



Article

Rumen Degradability of Barley, Oats, Sorghum, Triticale, and Wheat In Situ and the Effect of Pelleting

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Abstract: Feeding cereal grain to cattle is common practice for optimal beef and milk production. High concentrations of starch and other soluble carbohydrates may cause acidosis. Information on the effect of processing on starch and protein degradability in the rumen are scarce. This study was to determine the ruminal degradation patterns of common grains and the effect of steam pelleting on starch and crude protein (CP) degradability in the rumen. The ruminal degradation pattern of dry matter (DM), starch, and CP of ground and pelleted sorghum, barley, wheat, and samples along with ground oats and triticale were determined using the in situ nylon bags method. Cereals were incubated for 0, 2, 4, 6, 8, 16, 32, and 60 h, and the fast and slowly degradable fraction, the effective degradation rate, and effective degradability (ED) of DM, starch, and CP were calculated. The starch ED of ground and pelleted sorghum, barley, and two wheat samples were 57.3, 93.6, 95.2, and 97.2%; and 61.5, 93.8, 93.8, and 95.6%, and their crude protein ED was 54.8, 82.3, 83.3, 82.6% and 51.9, 79.2, 81.8, and 78.1% respectively. The starch ED of ground oat and triticale were 98.3 and 94.7%, and that of CP were 93.7 and 75.2%, respectively. The degradability of sorghum was significantly lower than that of the other grains. Pelleting increased the fast-degradable DM and starch fraction of sorghum and tended to improve its DM degradability ($p = 0.081$). Pelleting significantly reduced the fast-degradable fraction of DM and starch of wheat samples and numerically reduced its degradability.

Keywords: in situ; rumen; pelleting; degradability; cereal grains



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1. Introduction

As the world demand for milk and meat grows, the need for ruminant feed resources increases [1]. Rapidly growing beef cattle and high milk-producing dairy cows cannot meet their energy requirements from herbages alone, and cereal grains are commonly used in diets, globally, for intensively managed dairy cows and feedlot beef cattle to increase their energy intake and production [1]. The situation is similar in Australia [1], but unlike many countries, there is lower reliance on maize as a stock feed, with barley, sorghum, and wheat being used extensively for ruminants.

Starch, as a main component of grain, provides a large amount of energy for animal growth and production [2]. Starch digested in the small intestine of ruminants was 42% more efficiently used by animals than rumen fermentation of starch into volatile fatty acids (VFAs) [3]. The determination of the ruminal degradability rate of feed, especially of starch and crude protein (CP), has therefore become one of the most common methods to evaluate the nutritional value of ruminant feed [4,5]. Determination of the energetics of feed is critical when formulating diets as the oversupply of an energy feed containing a large amount of rapidly degradable starch can cause acidosis, a digestive disease that

commonly occurs in intensively fed ruminants [6,7]. When starch consumption is excessive, rapid rumen fermentation produces a large amount of lactic acid, causing a drop in rumen pH, leading to a change in the microbial population [6]. The change in microbiota is associated with changes in rumen function, reduced feed intake, and consequently, reduced productivity [6].

The form in which a feed is fed will influence degradability, and grain processing is a common practice to improve feed efficiency [8]. Pelleting has several advantages, e.g., pellets can incorporate minerals, vitamins, and different protein sources, other supplements and medications, preventing animals from rejecting essential supplementary ingredients [8]. However, studies on the effects of steam pelletting of feed ingredients on starch and CP degradability are limited, even though more and more ruminants are being fed pelleted feeds as a supplement [1].

This study investigated the degradability of the different fractions of the dry matter (DM), starch, and CP of ground and steamed pelleted grains *in situ*. The approach used was that of Ørskov and McDonald [9], which has been widely adopted internationally [5]. They used an *in situ* method and developed a model to describe different fractions and identified a rapidly degradable fraction and a slowly degradable fraction, which provided a guide for feeding grains to ruminants [9].

2. Materials and Methods

The experimental procedures used in this study involving cattle were approved by the Animal Ethics Committee of the University of Queensland and complied with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes.

2.1. Animal Management

Four crossbred Brahman steers, fitted with large diameter (10 cm) rumen cannulae (Bar Diamond #2C), were used. The steers were 4 to 5 years old with an average live-weight of 600 kg. Animals were held in individual pens, fed a diet comprising 65% lucerne and 35% green panic hay *ad libitum*, and 1 kg cottonseed meal per day, in equal portions, at 7:30 a.m. and 3:00 p.m.

