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Chemical Profile, Rumen Degradation Kinetics, and Energy Value of Four Hull-less Barley Cultivars: Comparison of the Zero-Amylose Waxy, Waxy, High-Amylose, and Normal Starch Cultivars

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The objective of this study was to compare three new Canadian hull-less barley cultivars with altered starch characteristics (zero-amylose waxy, CDC Fibar; waxy, CDC Rattan; and high-amylose, HB08302) with conventional normal starch hull-less barley (HB) cultivar (CDC McGwire) in terms of ruminant feed value. The study revealed that altered starch HB cultivars possessed several desirable feed characteristics, distinct from conventional normal starch HB, although they were similar in some respects: (1) basic chemical and carbohydrate subfraction profiles varied; (2) starch degradation kinetics showed altered starch HB containing higher soluble starch, rumen undegraded starch, lower degradable starch, and slower degradation rate; (3) all altered starch HB cultivars had similar soluble and degradable starch, different from that of conventional normal starch HB; (4) two waxy HB cultivars were lower, whereas the high-amylose cultivar was similar in effective degradability of the starch as compared to conventional normal starch HB; (5) zero-amylose waxy HB had the greater effective degradability of protein among HB cultivars; and (6) amylopectin in HB had a positive relationship with protein supply (increasing amylopectin was correlated with increased effective degradability of protein). Overall, these results demonstrate that the alteration of starch structure in granule affects not only starch fermentation and utilization but also protein value in hull-less barley. In summary, the HB cultivars with modified starch might be a better feed grain for ruminants than the normal starch HB.

KEYWORDS: Hull-less barley; protein and energy evaluation; starch structure; in situ; ruminants

INTRODUCTION

Barley (*Hordeum vulgare* L.) is the fourth largest cereal crop produced in the world. The versatile composition of barley makes it a suitable animal feed, malt, and food material. Worldwide, barley is predominantly used as feed (*1*). Canada is the third largest barley producer in the world, with an annual barley production close to 11 million tonnes (*2*). About 43% of the barley produced is exported, whereas 18% goes toward human consumption and industrial use and the remainder (39%) is used as animal feed. Canada has locally adapted and registered 200 cultivars of barley (*3*). There are over 50 barley cultivars produced in western Canada, including 8 hull-less types, 13 malting types, and some others suitable for the livestock industry. Starch, the major storage compound in cereal endosperm, is composed of two distinct types of glucose polymers: amylose and amylopectin. Normal barley starch consists of 750−850 g/kg amylopectin and 150−250 g/kg amylose (*4*). The concentrations of amylopectin and amylose influence the barley quality in both the malting and food industries (*5*−*7*). Amylopectin is a large branched polymer with linkages of α-1,4 that serve as the backbone and α-1,6 bridges that serve as branching points (*8*). Amylose is a mostly linear chain consisting of up to 3000 glucose molecules interconnected primarily by α-1,4 glycosidic linkages (*9*). Cattle in western Canadian feedlots are fed ad libitum with a ration containing up to 90% barley grain (personal communication, John J. McKinnon, University of Saskatchewan). Yet hull-less barley (HB) was developed primarily for swine and poultry feeding (*10*) and is characterized by the spontaneous loss of hulls during harvest (*11*). Hull-less barley has a higher concentration of protein and starch, but lower fiber concentration than hulled cultivars (*12*−*14*). Very few studies have addressed the feed quality of HB (*11*, *15*). Main concern with respect to feeding HB to ruminants is the rapid digestion in the rumen, resulting in increased incidences of digestive disorders such as acidosis, laminitis, and bloat (*11*, *15*). However, the hull-less barley tested in these studies was all normal starch HB (Condor cultivar). Recently, several new Canadian hull-less barleys with altered starch, including cultivars with reduced (waxy and with high amylopectin) and elevated levels of amylose, have been developed (*16*) by the University of Saskatchewan's Crop Development Centre as a part of its food barley breeding program using a

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pedigree breeding system. The variations in the molecular composition and characteristics of starches substantially affect functional properties; therefore, waxy or high-amylose barleys have enormous potential for unique food and industrial applications (*7*). These altered starch HB cultivars may be better alternatives as animal feed in terms of starch digestibility. Reasonably, the following questions are raised on HB with altered starch, from the point of view of ruminant nutrition: (1) What is their nutrient profile, and (2) how are these cultivars different from the normal starch hull-less barley? Answering these questions will help determine the place for these newer starch altered HB cultivars in ruminant feed. The objective of this study was to determine the nutritional quality for ruminants of zero-amylose waxy (CDC Fibar), waxy (CDC Rattan), and high-amylose HB (HB08302) in comparison to feed-type HB with normal starch characteristics (CDC McGwire). The items assessed included (1) chemical and nutrient profiles, (2) protein and carbohydrate subfractions and energy value, (3) rumen degradation kinetics, and (4) correlation analysis between the above-mentioned parameters.

