclusion level, whereas their rapidly and intermediately degradable fractions decreased. With increasing wDDGS inclusion, the rumen degradation rate of all measured parameters decreased linearly, the extent of degradability of organic matter was not affected, and the extent of CP degradability (g/kg DM) as well as the predicted protein supply in the small intestine and degraded protein balance in the rumen was increased. The inclusion of wDDGS in barley-based diets up to 50% did not alter energy values of the diet. Furthermore, optimum N to energy balance of the feed mixture for microbial growth in the rumen was reached by replacing 25% of barley by wDDGS. Thus, the nutritive value of the barley-based diets is manipulated by including wDDGS, which can be used to overcome the shortcomings of barley-dominated diets for beef cattle.

**KEYWORDS:** *barley, energy values, in situ degradation, nutrient variation and availability, ruminants, wheat-based dried distillers' grains with solubles*

## INTRODUCTION

Barley (*Hordeum vulgare* L.) is traditionally the mainstay of the western Canadian feedlot industry,[1] with feedlot rations containing up to 90% barley grain.[2] However, barley has a high ruminal rate and extent of starch degradation (>80%),[3,4] which result in digestive disorders such as bloat and acidosis[5] with serious economic impacts on the feeding program.[6] Furthermore, high inclusion of barley results in shortage of protein for optimal microbial protein synthesis, which results in the requirement for protein-rich supplements to balance the ration.[4] Feed is the single largest cost (60−70%) of production for beef operations in Canada.[7] Hence, there is a need to develop strategies to optimize barley utilization and reduce the risk of metabolic disorders for the cattle industry. Due to the expansion of the bioethanol industry in North America, a large supply of bioethanol coproducts such as dried distillers' grains with solubles (DDGS; dried stillage remaining after ethanol distillation) is available in western Canada.[8,9] Barley grain averages 12% CP and wheat DDGS (wDDGS) 39% CP, whereas energy values are similar for barley and wDDGS.[10] Therefore, wDDGS might be a good substitute for barley-dominated rations for cattle. We hypothesized that feeding barley in combination with wDDGS will improve the availability of nutrients to the animal (i.e., metabolizable protein) and synchronizes protein to energy fermentation in the rumen. The objectives of this study were to determine the effects of replacing barley grain by wDDGS on nutritive value for ruminants in terms of detailed nutritional profiles, energy values, protein and carbohydrate subfractions, in situ rumen degradation kinetics, protein to energy degradation ratios, and protein supply to the intestine.

## MATERIALS AND METHODS

**Sample Preparation.** Barley grains from two sources grown at the Kernen Crop Research Farm (University of Saskatchewan, Saskatoon, SK, Canada) were used for this experiment and replaced at graded levels by two wheat DDGS batches 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 barley source was mixed with one batch of wDDGS and the other barley source with the other wDDGS batch in ratios of 100:0, 75:25, 50:50, and 25:75 (DM weight basis; denoted B0, B25, B50, and B75, respectively; $n = 8$). For chemical analysis, samples were milled to pass through a 1 mm screen (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, samples were processed through a 0.203 mm gap roller

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mill (Seven Grain Mill, Apollo Machine and Products Ltd., Saskatoon, Canada). Milled 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 procedures of AOAC.[11] 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 $\alpha$-amylase (NDF), and acid detergent lignin (ADL) were analyzed according to the procedures of Van Soest et al. [12] using an ANKOM Fiber Analyzer (ANKOM Technology Corp., Fairport, NY, USA). Samples were analyzed for total starch using the Megazyme Total Starch Assay Kit[13] (Megazyme International Ltd., Wicklow, Ireland). Sugars were determined after extraction in 80% ethanol for 4 h followed by measuring the absorbance at 490 nm in a Ultrospec III spectrophotometer (Pharmacia LKB, Cambridge, U.K.) using the phenol−sulfuric acid assay according to the method of Hall.[14] Nonprotein nitrogen (NPN) was determined after precipitation of true protein in the filtrate with tungstic acid ($Na_2WO_4 \cdot 2H_2O$; final concentration = 10%) and determined as the difference between total N and the Kjeldahl-N content of the residue after filtration.[15] The amounts of CP associated with NDF (NDICP) and ADF (ADICP) were determined by analyzing the Kjeldahl-N content of the NDF and ADF.[15] The reported NDF and ADF 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.[16] Total carbohydrates (CHO), true protein, hemicelluloses, cellulose, and nonstructural carbohydrate (NSC) were calculated according to NRC methods.[17] All samples were analyzed in duplicate and repeated if 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.[18]

