Effects of Different Rumen-Degradable Starch Levels on Lactation Performance, Apparent Nutrient Digestibility, and Nitrogen Balance in Dairy Cows Fed High-Starch Diets (Postprint)

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Abstract

This experiment aimed to investigate the effects of different rumen-degradable starch levels on lactation performance, nutrient apparent digestibility, and nitrogen balance in dairy cows fed high-starch diets. Ten Holstein multiparous cows [average days in milk = (214$±38)*d, averagemilkyield* = (26.2±2.4)*kg/d, averagebodyweight* = (727±$65) kg] were selected as experimental animals and randomly divided into 2 groups with 5 cows per group. Two experimental diets with different rumen-degradable starch levels were formulated: a low rumen-degradable starch diet (L-RDS group) with rumen-degradable starch level at 62.3% (as a percentage of total starch) and a high rumen-degradable starch diet (H-RDS group) with rumen-degradable starch level at 72.1% (as a percentage of total starch). A crossover experimental design was adopted, with the experiment divided into 2 periods, a 7-d transition period, and each experimental period lasting 21 d, including a 14-d adaptation period and a 7-d sampling period. The results showed that: 1) Compared with the L-RDS group, the H-RDS group had significantly increased apparent digestibility of organic matter and starch (P<0.05), significantly decreased apparent digestibility of neutral detergent fiber and acid detergent fiber (P<0.05), a tendency for increased apparent digestibility of dry matter (P=0.07), and no significant difference in apparent digestibility of protein (P>0.05). 2) Compared with the L-RDS group, the H-RDS group showed a tendency for decreased urea nitrogen and its proportion of nitrogen intake (P=0.09), with no significant changes in nitrogen intake, milk nitrogen, fecal nitrogen, urinary nitrogen, and retained nitrogen and their proportions of nitrogen intake (P>0.05), and no significant changes in total urinary purine derivative excretion and microbial protein production (P>0.05). 3) Dietary rumen-degradable starch level had no significant effects on dry matter intake, milk yield, or milk composition in dairy cows (P>0.05). Based on these results, it can be concluded that different rumen-degradable starch levels in high-starch diets affect dietary nutrient apparent digestibility but have no significant effects on lactation performance and nitrogen balance.

Full Text

Effects of Different Ruminally Degradable Starch Levels on Lactation Performance, Nutrient Apparent Digestibility, and Nitrogen Balance in Dairy Cows Fed High-Starch Diets

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Abstract

This study investigated the effects of different ruminally degradable starch levels on lactation performance, nutrient apparent digestibility, and nitrogen balance in dairy cows fed high-starch diets. Ten multiparous Holstein cows [average lactation days: (214$±38)*d*; *averagemilkyield* : (26.2±2.4)*kg*/*d*; *averagebodyweight* : (727±$65) kg] were randomly assigned to two groups of five cows each. Two experimental diets with different ruminally degradable starch levels were formulated: a low ruminally degradable starch diet (L-RDS group) containing 62.3% ruminally degradable starch (as a percentage of total starch) and a high ruminally degradable starch diet (H-RDS group) containing 72.1% ruminally degradable starch (as a percentage of total starch). A crossover experimental design was employed, consisting of two periods with a 7-day transition interval. Each period lasted 21 days, comprising a 14-day adaptation phase followed by a 7-day sampling phase. The results showed that: (1) Compared with the L-RDS group, the H-RDS group exhibited significantly higher apparent digestibility of organic matter and starch (P<0.05), significantly lower apparent digestibility of neutral detergent fiber and acid detergent fiber (P<0.05), and a tendency for increased apparent digestibility of dry matter (P=0.07), while crude protein apparent digestibility remained unaffected (P>0.05). (2) The H-RDS group showed a tendency for reduced urinary urea nitrogen and its proportion of nitrogen intake compared with the L-RDS group (P=0.09). No significant differences were observed between groups in nitrogen intake, milk nitrogen, fecal nitrogen, urinary nitrogen, nitrogen retention, or their proportions of nitrogen intake (P>0.05). Similarly, urinary purine derivative excretion and microbial protein yield were not significantly affected (P>0.05). (3) Dietary ruminally degradable starch level had no significant effect on dry matter intake, milk yield, or milk composition (P>0.05). In conclusion, different ruminally degradable starch levels in high-starch diets affect nutrient apparent digestibility but exert no significant influence on lactation performance or nitrogen balance in dairy cows.