MATERIALS AND METHODS

Sample Preparation. Four cultivars of HB with a range of amylopectin (and amylose) were selected (500 g sample of each barley cultivar) for the study. CDC McGwire is a normal starch, feed-type HB, whereas CDC Fibar, CDC Rattan, and HB08302 are zero-amylose waxy, waxy, and high-amylose HB cultivars, respectively. Amylopectin contents were 75, 100 (zero-amylose waxy), 95, and 60% (high-amylose) for the normal starch, zero-amylose waxy, waxy, and high-amylose cultivars, respectively (*16*). CDC McGwire, CDC Fibar, and CDC Rattan are two-row head-type cultivar, and HB08302 is a six-row head-type cultivar. CDC McGwire is a widely cultivated feed-type HB in western Canada and is used as a reference by barley breeders. All cultivars were grown at the University of Saskatchewan Research Station (Saskatoon). Potential yields averaged about 78, 98 (*16*), and 92% (personal communication, B. G. Rossnagel, University of Saskatchewan, Saskatchewan, Canada) of normal starch HB yield for zero-amylose waxy, waxy, and high-amylose cultivars, respectively. Samples were ground using a Retsch mill [Retsch ZM-1, Brinkmann Instruments (Canada) Ltd., Ontario, Canada] through a 0.5 mm screen for starch analysis and through a 1 mm screen for other chemical analyses. For rumen kinetics in situ, the barley samples were processed through a 1.58 mm gap roller mill (Seven Grain Mill, Apollo Machine and Products Ltd., Saskatoon, Canada) at the Engineering Laboratory, University of Saskatchewan (Saskatoon, SK, Canada), which is a common practice in the western Canada feedlots to coarsely process barley.

Chemical Analysis. Dry matter (DM), ash, crude fat, and crude protein (CP) contents were analyzed according to the procedure of the AOAC (*17*). The acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL) values were analyzed according to the procedures of Van Soest et al. (*18*). For determination of NDF, ADF, and ADL, an ANKOM Fiber Analyzer (ANKOM Technology Corp., Fairport, NY) was used. For NDF determination, 4 mL of Ankom heat stable α-amylase (ANKOM Technology FAA) with an activity level of 340−374 MWU/mL was added to each of the first three rinses. The starch was analyzed using the Megazyme Total Starch Assay Kit (Megazyme International Ltd., Wicklow, Ireland). The nonprotein nitrogen content was obtained by precipitation of true protein in the filtrate with trichloroacetic acid (final concentration = 10%) and determined as the difference between total N and the N content of the residue after filtration. The amount of CP associated with NDF (neutral detergent insoluble CP) was determined by analyzing the NDF residues for CP (*17*). Soluble crude protein was determined by incubating the sample with bicarbonate−phosphate buffer and filtering through Whatman filter paper. The nonstructural carbohydrates were measured by enzymatic methods (*19*). The carbohydrate (CHO) and true protein were calculated according to the formulas of the NRC dairy (*20*).

Subfractioning of Protein and Carbohydrate. Crude protein and carbohydrate fractions were partitioned according to the Cornell Net Carbohydrate Protein System (*21*, *22*). The characterizations of the CP fractions as applied in this system are as follow: (1) nonprotein nitrogen, (2) true protein, and (3) unavailable protein. The true protein fraction is further divided into three fractions: (1) rapidly degradable, (2) intermediately degradable, and (3) slowly degradable. The rapidly degradable fraction was determined as the trichloroacetic acid-precipitable fraction (*23*). The intermediately degradable fraction of true protein is insoluble in buffer, but soluble in neutral detergent, whereas the slowly degradable fraction is insoluble in both buffer and neutral detergent, but soluble in acid detergent (*24*). The intermediately degradable fraction is fermented in the rumen at a lower rate than buffer-soluble fractions, and some of this fraction escapes to the lower gut. The slowly degradable fraction is believed to be more slowly degraded in the rumen than fractions rapidly and intermediately degradable because of its association with the plant cell wall; thus, a large proportion of this fraction is believed to escape the rumen. The unavailable protein fraction is the acid detergent insoluble N. The relative rumen degradation rates of the five protein fractions have been described by Sniffen et al. (*22*) as follows: the nonprotein nitrogen fraction is assumed to be infinity, the rapidly degradable fraction is 1.20−4.00 h^{-1}, the intermediately degradable fraction is 0.03−0.16 h^{-1}, and the slowly degradable fraction is 0.0006−0.0055 h^{-1}. The unavailable protein fraction is considered to be, also, undegradable. Carbohydrate was fractionated into a soluble fraction, which is composed of fermentable soluble sugars that have a rapid degradation rate of 3.00 h^{-1}, an intermediately degradable fraction, which is starch and pectin with an intermediate degradation rate of 0.20−0.50 h^{-1}, a slowly degradable fraction, which is the available cell wall with a slow degradation rate of 0.02−0.10 h^{-1}, and an unfermentable fraction, which is the unavailable cell wall (*22*). The energy values of total digestible nutrient ($TDN_{1\times}$), digestible energy for lactation ($DE_{3\times}$), and net energy for lactation ($NE_{L3\times}$) were estimated using the NRC dairy (2001) model, and net energy for maintenance (NE_m) and net energy for growth (NE_g) were estimated using the NRC beef (*25*) model.