**Fractionation of Protein and Carbohydrates.** Crude protein and carbohydrates were partitioned according to the Cornell Net Carbohydrate Protein System.[19] The CP fractions in this system are characterized into a directly available protein (PA; i.e., NPN), true potentially degradable protein (PB; i.e., CP-NPN-ADICP), and unavailable protein (PC; i.e., ADICP). The PB fraction was further divided into rapidly degradable (PB1; i.e., SCP-NPN), intermediately 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.[19] 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 completely undegradable. Carbohydrates were fractioned into a soluble fraction (CA; composed of soluble sugars with a rapid degradation rate of 3.00/h), an intermediately 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).[19,20]

**In Situ Rumen Incubation Technique.** Rumen degradation characteristics were determined using the in situ method as described by McKinnon et al.[21] and Yu et al.[22] 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 during in situ rumen incubations.[20] 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.[17] 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 guidelines of the Canadian Council on Animal Care.[23] Before incubations, 7 g of an individual sample was weighed into preweighed and numbered nylon bags (10 × 20 cm; Nitex 03-41/31 monofilament open mesh fabric, Screentec Corp., Mississagua, ON, Canada) with a pore size of approximately 40 $\mu$m. 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.[20,24] Data from Urdl et al.[25] were used to determine the number of bags to be incubated for each sample, which was increased in relation to incubation time. 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 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 stream of cold 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.[20] 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, OM, CP, NDF, and starch, as described previously. Dry matter, OM, CP, NDF, and starch disappearances were calculated by the difference between original and residue amounts after ruminal incubation. In vitro intestinal digestibility (IDP) 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 to describe the rumen degradation characteristics of DM, CP, NDF, and starch was calculated using the NLIN procedure of SAS with iterative least-squares regression (Gauss−Newton method). The first-order kinetics equations used were

$$R(t) = U + D \times \exp(-K_d \times (t - t_0)) \text{ for OM, NDF, and CP (ref 27)} \quad (1)$$

$$R(t) = D \times \exp(-K_d \times t) \text{ for starch (ref 28)} \quad (2)$$

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/kg); $t_0$ is lag time (h); and $K_d$ is the degradation rate (%/h).

The effective degradability (ED) values were calculated as

$$\text{EDCP (or EDOM, EDNDF, or EDST) (g/kg)} = S + D \times K_d/(K_p + K_d) \quad (3)$$

where soluble fractions ($S$) are in g/kg and a passage rate ($K_p$) of 6%/h was assumed.[28] The rumen undegradable feed protein (RUP) value was calculated as

$$\text{RUP (g/kg DM)} = 1.11 \times (\text{CP (g/kg DM)} \times \text{EDCP (g/kg)}) \quad (4)$$

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

$$\text{RUST (g/kg)} = D \times K_p/(K_p + K_d) + 0.1 \times S \quad (5)$$

where $K_p$ of 6%/h was adapted[37] 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 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

Table 1. Effect of Replacing Barley Grain with Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on the Chemical Profiles and Energy Values for Beef Cattle[a]

| item | feed[b] | | | | SEM | P value[c] |
|---|---|---|---|---|---|---|
| | B0 | B25 | B50 | B75 | | linear |
| basic chemical profile (g/kg DM) | | | | | | |
| ash | 21.3 d | 30.5 c | 38.5 b | 48.3 a | 1.22 | 0.001 |
| crude fat | 16.5 c | 23.5 bc | 32.5 b | 43.8 a | 2.59 | 0.001 |
| structural carbohydrate profile (g/kg DM) | | | | | | |
| neutral detergent fiber | 149.5 c | 181.5 bc | 217.8 ab | 257.0 a | 11.90 | 0.000 |
| acid detergent fiber | 51.8 c | 84.5 bc | 116.8 b | 156.8 a | 8.89 | 0.001 |
| acid detergent lignin | 7.3 d | 17.8 c | 28.8 b | 39.0 a | 2.13 | 0.001 |
| hemicellulose | 120.3 d | 162.3 c | 207.3 b | 249.5 a | 8.24 | 0.001 |
| cellulose | 44.5 c | 66.5 bc | 87.8 b | 118.0 a | 6.99 | 0.001 |
| nonstructural carbohydrate profile (g/kg DM) | | | | | | |
| starch | 609.3 a | 449.8 b | 320.0 c | 161.3 d | 12.53 | 0.001 |
| sugar | 25.5 b | 31.5 ab | 41.8 ab | 49.3 a | 5.42 | 0.006 |
| crude protein profile (g/kg CP) | | | | | | |
| crude protein (g/kg DM) | 138.0 d | 201.8 c | 263.3 b | 340.3 a | 7.42 | 0.001 |
| nonprotein-N (g/kg SCP) | 636.3 | 881.3 | 919.0 | 941.8 | 70.19 | 0.001 |
| soluble CP | 245.0 b | 279.5 b | 285.3 b | 356.3 a | 11.64 | 0.001 |
| neutral detergent insoluble CP | 164.0 b | 321.8 a | 406.3 a | 444.5 a | 31.34 | 0.001 |
| acid detergent insoluble CP | 11.0 d | 88.8 c | 123.3 b | 145.3 a | 4.47 | 0.001 |
| total digestible nutrient at maintenance level (g/kg DM) | | | | | | |
| total digestible nutrients$_{1\times}$ | 859.2 a | 825.7 b | 795.9 c | 760.3 d | 6.37 | 0.001 |
| energy values (MJ/kg DM[18]) | | | | | | |
| net energy for maintenance | 8.9 a | 8.7 ab | 8.6 ab | 8.4 b | 0.08 | 0.002 |
| net energy for gain | 6.1 a | 5.9 ab | 5.8 ab | 5.7 b | 0.07 | 0.002 |