2.2. Sample Preparation and Incubation

The procedure for the *in situ* evaluation of samples was based on the procedure described by [10]. Briefly, ground barley, oats, sorghum, triticale, and two wheat samples were supplied by a local feed mill. All samples were ground in a commercial mill, and half of the sample of barley, sorghum, and both kinds of wheat were pelleted. Samples, both ground and pelleted, were then ground to pass through a 2.0-mm screen prior to incubation.

A sample of approximately 5 g was weighed into a monofilament polyester nylon bag (24 × 10 cm (#R510), 45 Φm pore size). Prior to incubation, each nylon bag was numbered with a permanent marker and washed, disinfected, and dried in an oven at 60 °C until a constant weight. Two bags per sample were prepared for each animal per incubation time except for 0 h, in which one bag per sample per animal was prepared. All the bags were tied to a 1.87 kg steel chain and inserted into the rumen. The samples were incubated for 0, 2, 4, 6, 8, 16, 32, and 60 h. After removal, all bags were placed in ice-cold water to stop the activity of bacteria, then rinsed in a washing machine at 37 °C; a standardized two, 6-min agitation cycles, and one 2-min spin cycle were applied. Bags were then dried in a forced draught oven at 65 °C for 48 h and cooled in a desiccator before weighing.

2.3. Chemical Analysis

The grain residues following incubation and grain samples were ground to pass a 0.5-mm screen before starch and CP analysis. DM and starch were determined according to AFIA methods (2011) [11]. CP was determined using a LECO® CN-928 Carbon and Nitrogen Macro Determinator, and 0.3-g samples were weighed into ceramic boats, transferred automatically into the furnace, and combusted at 1100 to 1450 °C. The gases produced

were equilibrated and mixed in the ballast, then a representative portion was introduced to a thermal conductivity cell to determine nitrogen. Crude protein content was calculated by multiplying the percentage nitrogen by 6.25.

2.4. Calculations

The grain nutrient degradation kinetics were described by the exponential equation (Ørskov & McDonald 1979) as follows:

$$D_p = a + b \times (1 - e^{-K_d(t)}) \quad (1)$$

where D_p is the nutrient degradation rate (%) at t time; a is the rapidly degradable fraction (%), b is the slowly degradable fraction (%); t is the feed retention time in the rumen (hr); K_d is the fractional degradation rate (%/hr) of b .

The ED of nutrients were calculated as follows:

$$ED = a + (b \times K_d) / (K_d + K_p) \quad (2)$$

ED is effective degradability (%) of nutrients; K_p (%) is the feed flow rate in the rumen ($K_p = 0.06$).

2.5. Statistical Analysis

Analysis of variance was conducted using IBM SPSS 27.0. Differences between ground and pelleted samples were determined using the independent-sample t -test, and differences between ground samples with a one-way ANOVA LSD procedure.

3. Results

The DM, starch, and CP contents of the samples are presented in Table 1.

Table 1. Chemical composition (g/kg) of ingredients.

Ingredients		DM	Starch	CP
Barley	Ground	910	520	121
	Pelleted	920	520	121
Oats	Ground	920	410	83
Sorghum	Ground	910	570	120
	Pelleted	910	540	116
Triticale	Ground	920	550	96
Wheat 1	Ground	930	560	109
	Pelleted	920	540	121
Wheat 2	Ground	920	530	128
	Pelleted	920	530	140

3.1. The Degradability of Grain Samples

The nutrient degradation pattern of grains is shown in Table 2 and was determined by integrating the nutrient remaining in nylon bags and particle turn-over rate (Ørskov and McDonald 1979). The degradability of DM, starch, and CP in all the samples fitted the non-linear regression equation, and except for CP of sorghum and triticale ($R^2 = 0.93$ and 0.94 , respectively), the R^2 values of all other samples were higher than 0.95.

Table 2. The rapidly degradable nutrient (a, %), slow-degradable nutrient (b, %), effective degradation rate (Kd), and the effective degradability (ED, %) of different cereal grains.