In Situ Rumen Incubation Technique. Rumen degradation characteristics were determined using the in situ method (*26*, *27*). Four dry Holstein cows weighing an average of 891 (±54 kg) were fitted with a flexible rumen cannulae with an internal diameter of 10 cm 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 the in situ rumen incubation times. The cows were fed a 50:50 barley silage (26.8% DM) to concentrate diet according to the NRC maintenance requirement (*20*). The cows were fed half of the ration twice daily at 8:00 a.m. and 4:00 p.m. Water was available ad libitum. Care for the animals followed guidelines described in the CCAC (*28*). Seven grams of an individual ground sample was weighed into a preweighed and numbered nylon bag (10 × 20 cm) with the 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 19 mg/cm^2. Samples were incubated in the rumen for 0, 2, 4, 8, 12, 24, and 48 h. Rumen incubations were performed according to the "gradual addition/all out" schedule (*29*). In this technique, the bags assigned for the longest incubation time (48 h) are put in the rumen first, then at 24 h since the first bags were incubated in the rumen, the next bags with the next longest incubation time (24 h) are added and so on; in this way the bags are added into the rumen gradually in a descending order of their assigned incubation time until the 0 h bags and then all bags are removed from the rumen at the same time or at 48 h of the first and 0 h of the last bags, because each bag is supposed to have been incubated for the designated time. Data from Urdl et al. (*30*) were used to determine the number of bags to be incubated from each sample, which is increased in relation to incubation time. The maximum number of bags in the rumen at any one 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 washed with cool water without detergent and subsequently dried at 55 °C for 48 h. The 0 h incubation samples were washed only, under the same conditions. Dry samples were stored in a refrigerated room (4 °C) until analysis. The residues were pooled for laboratory chemical analysis according to barley cultivar, incubation time, and animal.

Rumen Degradation Kinetics. The first-order kinetic degradation model described by Orskov and McDonald (*26*) and by Tamminga et al. (*31*) was applied to describe the rumen degradation characteristics of DM, CP, and starch. In this technique, the results were calculated using the NLIN procedure of SAS and iterative least-squares regression (Gauss−Newton method) by the first-order kinetics equations (*30*)

$$R(t) = U + D \times \exp(-K_d \times (t - T_0)) \text{ for the DM and CP} \quad (1)$$

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

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 (in g/kg), T_0 is lag time (h), and K_d is the degradation rate (h^{-1}).

The effective degradability (ED) values were calculated as

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

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

$$\text{EDST (g/kg DM)} = \text{ST (g/kg DM)} \times \text{EDST (g/kg)} \quad (5)$$

where soluble fraction (S) in grams per kilogram and passage rate (K_p) of 0.06 h^{-1} were adapted (*31*). The rumen undegradable feed protein (RUP) value was calculated as

$$\text{RUP (g/kg of CP)} = U + D \times K_p/(K_p + K_d) \quad (6)$$

$$\text{RUP (g/kg DM)} = 1.11 \times \text{CP (g/kg DM)} \times \text{RUP (g/kg)} \quad (7)$$

where K_p of 0.06 h^{-1} was adapted. The rumen undegraded feed starch (RUST) values were calculated as

$$\text{RUST (g/kg)} = D \times K_p/(K_p + K_d) + 0.1 \times S \quad (8)$$

$$\text{RUST (g/kg DM)} = \text{ST (g/kg DM)} \times \text{RUST (g/kg)} \quad (9)$$

where K_p of 0.06 h^{-1} was adapted (*31*). For the factor 0.1 in the formula, it was assumed that for starch, 100 g/kg of soluble fraction (S) escapes rumen fermentation (*31*).

