

Effects of Total Mixed Ration Particle Size on Feed Intake, Chewing Activity, and Production Performance in Dairy Cows (Postprint)

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Abstract

This study investigated the effects of Total Mixed Ration (TMR) particle size on feed intake, chewing activity, and production performance of dairy cows, to explore the appropriate particle size of TMR and suitable mixing times for alfalfa and Chinese wildrye during processing. Four multiparous Holstein dairy cows in mid-lactation [days in milk (85 ± 7) d] [body weight (616.8 ± 44.3) kg] were used in a 4×4 Latin square design. TMR particle size was altered by changing the mixing times of alfalfa and Chinese wildrye, dividing into four groups: Fine particle forage (FH) group (alfalfa mixed for 12 min, Chinese wildrye mixed for 20 min), Medium-fine particle forage (MFH) group (alfalfa mixed for 9 min, Chinese wildrye mixed for 15 min), Medium-long particle forage (MLH) group (alfalfa mixed for 6 min, Chinese wildrye mixed for 10 min), and Long particle forage (LH) group (alfalfa mixed for 3 min, Chinese wildrye mixed for 5 min). The experiment consisted of 4 periods, each lasting 19 d, including a 14-d preliminary period and a 5-d sampling period. Milk yield was recorded and milk samples were collected for milk composition analysis during the first 3 d of the sampling period; chewing activity was recorded by video monitoring on days 2 and 3 of the sampling period; and fecal samples were collected during the last 2 d of the sampling period to determine nutrient apparent digestibility. The results showed that TMR particle size had significant effects on the apparent digestibility of dry matter, organic matter, neutral detergent fiber, and nitrogen ($P<0.05$), with the FH and MFH groups exhibiting higher apparent digestibility compared to the MLH and LH groups. TMR particle size had no significant effects on dry matter intake, physically effective neutral detergent fiber intake, neutral detergent fiber intake, nitrogen intake, milk yield, or milk composition of dairy cows ($P>0.05$). No significant effects of TMR particle size on chewing time or plasma biochemical indices of dairy cows were observed ($P>0.05$). The results suggest that the appropriate particle size distribution of TMR is as follows: the proportions of dry matter for 19.00 mm, 8.00-(<19.00) mm, 1.18-(<8.00)

mm, and <1.18 mm are 45.20%, 25.50%, 16.55%, and 12.75%, respectively; the suitable mixing times for alfalfa and Chinese wildrye in TMR are 9 and 15 min, respectively.

Full Text

Effects of Total Mixed Ration Particle Size on Feed Intake, Chewing Activity, and Performance in Dairy Cows

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Abstract: This experiment investigated the effects of total mixed ration (TMR) particle size on feed intake, chewing activity, and performance in dairy cows to determine the appropriate particle size of TMR and optimal mixing times for alfalfa and *Leymus chinensis* during TMR preparation. Four multiparous Holstein dairy cows in mid-lactation [days in milk (85 ± 7) d] with body weight (616.8 ± 44.3) kg were used in a 4×4 Latin square design. TMR particle size was manipulated by varying the mixing time of alfalfa and *Leymus chinensis*, resulting in four treatment groups: fine particle hay (FH) group (alfalfa mixed for 12 min, *Leymus chinensis* for 20 min), medium-fine particle hay (MFH) group (alfalfa mixed for 9 min, *Leymus chinensis* for 15 min), medium-long particle hay (MLH) group (alfalfa mixed for 6 min, *Leymus chinensis* for 10 min), and long particle hay (LH) group (alfalfa mixed for 3 min, *Leymus chinensis* for 5 min). The experiment comprised four periods, each lasting 19 days (14-day adaptation period and 5-day sampling period). Milk yield was recorded and milk samples were collected during the first three days of each sampling period for milk composition analysis. Chewing activity was monitored via video surveillance on days 2 and 3 of the sampling period, and fecal samples were collected during the last two days to determine nutrient apparent digestibility. The results showed that TMR particle size significantly affected the apparent digestibility of dry matter (DM), organic matter (OM), neutral detergent fiber (NDF), and nitrogen (N) ($P<0.05$), with FH and MFH groups exhibiting higher digestibility compared to MLH and LH groups. However, TMR particle size had no significant effects on DM intake, physically effective NDF intake, NDF intake, N intake, milk yield, or milk composition ($P>0.05$). No significant effects of TMR particle size were observed on chewing time ($P>0.05$) or plasma biochemical indicators ($P>0.05$). These findings suggest that the suitable particle size distribution for TMR is as follows: DM proportions of 19.00 mm, 8.00–<19.00 mm, 1.18–<8.00 mm, and <1.18 mm should be 45.20%, 25.50%, 16.55%, and 12.75%, respectively. The optimal mixing times for alfalfa and *Leymus chinensis* in TMR are 9 min and 15 min, respectively.