Grains (fine)	Dry Matter		Kd	ED (%)	R ²
	a (%)	b (%)			
Barley	39.6 ^d	48.6 ^b	0.39 ^a	82.4 ^b	0.97 ^{ab}
Oats	61.4 ^a	25.7 ^f	0.11 ^b	78.1 ^c	0.95 ^b
Sorghum	19.4 ^e	80.5 ^a	0.05 ^b	54.6 ^e	0.98 ^{ab}
Triticale	40.7 ^d	34.9 ^e	0.11 ^b	63.1 ^d	0.96 ^{ab}
Wheat 1	53.7 ^b	39.4 ^d	0.32 ^a	86.8 ^a	0.99 ^a
Wheat 2	49.5 ^c	42.3 ^c	0.39 ^a	85.9 ^a	0.98 ^{ab}
SEM	3.43	4.24	0.04	3.67	0.005
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.05
Grains (fine)	Starch		Kd	ED (%)	R ²
	a (%)	b (%)			
Barley	43.3 ^e	55.2 ^b	0.64 ^a	93.6 ^b	0.99
Oats	94.8 ^a	4.5 ^f	0.22 ^{cd}	98.3 ^a	0.97
Sorghum	16.3 ^f	88.4 ^a	0.05 ^d	57.3 ^d	0.98
Triticale	68.7 ^c	33.0 ^d	0.39 ^{bc}	94.7 ^{bc}	0.98
Wheat 1	65.5 ^d	33.04 ^c	0.54 ^{ab}	95.2 ^{bc}	0.99
Wheat 2	72.4 ^b	27.3 ^e	0.66 ^a	97.2 ^{ab}	0.99
SEM	5.67	6.20	0.07	4.29	0.003
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	0.062
Grains (fine)	Protein			ED (%)	R ²
	a (%)	b (%)	c		
Barley	30.9 ^b	68.3 ^c	0.19 ^{bc}	82.3 ^b	0.97 ^{ab}
Oats	77.2 ^a	21.3 ^d	0.19 ^{bc}	93.7 ^a	0.95 ^{ab}
Sorghum	18.0 ^{cd}	100.5 ^a	0.04 ^d	54.8 ^b	0.93 ^b
Triticale	21.5 ^c	81.2 ^a	0.12 ^c	75.2 ^c	0.94 ^{ab}
Wheat 1	15.3 ^d	83.0 ^b	0.28 ^a	83.3 ^b	0.98 ^a
Wheat 2	20.4 ^c	78.6 ^b	0.26 ^{ab}	82.8 ^b	0.96 ^{ab}
SEM	1.63	3.14	0.028	3.22	0.009
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.05

^{a-d} Means within the same column with different superscripts differ ($p < 0.05$).

The two ground wheat samples had the highest ED of DM (86.8 and 85.9%) with a relatively high fast-degradable DM fraction (53.7 and 49.5%, respectively). The DM degradability of ground barley was relatively high (82.4%), while its fast-degradable portion was low (39.6%). On the other hand, oats had a higher fast-degradable DM fraction but did not lead to high degradability (78.1%). The fast-degradable DM of sorghum was at least two times lower than that of other grains (19.4%), and its DM degradability was also significantly lower (54.6%).

The rapid (a%) and slow (b%) starch content of each ground grain were significantly ($p < 0.05$) different. Around 94.8% of the starch in oats were fast-degradable. Wheat starches were also mainly rapidly degradable (65.5 and 72.4%), while barley and sorghum were dominated by slow-degradable starch. In contrast to sorghum (57.3%), the starch ED of all other grains was more than 93%. The degradability of barley was significantly ($p < 0.05$) lower than that of wheat. The degradation of starch was faster than that of DM and CP.

The protein degradability of sorghum was the lowest (54.8%), followed by higher values for triticale (75.2%), barley (82.3%), and the two wheat samples (83.3 and 82.6%), which were similar, even though their fast-degradable CP content varied. All grains, except oats (77.2%), had less than 31% fast-degradable protein. Moreover, oats had the highest CP degradability of 93.7%.

The initial rate of DM degradability (Figure 1) for sorghum and triticale was lower than for the other grains. However, this was not evident with the pattern for starch (Figure 2) and CP (Figure 3), with the exception of sorghum, which was much lower. For

all grains, except sorghum, more than 95% of the starch was degraded during the first six h of incubation. Interestingly, the initial rate of disappearance of starch was greater than that of CP and DM, except for sorghum, where the disappearance of starch was similar to that for DM and CP.