Keywords: dairy cows; ruminally degradable starch; milk yield; nitrogen balance; apparent digestibility

Introduction

Dairy cows continuously derive energy from their diets to meet maintenance and production requirements. Energy status largely determines peak milk yield and lactation persistency, while body condition loss is associated with altered blood metabolites and hormone levels that subsequently affect reproductive performance [1]. Carbohydrates constitute the primary energy source in dairy cow diets, typically accounting for 60–70% of dietary dry matter. Increasing dietary energy concentration through more fermentable cereal grains represents one approach to enhance energy intake in dairy cows.

Theurer et al. [2] reviewed comparisons between steam-flaked and steam-rolled corn and sorghum, finding that steam flaking increased milk yield without significantly affecting dry matter intake, which they attributed to enhanced ruminally degradable starch levels and increased microbial protein flow to the duodenum. However, the effects of high ruminal starch degradability have not been entirely consistent across studies [3-4].

Starch comprises 70–80% of non-structural carbohydrates in cereal grains and is rapidly degraded in the rumen, with nearly complete digestion (digestibility exceeding 90% for many cereal starches). The NRC (2001) [5] established minimum recommendations for neutral detergent fiber (NDF) and maximum recommendations for non-fibrous carbohydrates (NFC) in total mixed rations for lactating cows. Since ruminally degradable starch level influences the appropriate levels of NDF and NFC in diets, determining optimal ruminally degradable starch levels is essential for maximizing dairy cow performance. The generally recommended dietary starch level for lactating dairy cows is 23–30% (dry matter basis) [6]; however, few studies have examined the effects of different ruminally degradable starch levels when feeding high-starch diets. In China, corn serves as the primary starch source in dairy diets, with steam-flaked corn and ground corn being commonly used processing forms. Steam-flaked corn increases ruminal starch degradability compared with ground corn (80.3% vs. 67.9%) [7]. This experiment manipulated the ratio of ground corn to steam-flaked corn in the diet to create different ruminally degradable starch levels, investigating the effects on lactation performance, nutrient apparent digestibility, and nitrogen balance in dairy cows fed a high-starch diet (30% starch, dry matter basis), thereby providing a theoretical basis for the effective application of high-starch diets in dairy production.

1.1 Experimental Animals and Design

This trial was conducted at the Shandongtun Holstein Dairy Farm in Heilongjiang Province. Ten multiparous Holstein cows [average lactation days: (214$±38)*d*; *averagemilkyield* : (26.2±2.4)*kg*/*d*; *averagebodyweight* : (727±$65) kg] were randomly divided into two groups of five cows each. Two experimental diets with different ruminally degradable starch levels were formulated by altering the ratio of ground corn to steam-flaked corn: a low ruminally degradable starch diet (L-RDS) containing 62.3% ruminally degradable starch and a high ruminally degradable starch diet (H-RDS) containing 72.1% ruminally degradable starch. Steam-flaked and ground corn were provided by Heilongjiang Tianzheng Dingtai Feed Co., Ltd., with steam-flaked corn having a bulk density of 360 g/L. A crossover experimental design was employed, consisting of two periods with a 7-day transition interval. Each period lasted 21 days, including a 14-day adaptation phase and a 7-day sampling phase. Diet composition and nutrient levels are presented in Table 1 , and ruminal starch degradation parameters are shown in Table 2 .