[a]Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [c]There was no quadratic or cubic effect.

Table 2. Effect of Replacing Barley Grain with Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Protein and Carbohydrate Subfractions[a]

| item | feed[b] | | | | SEM | P value[c] |
|---|---|---|---|---|---|---|
| | B0 | B25 | B50 | B75 | | linear |
| protein subfractions (g/kg CP)[19] | | | | | | |
| PA (soluble) | 155.5 b | 246.1 ab | 262.1 ab | 336.7 a | 26.82 | 0.003 |
| PB1 (rapidly degradable) | 89.2 | 33.1 | 20.2 | 15.6 | 20.53 | 0.039 |
| PB2 (medium degradable) | 591.5 a | 399.0 b | 308.7 b | 199.1 c | 24.76 | 0.001 |
| PB3 (slowly degradable) | 152.9 b | 233.0 ab | 283.0 a | 299.6 a | 29.17 | 0.003 |
| PC (undegradable) | 10.9 d | 88.8 c | 123.1 b | 145.1 a | 4.43 | 0.001 |
| true protein | 833.5 a | 665.2 b | 611.8 bc | 554.2 c | 25.48 | 0.001 |
| carbohydrate subfractions (g/kg CHO)[19] | | | | | | |
| total CHO (g/kg DM) | 824.6 a | 744.7 b | 665.9 c | 567.8 d | 5.81 | 0.001 |
| nonstructural CHO | 818.4 a | 756.0 a | 673.5 b | 547.6 c | 15.36 | 0.001 |
| CA (soluble) | 79.3 c | 152.1 bc | 192.7 ab | 262.7 a | 18.75 | 0.001 |
| CB1 (rapidly degradable) | 739.1 a | 603.9 b | 480.9 c | 285.0 d | 18.76 | 0.001 |
| CB2 (slowly degradable) | 159.9 c | 186.7 bc | 223.5 b | 287.6 a | 10.06 | 0.001 |
| CC (undegradable) | 21.6 d | 57.3 c | 103.0 b | 164.9 a | 6.80 | 0.001 |

[a]Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [c]There was no quadratic or cubic effect ($P > 0.05$).

$$\text{hourly ED (g/kg)} = S + [(D \times K_d)/(K_p + K_d)] \times [1 - e^{-t\times(K_d+K_p)}] \quad (6)$$

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:[30,31] (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; (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[32] or 32 g N/kg CHO truly digested in rumen,[29,30] which were used as benchmarks to interpret results.

**Modeling Intestinal Protein Supply.** The potential protein supply from the feed mixture in terms of truly absorbed rumen

**Table 3. Effect of Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) Inclusion on Barley-Based Feed Organic Matter and Protein Rumen Degradation Characteristics[a]**