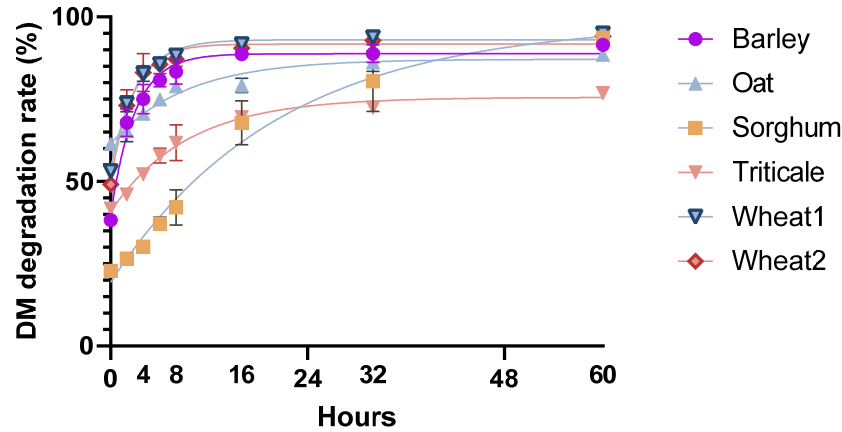


Figure 1. In situ disappearance pattern of DM (dry matter) in six ground grains.

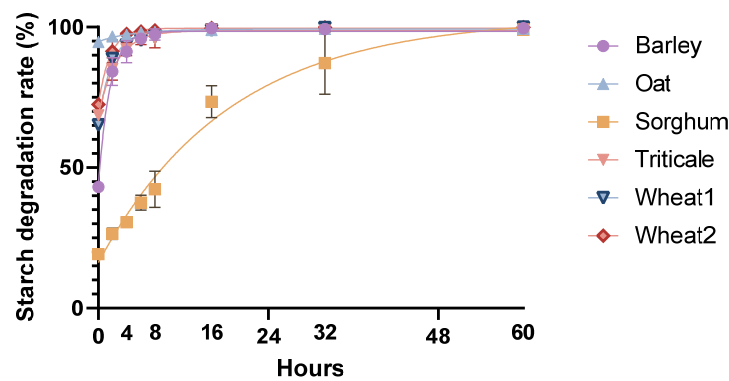


Figure 2. In situ disappearance pattern of starch in six ground grains.

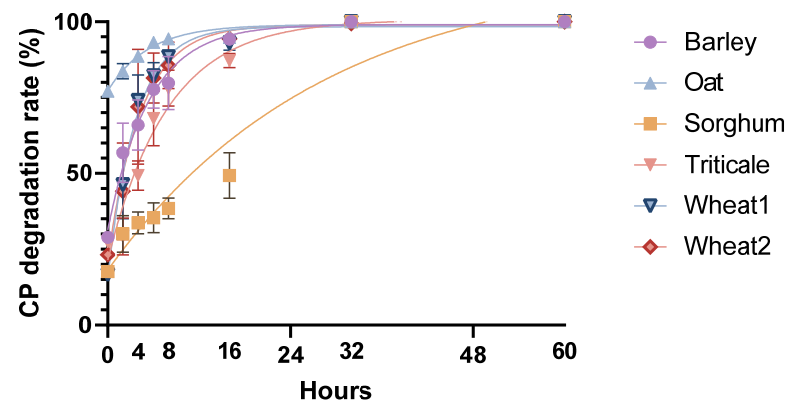


Figure 3. In situ disappearance pattern of CP (crude protein) in six ground grains.

3.2. The Effect of Pelleting on Degradability

The pelleting process (Table 3) increased the fast-degradable starch (16.3 to 26.8%) and DM (19.4 to 32.6%) of sorghum but reduced its fast-degradable CP content (18 to 12%) and CP degradability (54.8 to 51.9%). On the other hand, the fast-degradable fraction of the starch (65.5 and 72.4% to 27.6 and 43.5%) and DM (53.7 and 49.5% to 28.9 and 41.1%) of wheat samples were significantly reduced after pelleting, but only a small ED reduction was observed (around 2%). No effect on wheat CP was observed, but the fast-degradable CP (30.9 to 23.8%) of barley was reduced by pelleting.

Table 3. The comparison of the rapidly degradable (a%) and the effective degradability (ED, %) between the ground and pelleted cereals.