Statistical Analysis. Statistical analysis was performed using the MIXED procedure of SAS 9.2 (*31*). Data were analyzed with a CRD model

$$Y_{ij} = \mu + T_i + e_{ij}$$

where Y_{ij} is an observation of the dependent variable ij, μ is the population mean for the variable, T_i is the effect of the HB cultivars, as a fixed effect, 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 test. If data were unbalanced, pooled standard error was calculated and reported. The mean separation was done by using the PDIFF statement. The correlations between (1) amylopectin and (2) starch and chemical profiles, nutrient supply, and in situ degradation kinetics were analyzed using the PROC CORR of SAS.

RESULTS

Chemical and Nutrient Profiles. Chemical composition, protein and carbohydrate fraction profiles, and predicted energy values for HB are shown in **Table 1**. Chemical composition varied among the HB cultivars. Normal starch HB contained numerically higher (> 5% unit) nonstructural carbohydrate, soluble protein, and nonprotein nitrogen, as well as neutral detergent insoluble CP. Zero-amylose waxy was high in CP and NDF, but was low in CHO and nonstructural carbohydrate among HB cultivars. Waxy was high in ADF, intermediately degradable CP, and soluble carbohydrate, but was low in soluble protein, neutral detergent insoluble CP, and slowly degradable CP, as well as intermediately degradable carbohydrate among HB cultivars. High-amylose HB was highest in starch, ADL, rapidly degradable CP, and intermediately degradable CHO, but was lowest in CP, nonprotein nitrogen, and soluble carbohydrate among HB cultivars. Furthermore, among HB cultivars, slowly degradable carbohydrate varied greatly (**Figure 1**). However, the energy density showed very little variation among the cultivars.

Rumen Degradation Kinetics. In situ rumen degradation kinetics of DM, starch, and CP of HB are reported in **Table 2**. The rate of degradation of DM or CP showed no differences between the HB cultivars ($P > 0.05$), whereas significant differences ($P = 0.0169$) were detected in the rate of starch degradation among HB cultivars. The normal HB had the highest rate of starch degradation ($P < 0.05$), whereas the rest of the cultivars had rates similar to each other. Differences ($P < 0.05$) were detected in the soluble fraction of DM, CP, and starch among HB cultivars. Zero-amylose waxy and high-amylose had low soluble fractions ($P < 0.05$), whereas waxy had a comparable soluble fraction of DM ($P > 0.05$) to normal starch HB. All three altered starch HB cultivars had similar levels of soluble fraction of starch ($P > 0.05$), that were, nevertheless, higher ($P < 0.05$) than that of normal starch. Although zero-amylose waxy was lower ($P < 0.05$), waxy and high-amylose were similar ($P > 0.05$) to normal starch HB in soluble fraction of protein. There was no difference ($P > 0.05$) in degradable and undegradable fraction of DM and CP for all of the HB cultivars. In contrast, normal starch HB had a greater ($P < 0.05$) degradable fraction of starch than the three altered starch HB cultivars. The differences between the effective degradability of DM among cultivars have not reached a significant level ($P = 0.0557$). Zero-amylose waxy and waxy HB were lower ($P < 0.05$), whereas high-amylose HB was similar ($P > 0.05$) to normal starch HB in the effective degradability of starch. On the basis of rumen undegraded starch levels, the HB cultivars can be ranked as follows: normal starch (160.9 g/kg DM) < zero-amylose waxy (172.7 g/kg DM) < waxy (178.0 g/kg DM) < high-amylose (211.2 g/kg DM). Furthermore, waxy, high-amylose, and normal starch HB cultivars have similar ($P > 0.05$) effective degradability of protein and rumen undegraded protein, whereas zero-amylose waxy has greater ($P < 0.05$) levels of these proteins present. In the current study, the ratio of starch degradation rate to CP degradation rate was 1.9, 1.2, 1.1, and 1.1 for normal starch, zero-amylose waxy, waxy, and high-amylose HB, respectively. Excluding the effective degradability of starch and rumen undegraded starch, the major parameters of starch degradation kinetics (degradation rate, soluble and degradable fraction) were not affected ($P > 0.05$) by the magnitude of starch content.