| item | feed[b] B0 | B25 | B50 | B75 | SEM | Pvalue[c] linear |
|---|---|---|---|---|---|---|
| rumen degradation kinetics of organic matter (g/kg OM) | | | | | | |
| lag time (h) | 0.7 a | 0.0 b | 0.0 b | 0.0 b | 0.08 | 0.003 |
| soluble OM | 6.8 | 95.1 | 155.0 | 215.1 | 51.67 | 0.041 |
| potentially degradable OM | 866.4 a | 763.8 ab | 680.6 ab | 631.7 b | 40.41 | 0.012 |
| undegradable OM | 126.9 | 141.2 | 164.4 | 153.2 | 49.00 | 0.665 |
| degradation rate (%/h) | 11.6 | 8.6 | 8.5 | 7.9 | 0.01 | 0.068 |
| rumen undegradable-OM (g/kg DM) | 415.4 | 442.9 | 428.1 | 405.5 | 27.63 | 0.737 |
| effective degradable-OM | 575.4 | 543.1 | 554.8 | 574.2 | 29.16 | 0.953 |
| effective degradable-OM (g/kg DM) | 563.1 | 526.6 | 533.4 | 546.7 | 28.82 | 0.758 |
| rumen degradation kinetics of crude protein (g/kg CP) | | | | | | |
| lag time (h) | 0.7 a | 0.0 b | 0.0 b | 0.0 b | 0.09 | 0.007 |
| soluble CP | 117.0 | 247.0 | 263.0 | 334.5 | 87.96 | 0.164 |
| potentially degradable CP | 796.4 | 684.2 | 637.0 | 590.0 | 82.87 | 0.147 |
| undegradable CP | 86.7 | 68.9 | 100.0 | 75.5 | 26.41 | 0.985 |
| degradation rate (%/h) | 8.0 | 5.9 | 7.1 | 6.5 | 0.84 | 0.438 |
| rumen undegradable CP (RUP; g/kg DM) | 59.0 | 83.7 | 103.3 | 22.5 | 15.56 | 0.039 |
| effective degradable-CP | 571.5 | 583.8 | 603.2 | 634.1 | 68.87 | 0.538 |
| effective degradable-CP (g/kg DM) | 78.7 | 117.7 | 159.8 | 217.7 | 27.71 | 0.021 |
| intestinal digestible CP (g/kg RUP) | 803.2 | 798.1 | 799.6 | 793.5 | 43.81 | 0.895 |

[a]Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [c]There was no quadratic or cubic effect.

**Table 4. Effect of Replacing Barley Grain with Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Starch and Neutral Detergent Fiber Degradation Characteristics[a]**

| item | feed[b] B0 | B25 | B50 | B75 | SEM | P value[c] linear | quadratic |
|---|---|---|---|---|---|---|---|
| rumen degradation kinetics of starch (ST; g/kg starch) | | | | | | | |
| soluble ST | 186.8 ab | 252.4 a | 218.5 ab | 126.0 b | 17.01 | 0.047 | 0.010 |
| potentially degradable ST | 813.2 ab | 747.6 b | 781.5 ab | 874.0 a | 17.01 | 0.047 | 0.010 |
| degradation rate (%/h) | 12.3 | 9.1 | 9.0 | 7.7 | 0.8 | 0.019 | 0.316 |
| rumen undegradable ST (g/kg DM) | 174.1 a | 145.3 b | 107.0 c | 64.0 d | 4.10 | 0.001 | 0.158 |
| effective degradable ST | 714.4 a | 675.7 ab | 665.1 ab | 604.1 b | 13.84 | 0.005 | 0.467 |
| effective degradable ST (g/kg DM) | 435.3 a | 304.6 b | 213.0 b | 97.4 c | 17.07 | 0.001 | 0.681 |
| rumen degradation kinetics of NDF (g/kg NDF) | | | | | | | |
| soluble NDF | 149.5 ab | 77.2 b | 108.2 ab | 189.1 a | 16.06 | 0.105 | 0.009 |
| potentially degradable NDF | 520.2 | 568.0 | 548.5 | 586.1 | 84.81 | 0.663 | 0.955 |
| undegradable NDF | 330.3 | 354.8 | 343.3 | 224.8 | 88.76 | 0.455 | 0.466 |
| degradation rate (%/h) | 5.3 | 4.7 | 4.5 | 3.5 | 0.66 | 0.124 | 0.790 |
| rumen undegradable-NDF (g/kg DM) | 82.3 | 112.1 | 135.4 | 152.0 | 18.21 | 0.046 | 0.737 |
| effective degradable-NDF | 383.6 | 324.3 | 342.5 | 403.1 | 33.96 | 0.641 | 0.152 |
| effective degradable-NDF (g/kg DM) | 48.2 b | 53.2 b | 70.2 ab | 102.6 a | 5.83 | 0.002 | 0.079 |

[a]Means within a row with different letters differ ($P < 0.05$)according to the Tukey–Kramer method. [b]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [c]There was no cubic effect.

synthesized microbial protein in the small intestine (AMCP, g/kg of DM), truly absorbed rumen undegraded feed protein in the small intestine (ARUP, g/kg of DM), total truly absorbed protein in the small intestine (DVE in DVE/OEB system; MP in NRC model), and rumen degraded 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.[17] Details of two models including principles, similarities, and differences were described previously by Yu et al.[4] and Nuez Ortin and Yu.[10]