1.2 Management

Cows were housed individually with ad libitum access to water and sand-bedded free stalls. Total mixed rations were fed twice daily at 05:30 and 17:30, with refusals maintained at 5–10% of feed offered. Cows were milked twice daily at 09:00 and 21:00.

1.3.1 Feed Sampling and Analysis

Feed and orts were collected continuously on days 15, 16, and 17 of each period. After collection, samples were pooled and subsampled to approximately 500 g, then stored at -20°C for subsequent analysis. Feed and ort samples were dried at 65°C for 48 hours, ground to pass a 1-mm screen, and stored for analysis. Dry matter, crude ash, and crude protein contents were determined according to AOAC (1990) [10] methods. Neutral detergent fiber and acid detergent fiber contents were analyzed using the method of Van Soest et al. [11]. Starch content was determined using the amyloglucosidase/α-amylase method with assay kits purchased from Megazyme.

1.3.2 Fecal Sampling and Analysis

Fecal samples were collected continuously on days 19, 20, and 21 using the grab sampling method. Approximately 200 g of feces was collected rectally from each cow at 6-hour intervals. Samples from each cow and time point were mixed and divided into two portions: one portion was preserved with 10 mL of 6 mol/L HCl and stored at -20°C for nitrogen analysis, while the other portion was stored at -20°C for analysis of other nutrients (except crude protein). Finally, samples collected over three days were pooled and subsampled to 500 g per cow. Fecal samples were dried at 60°C for 72 hours, ground to pass a 1-mm screen, and stored for analysis. Analytical methods for dry matter, crude ash, crude protein, neutral detergent fiber, acid detergent fiber, and starch were identical to those described in section 1.3.1. Nutrient apparent digestibility was calculated using indigestible neutral detergent fiber (iNDF) as an internal marker. Fecal nitrogen was calculated from crude protein apparent digestibility and nitrogen intake.

1.3.3 Urine Sampling and Analysis

Urine samples were collected continuously on days 19, 20, and 21 using the spot sampling method. Fifty milliliters of urine was collected at 6-hour intervals. After collection, sulfuric acid (0.036 mol/L) was added at a 4:1 ratio to preserve nitrogen. Samples were pooled and subsampled to 100 mL per cow, then stored at -20°C for determination of urinary nitrogen, creatinine, allantoin, urea nitrogen, and uric acid. Urinary nitrogen was determined by the Kjeldahl method, creatinine by the picric acid colorimetric method, uric acid by the phosphotungstic acid colorimetric method, urea nitrogen by the diacetyl monoxime method, and allantoin by the colorimetric method [12]. Assay kits for urea nitrogen, creatinine, and uric acid were purchased from Nanjing Jiancheng Bioengineering Institute.

1.3.4 Milk Sampling and Analysis

Milk yield was recorded and milk samples were collected on days 15, 16, and 17. Fifty milliliters of milk was collected at each morning and evening milking. Daily samples were pooled at a 6:4 ratio (morning:evening), and 0.03 g of potassium dichromate was added to each 50 mL sample. Milk protein percentage, milk fat percentage, lactose percentage, and milk dry matter and urea nitrogen contents were determined using an infrared spectroscopy milk composition analyzer (MilkoScan FT6000, FOSS, Denmark) at the Daqing Livestock Breeding Guidance Station.

1.3.5 Ruminal Microbial Protein Yield Determination

Ruminal microbial protein yield was estimated using the purine derivatives method [13]. Daily urine volume and excretion of nitrogen and purine derivatives (allantoin and uric acid) were calculated based on urinary creatinine content, assuming a fixed creatinine excretion rate of 29 mg/kg body weight [14]. Calculations were performed as follows:

Urine volume (L/d) = Body weight (kg) × 29 (mg/kg BW) / Urinary creatinine content (mg/L) [14];

$X = (Y - 0.385 \times W^{0.75}) / 0.85$;

Microbial protein yield (kg/d) = 6.25 × (70 × X) / (0.83 × 0.116 × 1,000) = 4.544X.