Correlations. Pearson correlation coefficients between starch and its subfractions, chemical and nutrient profiles, carbohydrate subfractions, rumen degradation kinetics, and nutrient supply of HB are given in **Table 3**. Starch amylopectin had positive correlation with CP ($r = 0.88$, $P = 0.004$), rumen undegraded protein ($r = 0.92$, $P = 0.001$), and the effective degradability of protein ($r = 0.70$, $P = 0.053$), but had negative correlation with total carbohydrate ($r = -0.75$, $P = 0.032$), intermediately degradable carbohydrate ($r = -0.94$, $P = 0.001$), and rumen soluble protein ($r = -0.84$, $P = 0.009$). Also, a moderate positive correlation ($r = 0.64$, $P = 0.091$) was detected between amylopectin and rumen degradable protein. Intermediately degradable carbohydrate ($r = 0.98$, $P < 0.001$), effective degradability of starch ($r = 0.88$, $P = 0.004$), and rumen soluble protein ($r = 0.80$, $P = 0.018$) were positively correlated, whereas CP ($r = -0.81$, $P = 0.015$) and rumen undegradable protein ($r = -0.89$, $P = 0.003$) were negatively correlated with the starch level of HB.

Table 1. Chemical Composition, Protein and Carbohydrate Subfractions, and Energy Values of the Hull-less Barleys: Comparison of Zero-Amylose Waxy, Waxy, High-Amylose, and Normal Starch Barley Grown at the University of Saskatchewan Research Station (Saskatoon)

	cultivars			
item	normal starch	zero-amylose waxy	waxy	high-amylose
chemical and nutrient profiles				
ash (g/kg DM)	20 (±1)	23 (±1)	20 (±1)	20 (±1)
crude fat (g/kg DM)	25 (±1)	32 (±2)	24 (±2)	30 (±1)
crude protein (CP) (g/kg DM)	128 (±1)	155 (±1)	135 (±1)	122 (±1)
total carbohydrate (CHO) (g/kg DM)	828 (±2)	790 (±2)	821 (±2)	829 (±1)
nonstructural carbohydrate (g/kg DM)	677 (±2)	567 (±3)	635 (±2)	625 (±3)
starch (g/kg DM)	534 (±15)	479 (±23)	477 (±7)	574 (±11)
acid detergent fiber (g/kg DM)	32 (±1)	32 (±1)	37 (±1)	34 (±1)
neutral detergent fiber (g/kg DM)	162 (±4)	236 (±2)	196 (±1)	209 (±5)
acid detergent lignin (g/kg DM)	20 (±1)	28 (±1)	27 (±1)	35 (±1)
soluble protein (SCP) (g/kg CP)	300 (±7)	271 (±16)	260 (±5)	285 (±7)
nonprotein nitrogen (g/kg SCP)	391 (±67)	312 (±23)	235 (±54)	219 (±35)
neutral detergent insoluble CP (g/kg CP)	91 (±4)	81 (±7)	64 (±1)	80 (±11)
protein and carbohydrate subfractions (Cornell Net Carbohydrate and Protein System)				
nonprotein nitrogen (g/kg CP)	117 (±3)	84 (±1)	61 (±1)	62 (±1)
rapidly degradable CP (g/kg CP)	183 (±2)	186 (±2)	199 (±3)	222 (±2)
intermediately degradable CP (g/kg CP)	603 (±2)	624 (±2)	651 (±2)	605 (±2)
slowly degradable CP (g/kg CP)	77 (±1)	82 (±2)	63 (±2)	83 (±2)
unavailable CP (g/kg CP)	14 (±1)	−2 (±1)	0 (±1)	−3 (±1)
soluble carbohydrate (g/kg CHO)	172 (±3)	111 (±2)	193 (±2)	61 (±1)
intermediately degradable CHO (g/kg CHO)	646 (±4)	606 (±6)	579 (±6)	698 (±4)
slowly degradable CHO (g/kg CHO)	177 (±3)	274 (±2)	220 (±3)	230 (±1)
unfermentable CHO (g/kg CHO)	6 (±1)	8 (±1)	8 (±1)	10 (±1)
energy value (MJ/kg DM; NRC-2001 dairy and NRC-1996 beef)				
total digestible nutrient (g/kg DM)	886 (±15)	867 (±23)	872 (±11)	875 (±13)
digestible energy for lactation (NRC-2001 dairy)	15 (±4)	15 (±4)	15 (±4)	15 (±4)
net energy for lactation (NRC-2001 dairy)	8 (±2)	8 (±2)	8 (±2)	8 (±2)
net energy for maintenance (NRC-1996 beef)	9 (±2)	9 (±2)	9 (±2)	9 (±2)
net energy for growth (NRC-1996 beef)	6 (±2)	6 (±2)	6 (±2)	6 (±2)