**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 observation of the dependent variable $ij$, $\mu$ is the population mean for the variable, $T_i$ is the fixed effect of the 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 posthoc test. Orthogonal polynomial contrasts[34] were used to examine the linear, quadratic, and cubic effects of wDDGS inclusion level (0, 25, 50, and or 75% of the mixture). The correlations between feed chemical profile and rumen degradation kinetics or protein supply values from feeds were obtained using the CORR procedure of SAS.[33]

## ■ RESULTS

**Chemical and Nutrient Profiles.** With increasing inclusion level of wDDGS, ash, crude fat, NDF, ADF, ADL, sugars CP, SCP, NPN, NDICP, and ADICP 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.

**Protein and Carbohydrate Subfractions.** Protein fractions PA, PB3, and PC and CHO fractions CA, CB2, and CC increased linearly ($P < 0.05$) with increasing inclusion level of wDDGS, whereas CP fractions PB2 and true protein and CHO fractions NSC and CB1 linearly decreased ($P < 0.05$) with increasing inclusion level of wDDGS (Table 2).

**Rumen Degradation Kinetics.** Lag time of OM degradation was only relevant for B0. As wDDGS increased in the mixture, the *S* fraction of OM increased ($P < 0.05$), whereas the *D* fraction of OM linearly declined ($P < 0.05$) (Table 3). The rate of degradation of OM tended to decrease linearly ($P = 0.07$) when wDDGS increased in the mixture, whereas the mean values of RUOM (422.9 g/kg DM), as well as EDOM (542.5 g/kg DM), were not different among treatments. In situ CP degradation characteristics (*S*, *D*, *U*, and $K_d$) and IDP were not different among treatments (Table 3). Effective degradable CP and RUP increased linearly ($P < 0.05$) with increasing inclusion of wDDGS in the mixture.

A quadratic response was observed ($P < 0.05$) for *S* and *D* fractions of starch. The rate of starch degradability linearly ($P < 0.05$) declined as wDDGS inclusion increased, ranging from 0.12 to 0.08/h for B0–B75. As expected, both RUST and EDST decreased ($P < 0.05$) as the wDDGS inclusion increased in the mixture. In situ NDF degradation characteristics *D*, *U*, and $K_d$ were not different among treatments (Table 4). Effective degradable NDF, as well as RUNDF, increased linearly ($P < 0.05$) with greater wDDGS inclusion in the mixture.

**Ratio of Rumen Available Protein to Carbohydrates and Organic Matter.** The largest hourly ED of N/OM ratios were seen at longer incubation times across all feeds and mixtures (Figure 1). Also, B50 and B75 exhibited higher than optimal rumen fermentation ratio at all incubation times. Barley (B0) exhibited an extremely high ratio (∼10-fold greater than optimal level) at 0 h, then dramatically fell to suboptimal level from 1 to 13 h of incubation time, then gradually increased and reached approximately optimal level (23–27 N g to kg OM) at 14–18 h of incubation time; likewise, the ratio increased continuously and became greater than optimal level at the incubation time of ≥19 h. Whereas B25 also showed a greater N/OM ratio (∼4-fold greater than optimal level) at the beginning of fermentation, it dropped to lower than suboptimal level (<23.0) at 1–4 h of fermentation time, then elevated back and reached close to approximate (23 < N/OM ratio > 27) with optimal level at 5–11 h of incubation time, and became greater than optimal level thereafter. In general, from the point of view of microbial protein synthesis, B25 showed relatively optimal hourly ED ratios of N/OM and N/CHO.

Insoluble rumen available EN to EOM and ECHO ratio and total rumen available FN to FOM and FCHO increased linearly ($P < 0.05$) as wDDGS inclusion increased (Table 5).

**Protein Supply.** Using the DVE/OEB system,[28] the mean of AMCP was not different among all treatments, whereas all three mixtures had greater AMCP ($P < 0.05$) than barley (59.8 vs 42.8 g/kg DM) when calculated according to NRC[17] (Table 6). The ARUP tended to increase linearly ($P = 0.087$) as the wDDGS inclusion increased when calculated with either model. Both metabolizable protein (MP and DVE) and rumen degraded protein balance (OEB and DPB) increased linearly ($P < 0.05$) as the wDDGS inclusion increased.