Where: X represents the absorption of microbial purine derivatives at the duodenum (mmol/d); Y represents urinary purine derivative excretion (mmol/d); 0.385 × W^0.75 represents endogenous purine derivative excretion (mmol/d); 0.85 represents the proportion of purine derivatives absorbed at the duodenum that are excreted in urine; 70 represents the nitrogen content of purine derivatives (mg/mmol); 0.116 represents the ratio of purine derivative nitrogen to total microbial nitrogen; and 0.83 represents the digestibility of microbial purine derivatives at the duodenum.

1.3.6 Dietary Starch Rumen Degradability Determination

Dietary starch rumen degradation parameters were determined using the in situ nylon bag technique at the Acheng Experimental Farm of Northeast Agricultural University. Three ruminally cannulated Holstein cows [body weight: (678.0$±26.5)*kg*; *milkyield* : (20.6±2.5)*kg*; *lactationdays* : (276±$19) d] were used as experimental animals and housed individually. The basal diet (dry matter basis) consisted of 28.9% whole-plant silage, 24.2% Chinese wild rye grass, and 46.9% concentrate. Cows were fed twice daily at 05:30 and 17:30 at approximately 3% of body weight (dry matter basis). Samples were ground to pass a 3-mm screen, and 5 g of each sample was weighed into pre-labeled nylon bags (10 cm × 20 cm, 50 µm pore size, Ankom, USA). Bags were incubated in the rumen for 72, 48, 24, 12, 8, 4, 2, and 0 hours. Nylon bag incubation and post-incubation procedures followed Yu et al. [15]. Samples were dried at 65°C for 48 hours, re-equilibrated, ground to pass a 1.0-mm screen, and analyzed for starch content using the method described in section 1.3.1.

1.4 Statistical Analysis

Starch rumen degradability was calculated using a first-order kinetic exponential model [16], and data were processed using nonlinear regression with the least squares method in SAS 9.2. Statistical analysis was performed using the MIXED procedure in SAS 9.1, with Tukey’ s method applied for multiple comparisons. Differences were considered significant at P<0.05, and trends were identified at 0.05≤P<0.10.

2.1 Effects of Different Ruminally Degradable Starch Levels on Nutrient Apparent Digestibility in Dairy Cows Fed High-Starch Diets

As shown in Table 3 , the H-RDS group exhibited significantly higher apparent digestibility of organic matter and starch compared with the L-RDS group (P<0.05), while apparent digestibility of neutral detergent fiber and acid detergent fiber was significantly lower (P<0.05). Increasing ruminally degradable starch level tended to improve dry matter apparent digestibility (P=0.07), but had no significant effect on crude protein apparent digestibility (P>0.05).

2.2 Effects of Different Ruminally Degradable Starch Levels on Nitrogen Balance in Dairy Cows Fed High-Starch Diets

Table 4 shows that the L-RDS and H-RDS groups did not differ significantly in nitrogen intake, milk nitrogen, fecal nitrogen, urinary nitrogen, nitrogen retention, or their proportions of nitrogen intake (P>0.05). The H-RDS group tended to have lower urinary urea nitrogen and its proportion of nitrogen intake compared with the L-RDS group (P=0.09). Urinary excretion of allantoin, uric acid, total purine derivatives, and microbial protein yield did not differ significantly between groups (P>0.05).

2.3 Effects of Different Ruminally Degradable Starch Levels on Lactation Performance in Dairy Cows Fed High-Starch Diets

Table 5 demonstrates that dietary ruminally degradable starch level had no significant effect on dry matter intake, milk yield, energy-corrected milk yield, 4% fat-corrected milk yield, milk fat yield, milk protein yield, lactose yield, milk fat percentage, milk protein percentage, lactose percentage, total solids percentage, milk urea nitrogen content, or dairy efficiency (P>0.05).