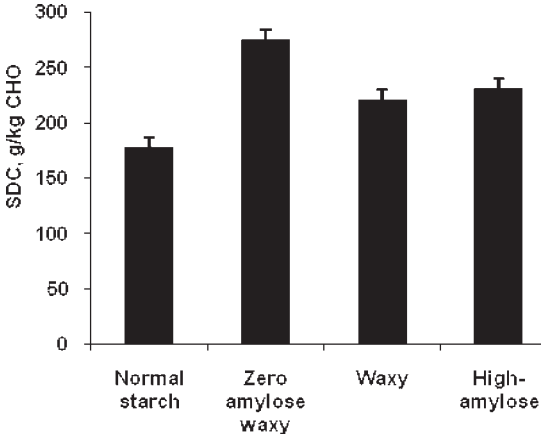

Figure 1. Slowly degradable carbohydrate fractions of four hull-less barley (normal starch, CDC McGwire; zero-amylose waxy, CDC Fibar; waxy, CDC Rattan; high-amylose, HB08302) cultivars estimated by Cornell Net Carbohydrate and Protein System (*28*). SDC, slowly degradable carbohydrate fractions estimated by Cornell Net Carbohydrate and Protein System (CNCPS); CHO, total carbohydrate.

DISCUSSION

Chemical Profiles. Edney et al. (*12*) found that Condor HB had CP ranging from 13 to 17%, which is in agreement with our findings. Twelve Canadian HB cultivars grown at different locations contained 62−75% starch (*32*). NDF, ADF, and ADL observed in the present study were within the ranges reported by Yang et al. (*11*) and Ramsey et al. (*14*). The inverse relationship between starch and protein in HB can be found in previous studies (*10*, *12*). As expected, due to the absence of the hull, these HB cultivars had less ADF, NDF, neutral detergent insoluble protein, and nonprotein nitrogen and greater rapidly and intermediately degradable protein and energy values (*25*) compared to hulled barley (*27*).

Rumen Degradation Kinetics. As demonstrated previously, for in situ DM rumen degradation kinetics, only the soluble fraction differed among the HB cultivars. In parallel, soluble carbohydrate fraction estimated by CNCPS also varied greatly among the cultivars, similar to Yu et al. (*27*) results on Valier and Harrington (1.5 vs 11.6% DM) barley, owing to the difference of barley type (feed vs malting). Differences in nonprotein nitrogen and rapidly degradable protein levels were likely major factors contributing to the variable CP rumen degradation kinetic parameters among the HB cultivars. The greater rumen soluble fraction in normal starch HB may be explained by its higher nonprotein nitrogen. To our knowledge, research with altered starch barley in ruminants is scarce. In the current study, the effective degradability of starch was increased with decreased amylopectin (and increased amylose) level in starch of HB, which concurred with reports by others (*33*). The most likely reasons for these effects were the differences in starch characteristics and chemical composition and perhaps the different responses to processing between the HB cultivars. Previous studies (*33*, *34*) found that the percentage of relative crystallinity of the waxy (high amylopectin) barley starch was greater than that of the normal barley and, consequently, may have been more resistant to enzyme hydrolysis. Protein within the endosperm tissue of cereal grains is arranged in a matrix that surrounds and protects the starch granules, making them less available for digestion by rumen bacteria (*35*). Likewise, a greater protein to starch ratio (i.e., more protein per unit of starch) may be indicative of a greater degree of protection of starch granules within the protein

Table 2. Rumen Degradation Characteristics of the Barley Cultivars: Comparison of Four Hull-less Barley Cultivars (CDC McGwire, CDC Fibar, CDC Rattan, and HB08302) Grown at the University of Saskatchewan Research Station (Saskatoon) in 2008[a]