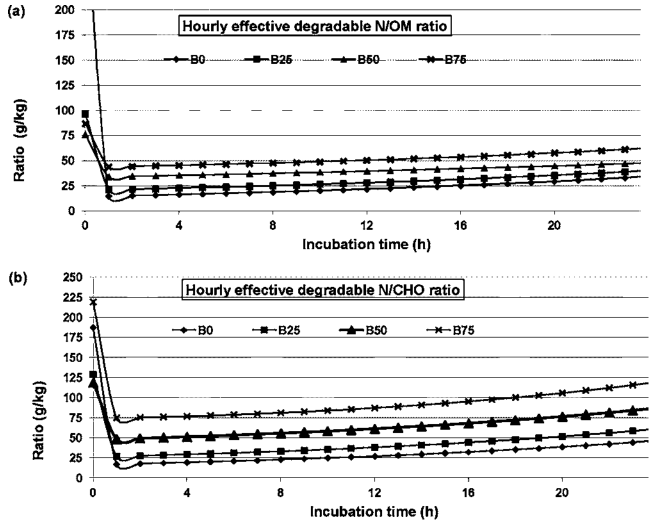


**Figure 1.** Effect of replacing barley grain with wheat-based dried distillers' grains with solubles (wDDGS) on hourly effective degradability ratios between N and OM (a) or CHO (b). Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). The hourly effective degradation was calculated as $ED = W + [(D \times K_d)/(K_d + K_p)] \times [1 - e^{-t(K_d+K_p)}]$, according to Sinclair et al.[29] The optimal ratio between the effective degradability of N and energy to achieve maximum microbial synthesis and to minimize N loss is 25 g N/kg OM[32] or 32 g N/kg CHO[29] in the rumen.

**Table 5. Effect of Replacing Barley Grain with Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Ruminal Degradation Ratios between N and OM or CHO[a]**

| | feed[c] | | | | | *P* value[d] |
|---|---|---|---|---|---|---|
| item[b] | B0 | B25 | B50 | B75 | SEM | linear |
| FN/FOM | 24.5 | 42.0 | 60.0 | 84.8 | 11.55 | 0.019 |
| FN/FCHO | 26.3 | 47.9 | 72.2 | 124.6 | 18.44 | 0.018 |
| EN/EOM | 20.0 b | 29.5 b | 46.8 ab | 63.4 | 5.08 | 0.001 |
| EN/ECHO | 21.9 c | 33.1 c | 55.0 b | 80.8 a | 3.74 | 0.000 |
| SN/SOM | 161.5 | 112.4 | 95.0 | 116.5 | 29.70 | 0.314 |
| SN/SCHO | 187.5 | 129.3 | 118.9 | 219.5 | 73.36 | 0.807 |

[a]Means within a row with different letters differ ($P < 0.05$) according to the Tukey–Kramer method. [b]FN/FOM of FCHO, total rumen available N/OM or CHO; EN/EOM or ECHO, insoluble rumen available N/OM or CHO; SN/SOM or CHO, soluble rumen N/OM or CHO.[30] [c]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [d]There was no quadratic and cubic effect.

## DISCUSSION

**Chemical and Energy Profiles and Rumen Degradation Kinetics.** Differences in chemical content of the mixtures in this study were reflected by the nutrient content of the barley grain and wDDGS. Barley in this study had chemical characteristics within the ranges seen for these plants grown in Saskatchewan.[35] Energy values were negatively correlated ($r = -0.68$ to $-74$; $P < 0.05$) with inclusion of wDDGS in the barley–wDDGS mixture, which is a reflection of the slightly lower energy value of wDDGS ($NE_m$ = 8.3 MJ/kg DM; data not shown) than of barley ($NE_m$ = 8.9 MJ/kg DM). Beliveau

**Table 6. Effect of Replacing Barley Grain with Wheat-Based Dried Distillers' Grains with Solubles (wDDGS) on Calculated Protein Supply (Grams per Kilogram DM) in Cattle According to NRC[17] and DVE/OEB[28] Systems[a]**

| item[b] | feed[c] | | | | SEM | Pvalue[d] |
|---|---|---|---|---|---|---|
| | B0 | B25 | B50 | B75 | | linear |
| 1. truly absorbed rumen synthesized microbial protein in the small intestine (AMCP) | | | | | | |
| AMCP (DVE/OEB) | 57.3 | 54.6 | 52.5 | 53.8 | 6.28 | 0.679 |
| AMCP (NRC) | 42.8 b | 60.6 a | 60.8 a | 58.1 a | 2.23 | 0.010 |
| 2. truly absorbed rumen undegraded feed protein in the small intestine (ARUP) | | | | | | |
| ARUP (DVE/OEB) | 52.7 | 74.3 | 92.6 | 109.5 | 18.72 | 0.087 |
| ARUP (NRC) | 47.4 | 66.9 | 83.4 | 98.7 | 16.87 | 0.087 |
| 3. total truly absorbed protein in the small intestine or total metabolizable protein supply (DVE or MP) | | | | | | |
| DVE (= AMCP + ARUP − ENDP) | 100.1 | 117.9 | 132.2 | 151.1 | 13.08 | 0.046 |
| MP (= AMCP + ARUP + AECP) | 94.5 | 131.8 | 148.5 | 161.1 | 16.38 | 0.042 |
| 4. degraded protein balance (OEB or PDB) | | | | | | |
| OEB (DVE/OEB) | −17.6 b | 22.8 ab | 66.0 ab | 119.9 a | 22.89 | 0.011 |
| DPB (NRC) | −42.3 | 1.4 | 47.7 | 110.6 | 27.47 | 0.015 |