3.1 Effects of Different Ruminally Degradable Starch Levels on Nutrient Apparent Digestibility in Dairy Cows Fed High-Starch Diets

The present study found that starch apparent digestibility was significantly higher in the H-RDS group than in the L-RDS group. This finding aligns with Zhong et al. [17] and Shen et al. [3], who reported that replacing ground corn with steam-flaked corn significantly improved dietary starch apparent digestibility. Steam flaking causes starch gelatinization, disrupting intracellular hydrogen bonds and weakening intermolecular forces, making starch more susceptible to enzymatic action and thereby increasing both ruminal degradability and post-ruminal small intestinal digestibility [18]. However, the difference in starch apparent digestibility between L-RDS and H-RDS groups in this study (97.84% vs. 98.78%) was smaller than the difference in ruminal degradability (62.3% vs. 72.1%), suggesting that more starch was digested post-ruminally in the L-RDS group. The H-RDS group showed significantly lower apparent digestibility of neutral detergent fiber and acid detergent fiber compared with the L-RDS group. Zhong et al. [17] reported that increasing the proportion of steam-flaked corn replacing ground corn gradually decreased neutral and acid detergent fiber apparent digestibility, and Ferraretto et al. [19] observed reduced neutral detergent fiber digestibility when steam-flaked corn replaced ground corn. These results are consistent with our findings and can be attributed to reduced ruminal pH from starch fermentation, which inhibits fiber degradation [20], and rapid starch fermentation affecting specific ruminal microbial strains that also suppress fiber digestion [21]. In contrast, Manríquez et al. [22] and Shen et al. [3] reported different results, possibly due to variations in ruminal pH and starch degradability. This study found no significant effect of ruminally degradable starch level on crude protein apparent digestibility, consistent with Shen et al. [3] and Hatew et al. [23]. However, Zhong et al. [17] reported that increasing steam-flaked corn replacement increased crude protein digestibility initially but decreased it thereafter, with maximum digestibility observed at 20% steam-flaked corn inclusion. Qiao [24] suggested that steam flaking disrupts corn protein spatial structure, increasing ruminal protein degradability. These inconsistent results warrant further investigation. The H-RDS group exhibited significantly higher organic matter apparent digestibility than the L-RDS group, consistent with Miyaji et al. [4], likely due to higher starch digestibility in the high ruminal degradability diet. Conversely, Zhou et al. [25] found no significant effect of ruminal degradability level on organic matter digestibility, possibly reflecting differences in diet composition and nutrient digestibility.

3.2 Effects of Different Ruminally Degradable Starch Levels on Nitrogen Balance in Dairy Cows Fed High-Starch Diets

Dietary ruminally degradable starch level did not significantly affect nitrogen intake in this study, primarily because both groups had similar dry matter intake and were fed isonitrogenous diets. The results also showed no significant effect on urinary nitrogen and its proportion of nitrogen intake, consistent with Shen et al. [3]. In contrast, Miyaji et al. [4] reported that increasing ruminally degradable starch level decreased urinary nitrogen and its proportion of intake. Ghorbani et al. [26] observed a tendency for reduced urinary nitrogen with high ruminal degradability diets. Ohtani et al. [27] suggested that high ruminal degradability diets increase glucogenic propionate production, reducing amino acid utilization for gluconeogenesis and consequently decreasing urea nitrogen production. Nocek and Russell [28] proposed that imbalanced ruminal availability of nitrogen and energy sources forces amino acids to be used for energy, resulting in greater ammonia absorption across the rumen wall. Therefore, discrepancies in milk urea nitrogen and urinary nitrogen among studies may stem from differences in ruminal energy-nitrogen balance. The tendency for reduced urinary urea nitrogen in the H-RDS group compared with the L-RDS group in this study aligns with Shen [29], possibly because steam flaking improves protein digestibility and utilization, increasing urea recycling to visceral and mammary tissues [2]. Dietary ruminally degradable starch level had no significant effect on milk nitrogen or its proportion of nitrogen intake, consistent with Chibisa et al. [30] and Miyaji et al. [31]. Additionally, nitrogen retention was not significantly affected, agreeing with Hatew et al. [23] and Chibisa et al. [30] but differing from Miyaji et al. [4], possibly due to variations in nitrogen intake, starch level, and ruminal starch degradability. Burkholder et al. [32]