	cultivars					
item	normal starch	zero-amylose waxy	waxy	high-amylose	SEM	*P* value
rumen degradation kinetics of dry matter (DM) (Orskov model)						
lag time (h)	0.8	1.0	0.8	0.9	0.23	0.844
soluble fraction (g/kg)	*36.5a*	*16.1b*	*23.0ab*	*17.4b*	*3.31*	*0.037*
degradable fraction (g/kg)	890.4	929.2	915.6	924.4	14.34	0.354
undegradable fraction (g/kg)	73.1	54.8	61.4	58.2	13.28	0.786
rate of degradation (%/h)	13.5	10.0	9.6	9.3	0.87	0.073
rumen undegradable DM (g/kg DM)	346.7	405.7	415.1	422.0	13.87	0.056
effective degradability (g/kg DM)	653.3	594.3	584.9	578.0	13.87	0.056
rumen degradation kinetics of starch (DVE/OEB system)						
soluble fraction (g/kg)	*0.0a*	*111.2b*	*168.5b*	*116.0b*	*17.24*	*0.010*
degradable fraction (g/kg)	*1000a*	*888.8b*	*881.5b*	*884.0b*	*17.24*	*0.010*
rate of degradation (%/h)	*13.9a*	*9.3b*	*8.0b*	*8.9b*	*0.75*	*0.017*
rumen undegraded starch (g/kg DM)	*160.9a*	*172.7a*	*178.0ab*	*211.2b*	*6.18*	*0.018*
effective degradability (g/kg DM)	*373.4a*	*306.3b*	*298.8b*	*363.2a*	*6.18*	*0.002*
rumen degradation kinetics of protein (Orskov model)						
lag time (h)	0.5	1.5	1.1	1.3	0.29	0.257
soluble fraction (g/kg)	*45.2a*	*8.9b*	*24.0ab*	*43.3a*	*5.52*	*0.026*
degradable fraction (g/kg)	921.8	968.4	945.4	924.2	17.91	0.349
undegradable fraction (g/kg)	33.0	22.7	30.6	32.5	15.87	0.962
rate of degradation (%/h)	7.4	7.7	7.0	7.8	0.61	0.805
rumen undegraded protein (g/kg DM)	*70.0a*	*83.5b*	*77.5ab*	*67.1a*	*1.82*	*0.010*
effective degradability (g/kg DM)	*86.7a*	*103.4b*	*88.8a*	*86.4a*	*1.81*	*0.007*

[a] Means within a row with different letters differ ($P < 0.05$). SEM, standard error of mean. Means in italic type differ ($P < 0.05$).

matrix, resulting in a lower rate and extent of rumen degradation (*36*). In this study, the starch to protein ratio was greater for normal starch (4.2) and high-amylose (4.7) than for zero-amylose waxy (3.1) and waxy HB (3.5). Hence, there would have been more protein surrounding starch in normal starch and high-amylose HB, but less in zero-amylose waxy and waxy HB, which would directly affect starch degradation. Correspondingly, as discussed earlier, the two cultivars with the highest starch to protein ratios had similar ($P > 0.05$) larger effective degradability of starch (373.4 and 363.2 g/kg DM) compared to the other cultivars with lower starch to protein ratios (306.3 and 298.8 g/kg DM). Thus, our results were partly in agreement with the latter findings on effects of cereal granule starch and protein ratio to their degradation characteristics. In addition, a strong positive correlation ($r = 0.63$; $P = 0.091$) was detected between the starch to protein ratio and effective degradability of starch. The current study further revealed that the protein rumen kinetics parameters are affected by the starch to protein ratio of grain. Specifically, rumen soluble fraction of protein was positively ($r = 0.83$, $P = 0.011$) correlated, but rumen undegraded protein ($r = -0.927$, $P = 0.001$) and effective degradability of protein ($r = -0.73$, $P = 0.039$) were negatively correlated, with the starch to protein ratio. Moreover, the decreased rate of degradation and effective degradability of DM of waxy and high-amylose cultivars (and starch) might have been influenced by a greater NDF content with the altered starch HB. Furthermore, others (*10*, *37*) indicated that barley with greater β-glucan content tended to remain in larger pieces after mechanical processing. Simultaneously, several studies have shown that the larger particle of grain facilitates slower degradation of feed in the rumen (*6*, *35*, *38*, *39*). Also, it is a fact that altered starch HB generally had greater β-glucan (*37*) content. In agreement with the latter finding, as Rossnagel et al. (*16*) reported, the 5-year (2000−2004) average total β-glucan content was 4.9 (3.9−5.5), 10.1 (9.1−11.8), 7.3 (6.6−7.8), and 7.3% for the normal starch, zero-amylose waxy, waxy, and high-amylose HB, respectively. Considering these findings, we speculated that a higher β-glucan level may also cause a slower degradation rate on altered starch HB. The rumen undegraded starch will be subjected to digestion in the small intestine. As Owens et al. (*40*) estimated, starch digested in the small intestine provides 42% more energy than starch digested in the rumen. Hence, the altered starch HB, specifically the high-amylose cultivar (211.2 g/kg DM), provides greater rumen undegraded starch for digestion in the small intestine. Moreover, it is well-known that barley with normal starch is rapidly fermented in the rumen following ingestion, which may increase the acidity of the rumen and reduce fiber-digesting bacteria necessary to ferment forage fiber into precursors for milk fat synthesis (*11*). Therefore, in terms of energy efficiency and animal health, the slower degradation of altered starch HB should be considered an important positive characteristic of a good feed grain for ruminants over the normal starch HB, which degraded more quickly in the rumen. Overall, our results agree with the previous findings (*27*, *41*) that the different cultivars of barley can have various rates and extents of rumen degradation due to the differences in the intrinsic physical structures and chemical components.