[a]Means within a row with different letters differ ($P < 0.05$). Mean separation was done using the Tukey−Kramer method. [b]ENDP, endogenous protein losses in the digestive tract; AECP, truly absorbed endogenous protein in the small intestine. [c]Barley and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (weight basis in % DM; denoted B0, B25, B50, and B75, respectively). [d]There was no quadratic or cubic effect.

and McKinnon[2] found that wDDGS has an energy value equal to that of barley grain when fed at levels up to 23% of the diet DM. In agreement with the latter finding, inclusion of wheat DDGS up to 50% of DM in barley-based diets did not show a major effect on energy values of barley−wDDGS mixture.

Previously, ruminal degradation kinetics were reported for barley[4,20,36,37] and wDDGS,[10] but not when incubated as barley−wDDGS mixtures. Ramsey et al.[36] found DM degradation rate ranging from 0.06 to 0.16/h and effective degradability ranging from 443 to 693 g/kg DM for eight Canadian barley cultivars, and Nuez-Ortin and Yu[10] found DM degradation rate of 0.06/h and effective degradability 577 g/kg DM for wDDGS. Rumen degradation kinetics of barley in our study fell within these ranges. The higher $K_d$ for barley (B0) than for the barley−wDDGS mixtures was consistent with previous findings.[10,36] The reduced $K_d$ of OM and EDOM in the barley−wDDGS mixtures (B25, B50, and B75) relative to barley (B0) (0.12 vs 0.08/h) might be explained by the disappearance of easily fermentable components during ethanol fermentation or formation of Maillard products during the drying process of wDDGS.

Good-quality RUP is digestible and available for absorption in the small intestine. The RUP digestibility (IDP in g/kg CP) did not decline due to inclusion of wDDGS in the mixture in the current study. Nuez-Ortin and Yu[10] found similar IDP in wheat and wDDGS (both 780 g/kg RUP), and NRC[17] reports IDP values of 850 and 800 g/kg RUP of rolled barley and wDDGS, respectively. Schroeder et al.[38] reported that the digestibility of RUP of heat-processed plant proteins did not decrease by ADICP (i.e., PC) levels up to 120−150 g/kg CP. The ADICP content of wDDGS in this study was below those levels, and there was no relationship between ADICP content and IDP ($r = 0.122$, $P = 0.737$). These suggest that RUP had a high quality in all barley/wDDGS mixtures.

Soluble protein fraction ($S$) increased from 117 to 335 g/kg of CP as wDDGS inclusion increased in the mixture, and that augmented the overall ruminal degradable protein content. Increases in soluble CP fraction[39] in DDGS depend on the solubles added back during the drying process. The increased RUP 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, data not shown) relative to barley (138 g/kg DM), not to rumen degradation kinetics of wDDGS. In our study, RUP 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 RUP values found before for wDDGS.[10,17] The ratio between EDCP and RUP in wDDGS is mainly influenced by the amount of solubles added back during drying and to a smaller degree by the temperature used during the drying process.[10,40] The high EDCP/RUP ratio of wDDGS in our study will result in a relatively high ruminal protein degradation of dietary protein and decreases the delivery of dietary protein (ARUP) to the small intestine.

A strong inverse correlation ($r = -0.83$, $P = 0.01$) was found between the rate of starch degradability and wDDGS inclusion. Consequently, RUST was linearly increased from 283 to 396 g/kg starch ($P < 0.05$) as wDDGS inclusion increased. It is well documented that barley grain is rapidly fermented in the rumen, which increases the acidity of the rumen and reduces the activity and numbers of fiber-digesting bacteria to ferment forage fiber.[4,41] In terms of the feed energy efficiency and animal health, the lower and slower starch degradation in the rumen of barley−wDDGS mixtures is an important positive characteristic for ruminants over barley alone.