Grain	DM		Starch		CP	
	a%	ED%	a%	ED%	a%	ED%
Barley						
Ground	39.6	81.5	43.3	93.6	30.9	82.3
Pelleted	37.8	82.4	42.8	93.8	23.8	79.2
SEM	0.52	0.53	0.16	0.38	1.54	1.27
<i>p</i>	>0.05	>0.05	>0.05	>0.05	<0.01	>0.05
Sorghum						
Ground	19.4	54.6	16.3	57.3	18.0	54.8
Pelleted	32.6	60.1	26.8	61.5	12.6	51.9
SEM	2.56	1.59	2.12	1.53	1.35	0.68
<i>p</i>	<0.01	>0.05	<0.01	>0.05	<0.05	<0.05
Wheat 1						
Ground	53.7	86.8	65.5	95.2	15.3	83.3
Pelleted	28.9	84.4	27.6	93.8	15.4	81.8
SEM	4.69	0.51	7.16	0.33	1.04	0.69
<i>p</i>	<0.01	<0.01	<0.01	<0.05	>0.05	>0.05
Wheat 2						
Ground	49.5	85.9	72.4	97.2	20.4	82.6
Pelleted	41.1	83.7	43.5	95.6	25.7	78.1
SEM	1.6	0.59	5.46	0.36	1.33	1.51
<i>p</i>	<0.01	<0.05	<0.01	<0.05	>0.05	>0.05

4. Discussion

Ingestion of a large proportion of rapidly degradable starch in ruminants may induce acidosis [6]. It is therefore essential when formulating ruminant diets to carefully consider the degradability of the grains being fed. As has been reviewed by others [4,5], many factors influence degradability, and it is important to test grains locally. The variations of the degradability of the same type of grains reported in different studies are relatively large. Factors that may affect the in situ grain degradation include cultivars [12], growth conditions, harvest season, and grinding size [13]; the incubation factors such as pore size of the nylon bag [14], relative insert time [15], and animal condition and diet [16]; and laboratory factors such as sample handling and washing procedures and analytical techniques [16].

Overall, in this study, the degradability of barley, oats, and wheat was rapid compared to triticale, with sorghum being much slower than the other grains. This attribute of sorghum was apparent for DM, CP, and starch. The degradation of these grain components is interlinked [17]. Starch degradation is affected by the molecular structure of starch granules, the type of starch, starch–protein interaction, and anti-nutritional factors such as tannins [18]. Different protein fractions may affect the solubility and ruminal degradability of grain protein [19], affecting starch degradation due to the interaction between the protein matrix and starch [12]. Interestingly, no lag phase was observed in this study. Grains disappeared rapidly from the beginning of incubation, which agreed with previous studies [13,20]. In the current study, starch degraded faster than CP and DM, which is at variance with the finding of Herrera–Saldana and Huber [20], who suggested that the degradation of CP is faster than that of starch.

The starch ED of barley was relatively high. The fast-degradable starch (43.3%) and degradability (93.6%) of barley was higher than that in some other studies, of 26.7 and 80.5% [21], 33.1 and 85.6% [13], and 66.2 and 90% [20], respectively.

The protein degradability of barley was 82.3%, which was higher than some results (72% [22]) but lower than that of others (85 [13]; 91% [20]). The variation of starch degradability between studies may be related to cultivars or growing conditions. Krieg and

Seifried [12] compared the effective starch and DM degradability of 20 different barley cultivars and reported a significant difference in nutrient fractions and degradability between cultivars. Moreover, Stevnebø, Seppälä [23] suggested that the degradability of low amylose barley cultivars was higher than that of high amylose cultivars.

The proportion of fast-degradable starch and CP in oats was the highest for all of the grains studied. Approximately 95% of the starch and 77% of the CP in oats were fast-degradable, and the degradability was 98.3 and 93.7%, respectively. The results were similar to the findings reported by other studies [20,24,25], where it was found that the fast-degradable starch and CP contents of oats were much higher than in other grains, resulting in a higher degradability rate. The starch particle size of oats was smaller than that of other grains [26]. As small particles easily escape from the nylon bag, this would contribute to the fast-degradable starch content of oats [25]. The current study assumed that all small particles that escaped from the nylon bags were in the fast-degradable fraction, which is fully digestible. However, the actual degradation rate of these particles is not clear. The fast-degradable portion may vary as the pore size of the nylon bag increases [14] or the sample particle size decreases [13].