In conclusion, this comparison between the new HB cultivars with altered starch and normal starch HB showed differences in the areas of (1) basic chemical and carbohydrate subfraction profiles and (2) starch rumen degradation kinetics, with altered starch HB containing a higher soluble fraction and a lower degradable fraction and having a slower degradation rate. In fact, three (soluble fraction, degradable fraction, and rate of degradation) of the five major measured parameters of starch rumen degradation kinetics all performed similarly in the altered starch HB. Subsequently, the altered starch HB showed some advantages over normal starch HB as ruminant feed grain, owing to slower starch degradation and greater starch supply in the small intestine. The results suggest that the alteration of starch in the HB through breeding can influence the rate and extent of starch and protein degradations in the rumen and digestion in the small intestine, thus providing a better synchronization of available energy and nitrogen for ruminal microorganisms.

Table 3. Pearson Correlation Analysis between the Amylopectin and Starch Level to Chemical Profiles, Cornell Net Carbohydrate and Protein System (CNCPS) Carbohydrate Fractions, and in Situ Rumen Degradation Kinetics in Four Cultivars of Hull-less Barleys

	correlations			
item	amylopectin	*P* value	starch	*P* value
chemical profiles, % DM				
crude fat	−0.05	0.915	0.16	0.710
total carbohydrate	−0.75	0.032	0.66	0.074
neutral detergent fiber	0.33	0.428	−0.25	0.558
acid detergent fiber	0.13	0.768	−0.20	0.627
acid detergent lignin	−0.42	0.298	0.45	0.267
nonstructural carbohydrate	−0.51	0.200	0.42	0.302
crude protein (CP)	0.88	0.004	−0.81	0.015
soluble crude protein	0.55	0.160	−0.45	0.266
neutral detergent insoluble protein	0.17	0.687	−0.07	0.871
carbohydrate subfractions, % CHO (CNCPS)				
soluble fraction of CHO	0.51	0.199	−0.59	0.121
intermediately degradable fraction of CHO	−0.94	0.000	0.98	0.001
slowly degradable fraction of CHO	0.47	0.239	−0.39	0.340
unfermentable fraction of CHO	−0.23	0.592	0.26	0.536
energy value (NRC-2001 dairy and NRC-1996 beef)				
total digestible nutrient	−0.56	0.151	0.52	0.188
net energy for lactation	−0.06	0.881	0.09	0.840
net energy for growth (NRC-1996 beef)	−0.06	0.881	0.09	0.840
in situ rumen degradation kinetics of DM (Orskov model)				
rate of degradation	−0.14	0.750	0.13	0.757
lag time; no degradation takes place	0.15	0.724	−0.10	0.807
soluble fraction	−0.17	0.683	0.12	0.773
degradable fraction	0.17	0.685	−0.13	0.757
undegradable fraction	−0.14	0.746	0.11	0.795
rumen undegradable DM	0.09	0.830	−0.09	0.833
effective degradability	−0.09	0.830	0.09	0.833
in situ rumen degradation kinetics of starch (DVE/OEB system)				
rate of degradation	−0.27	0.523	0.28	0.504
soluble fraction	0.35	0.391	−0.38	0.349
degradable fraction	−0.35	0.391	0.38	0.349
rumen undegraded starch	−0.56	0.145	0.57	0.142
effective degradability	−0.87	0.005	0.88	0.004
in situ rumen degradation kinetics of CP (Orskov model)				
rate of degradation	−0.19	0.657	0.24	0.574
lag time; no degradation takes place	0.22	0.605	−0.17	0.690
soluble fraction	−0.84	0.009	0.80	0.018
degradable fraction	0.64	0.091	−0.59	0.121
undegradable fraction	−0.19	0.655	0.17	0.695
rumen undegraded protein	0.92	0.001	−0.89	0.003
effective degradability	0.70	0.053	−0.61	0.110

ABBREVIATIONS USED

ADF, acid detergent fiber; ADL, acid detergent lignin; CHO, total carbohydrate; D, insoluble, but potentially degradable fraction in the in situ incubations; DM, dry matter; NDF, neutral detergent fiber; CP, crude protein; SCP, soluble protein.

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