The correlation between the $K_d$ rate of NDF degradability and wDDGS inclusion ratio in the mixture was strong and negative ($r = -0.69$, $P = 0.06$). However, EDNDF averaged 364 g/kg NDF, which was not influenced by the inclusion of wDDGS in the mixture. This was in agreement with Nuez-Ortin and Yu,[10] who found EDNDF of 347 and 356 g/kg NDF for wheat and wDDGS, respectively. Results of this study indicate that increased inclusion of wDDGS in the mixture increases rumen availability of NDF ($r = 0.91$, $P = 0.01$), which provides a significant amount of energy for the microbial growth in the rumen. Thus, the high amount of rumen degradable NDF of wDDGS can substitute barley starch as ruminal energy source. The high rumen degradability of NDF from wDDGS results mainly from the higher NDF content in wDDGS rather than higher NDF degradability.

**Ratio of Rumen Available Protein to Energy.** Ruminal available dietary CP and energy (CHO or OM) are needed for microbial protein synthesis[42,43] with an optimum ratio of around 25 g N/kg OM truly digested in rumen[32] or 32 g N/kg CHO truly digested in rumen.[29,30] In the current study, both the hourly ED ratio of N to energy (Figure 1) as well as total ED ratio of N to energy data (Table 5) indicate that barley has below optimal rumen N to energy fermentation ratios, whereas B50 and B75 exhibit higher than optimal rumen N to energy fermentation ratios. The lower N to energy ratio for barley will result in a decreased microbial growth (protein synthesis), whereas the higher N to energy ratio for B50 and B75 will result in deamination of excess CP into energy and $NH_3$.[44]

**Protein Supply.** The protein supply to the rumen and intestine for barley in the current study was similar to previously reported values.[4] Published information on nutrient supply from barley−wDDGS mixture is not available. Degraded protein balance (DPB or OEB) in the rumen is critical to achieve efficient synthesis of the microbial protein, which ultimately contributes to the postruminal pool of the true protein.[10,28] In the current study, both protein models detected that with barley (B0) microbial protein synthesis may be compromised because of a potential shortage of N in rumen, whereas B25 and B50 had close to optimal N to energy supply and B75 had nitrogen over supply relative to energy. These results were also in accordance with the hourly ED ratios between N and OM reported above, in which B25 was the feed mixture that was close to the optimal N to energy ratio (25 g N/kg OM kg) during the entire 24 h of incubation. Previously it was found that inclusion of wheat DDGS at 20−25% of the dietary DM optimizes growth performance in feedlot cattle.[2,40,45] Further research with higher numbers of samples with more mixtures with narrow scale of barley and wDDGS combinations will help to refine the most optimal ratio of barley−wDDGS mixture for ruminants.

In conclusion, this study suggested that the chemical and energy profiles of wDDGS make it a good source of protein and energy for ruminants. The inclusion of wheat DDGS up to 50% of DM in barley-based diets will not affect energy values of the overall diet. The rates of nutrient (OM, CP, starch, and NDF) degradability in the rumen were consistently decreased by replacing barley with wDDGS in the feed mixture, which may prevent digestive disorders caused by feeding large amounts of barley grain. The results of the current study also revealed that the inclusion of wDDGS in barley-based diets changed the ratio between nitrogen and energy supply in the rumen and the small intestine. Inclusion of wheat DDGS up to 25% of DM in the feed mixture created desirable nitrogen to energy balances for microbial growth in the rumen. Overall, through replacing barley by 25−50% wheat DDGS, the nutritive value of diets is manipulated to more efficiently utilize barley for the beef industry.

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## ABBREVIATIONS USED

ADF, acid detergent fiber; ADICP, acid detergent insoluble crude protein; ADIN, acid detergent insoluble nitrogen; ADL, acid detergent lignin; AMCP, truly absorbed rumen synthesized microbial protein in the small intestine; ARUP, truly absorbed rumen undegraded feed protein in the small intestine; CA, rapidly fermented carbohydrate fraction; CB1, intermediately degraded carbohydrate fraction; CB2, slowly degradable CHO; CC, unavailable cell wall CHO; CHO, total carbohydrates; CNCPS, Cornell Net Carbohydrate and Protein System; D, insoluble but potential degradation fraction; DM, dry matter; DPB, degraded protein balance; DVE, total truly absorbed 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; IDP, intestinal digestibility of protein; $K_d$, 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, instantaneously available 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 undegraded feed OM, CP, starch, or NDF, respectively; S, soluble fraction; SCHO, CHO soluble in rumen; SCP, soluble crude protein; SN, N soluble in rumen; TDN, total digestible nutrients; U, undegradable fraction; wDDGS, wheat-based dried distillers grains with soluble.

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