Triticale is a hybrid cereal developed by crossing wheat and rye. There are few studies on the in situ rumen degradation of triticale, and in this study, starch degradation was similar to wheat, but the degradation of CP and DM was slower. The fast-degradable starch in triticale was approximately 69% in this study, which is much higher than that reported by Krieg and Seifried [12]; however, their starch degradability was similar to the current study (94%). In other studies, it has been shown that triticale has a similar digestibility to maize in sheep [27] and in both dairy and beef cattle [28], and therefore can replace maize in ruminant diets.

The starch degradability of wheat samples in this study was more than 95%. The variation of the starch content and degradability of wheat in ruminants was as large as it is in non-ruminants [29]. In the wheat studies of Herrera–Saldana and Huber [20], Offner and Bach [30], and Cerneau and Michalet–Doreau [24], the fast-degradable starch content was 78.2, 60.4, and 82.8%, with a degradability of 95, 91.4, and 96.4%, respectively. The CP degradability of wheat samples in the current study was around 83%, which agrees with the 85% found in another Australian study [25].

Grain sorghum is commonly used in Australian livestock production, especially as a grain for non-ruminants [31]. Sorghums are relatively drought-tolerant compared to other common cereals, making them a suitable crop in drier tropical and subtropical areas [31]. The starch degradability of sorghum (57.4%) was significantly lower than other grains (over 90%). The results were lower than in the report Offner and Bach [30], who found the average ED of sorghum to be 75.6%. In the current study, the fast-degradable DM and starch content of sorghum was much lower than the other grains and agreed with the data of Rooney and Pflugfelder [18]. The presence of cross-linked kafirins, the primary storage protein in sorghum, with strong bonds between proteins and starch granules [31] may explain the low fast-degradable portion of sorghum. Kafirins prevent enzyme access to protein bodies, thus reducing sorghum protein and starch degradability. Conversely, condensed tannins that are anti-nutrient factors [32] are often cited as the cause of the reduced rumen degradability of sorghum. However, this is not the case in Australia, as plant breeding programs have eliminated condensed tannins from Australian grain sorghum varieties [31].

The current study demonstrated that the effect of pelleting on ruminal degradability depends on the cereal type and agrees with Razzaghi and Larsen [33]. In the current study, steam pelleting significantly increased the fast-degradable starch and DM and tended to improve the DM degradation of sorghum ($p = 0.081$), which agrees with previous studies [18,33]. On the other hand, pelleting reduced starch degradation slightly in both wheat samples, which is consistent with the findings of Razzaghi and Larsen [33]. The significant differences in the effect of pelleting between grains were also reported in in vivo studies. Theurer [34] suggested that pelleting improved the starch utilization of sorghum

and corn but had little effect on barley. Ørskov and Fraser [35] demonstrated that pelleting reduced the DM degradation of barley but slightly increased that of wheat. Grubješić and Titze [36] examined the effect of pelleting on compound feed and suggested that it improved the CP degradability of maize and barley-based feeds, which is implied from the current study.

5. Conclusions

This study confirmed that the ruminal degradability of sorghum starch is lower than the other grains examined. Sorghum is thus a potential source of by-pass starch and protein for ruminants. Wheat processing may decrease the incidence of acidosis, as pelleting significantly reduced the fast-degradable starch component and DM with a relatively small effect on degradability.

The differences in degradability between the ground and pelleted grain sample are statistically significant, but the change is relatively small compared with the difference between different cereals. Thus, when considering the effect of pelleting, attention should also be given to other factors such as palatability and forage intake that will impact rumen function and acidosis. Further studies should be conducted to determine the effect of pelleting on the starch and protein passage rate and the efficiency of the by-pass nutrients.

Author Contributions: X.L. and K.H.H. planned the work, which was agreed to by all participants and the experimental work was conducted by L.P., D.Z. and X.L., K.H.H. and T.M. arranged the grain samples and pelleting at Weston Animal Nutrition. L.P. drafted the paper that was edited by W.L.B. and X.L. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The experimental procedure was approved by the Animal Ethics Committee of the University of Queensland (AEC Approval number: SAS/037/05) and complied with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes.

Data Availability Statement: All data generated and analyzed during this study are included in this manuscript. Further details are available from the corresponding author upon request.

Conflicts of Interest: While conducting this study, K.H.H. and T.M. were employees of Weston Animal Nutrition, but the company had no input into the analysis or interpretation of results. The authors declare no other conflict of interest.

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