demonstrated that increasing ruminally degradable starch level enhances microbial nitrogen utilization, suggesting that high degradability diets provide more rumen-degradable starch and increase microbial protein yield. However, this study found no significant differences in urinary total purine derivative excretion or microbial protein yield between groups, consistent with Zhou et al. [25] and Shen [29]. High ruminal degradability diets reduced fiber digestion and increased starch degradability, resulting in similar rumen-fermentable organic matter as low degradability diets, and rumen-fermentable organic matter is a key determinant of microbial protein flow to the duodenum [33]. The discrepancy with Cabrita et al. [34] may be attributed to differences in dry matter intake, dietary nitrogen and energy sources, and rumen outflow rates affecting ruminal energy-nitrogen balance.

3.3 Effects of Different Ruminally Degradable Starch Levels on Lactation Performance in Dairy Cows Fed High-Starch Diets

This study found no significant effect of dietary ruminally degradable starch level on dry matter intake. High ruminal starch degradability does not necessarily reduce dry matter intake [25,35-36]. Zhou et al. [25] reported that replacing ground corn with steam-flaked corn (25.5%, dry matter basis) had no significant effect on dry matter intake, whereas Shen et al. [3] observed reduced intake with high ruminal degradability diets. It is widely accepted that increasing ruminal starch degradability elevates ruminal propionate production, thereby reducing dry matter intake [4,36]. Intraruminal infusions of equimolar [37] or isoenergetic [38] acetate and propionate have demonstrated that propionate has a stronger appetite-suppressing effect than acetate. The inconsistent effects on dry matter intake suggest that propionate may have a threshold concentration for affecting intake, with propionate-related mechanisms potentially overriding ruminal stretch receptor reflexes in regulating feeding behavior. Dietary ruminally degradable starch level had no significant effect on milk yield in this study, consistent with Zhou et al. [25] and Joy et al. [39], primarily due to similar dry matter intake between groups. Milk composition differences typically reflect dietary ruminal fermentation patterns [40] and variations in grain digestion site and extent [41]. Zhong et al. [17] and Gozho et al. [42] reported that increasing ruminal degradability decreased milk fat percentage. The prevailing view suggests that increasing fermentable carbohydrate levels elevates short-chain fatty acid production and risk of ruminal acidosis, reducing ruminal pH [30]. Under these conditions, biohydrogenation of C18 unsaturated fatty acids is impaired, increasing mammary absorption of trans-C18:1 isomers that inhibit milk fat synthesis [43]. This study found no significant effect on milk fat percentage, consistent with Oba and Allen [36] and Miyaji et al. [44] but inconsistent with Zhong et al. [17] and Gozho et al. [42], possibly due to differences in grain digestion site and extent [41]. Dietary ruminally degradable starch level had no significant effect on milk protein percentage, consistent with Oba and

Allen [36] and Hatew et al. [23].

Conclusion

Feeding dairy cows high-starch diets (30% starch, dry matter basis) with different ruminally degradable starch levels had no significant effects on dry matter intake, milk yield, or milk composition. Compared with the low ruminal degradability diet, the high ruminal degradability diet significantly reduced neutral detergent fiber and acid detergent fiber apparent digestibility while significantly increasing starch and organic matter apparent digestibility, without significantly affecting nitrogen balance.

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Note: Figure translations are in progress. See original paper for figures.