Keywords: dairy cow; total mixed ration; mixing time; particle size; feed intake; chewing activity; performance

Introduction

Total mixed ration (TMR) feeding technology has been widely adopted in large and medium-sized dairy farms across China. The mixing time of TMR significantly affects its particle size. Numerous domestic and international studies have investigated how TMR particle size, particularly forage particle size, influences dry matter intake, rumination activity, and nutrient digestibility in dairy cows, though findings remain inconsistent. Kong et al. [1] proposed that TMR particle size affects rumen fill, contact area between digesta and rumen microorganisms, and digesta outflow rate, thereby influencing rumen fermentation patterns, end products, and shifts in digestion sites (e.g., starch digestion moving from rumen to small intestine), ultimately affecting nutrient digestibility and animal performance. He Ming [2] reported that dairy cows fed alfalfa hay chopped to 2, 4, and 8 cm lengths had DM intakes of 12.61, 11.65, and 9.41 kg/d, respectively. Li et al. [3] suggested that when dairy cows consume excessive forage, DM intake becomes limited by rumen capacity, and smaller feed particles can accelerate rumen outflow, enabling greater feed intake. Zhang [4] found that alfalfa hay lengths of 1, 3, and 5 cm had no significant effect on DM intake but increased physically effective fiber (peNDF) intake, improved standard milk yield and milk fat percentage, though milk protein percentage remained unaffected. Several studies [5-8] reported that reducing feed particle size increased feed intake, while others [9-12] found no effect on intake. Kahyani et al. [13] observed that reducing TMR particle size did not affect DM intake when concentrate exceeded a certain proportion. Regarding feed sorting behavior, Leonardi et al. [14] and Alamouti et al. [8] suggested TMR particle size significantly influences sorting, whereas Bhandari et al. [15] found no effect. Research on optimal feed particle size for dairy cows has yet to reach consensus.

Previous studies predominantly used choppers to modify TMR particle size. However, in practical production, mixing time during TMR preparation further affects forage particle size. While numerous studies have examined TMR particle size effects on dairy cow intake, chewing activity, and performance, few have investigated these effects by manipulating mixing time. This experiment altered TMR particle size through varying mixing time to study its effects on feed intake, chewing activity, and performance, providing reference for determining appropriate particle size and mixing time in large-scale dairy farms.

Materials and Methods

1.1 Experimental Animals and Management

Four multiparous Holstein dairy cows in mid-lactation were selected, with average initial body weight of (616.8 ± 44.3) kg and lactation duration of (85 ± 7) days. TMR was offered twice daily at 06:00 and 18:00, with refusals maintained below 10% of offered amount.

1.2 Total Mixed Ration

All groups received TMR with identical formulation, with composition and nutrient levels shown in . Nutrient levels of individual ingredients were determined using conventional laboratory methods, and TMR nutrient levels were calculated based on ingredient nutrient content and proportions. Net energy for lactation (NEL, MJ/kg) was calculated as: $NEL = 0.5501 \times \text{digestible energy (DE, MJ/kg)} - 0.3905$, where $DE = \text{gross energy} \times \text{energy digestibility}$, and $\text{energy digestibility (\%)} = 94.2808 - 61.5730 \times [\text{NDF}/\text{OM}]$ [16].

1.3 Experimental Design

TMR preparation generally follows the principle of mixing roughage before concentrate, and dry ingredients before wet ingredients. *Leymus chinensis* and alfalfa are mixed first, with mixing time controlled between 10–20 min. Due to its coarser texture and higher fiber content, *Leymus chinensis* requires longer mixing time than alfalfa. Based on observations from Aoya Ranch, Jiabao Ranch, and Lubao Ranch, different mixing time gradients were designed to alter TMR particle size.

The experiment employed a 4×4 Latin square design with four treatments: fine particle hay (FH) group [alfalfa mixed for 12 min, *Leymus chinensis* for 20 min], medium-fine particle hay (MFH) group [alfalfa mixed for 9 min, *Leymus chinensis* for 15 min], medium-long particle hay (MLH) group [alfalfa mixed for 6 min, *Leymus chinensis* for 10 min], and long particle hay (LH) group [alfalfa mixed for 3 min, *Leymus chinensis* for 5 min]. The experiment comprised four periods, each lasting 19 days (14-day adaptation and 5-day sampling). TMR mixing was performed using a 9JSG-10 horizontal mixer manufactured by Tai'an Yimeite Machinery Co., Ltd.

1.4 Sampling Procedures

1.4.1 Feed Sampling During the sampling period, feed offered and refusals were recorded daily. TMR andorts samples were collected, dried at 65°C, ground, and stored at 4°C.

1.4.2 Milk Sampling Milk yield was recorded on days 15, 16, and 17 of each period. Cows were milked at 07:00 and 19:00, with 500 mL composite samples collected at a 4:6 morning:evening ratio. Samples were thoroughly mixed before collection. Two to three drops of 33% H₂O₂ solution were added per 100 mL milk as preservative, and samples were stored at -20°C for milk composition analysis.

1.4.3 Blood Sampling On days 16 and 17 of each period, blood samples were collected from the tail vein before morning feeding and 6 h post-feeding. Syringes and centrifuge tubes were anticoagulated with 2,500 IU/mL sodium

heparin solution. Plasma was separated by centrifugation at $503\times g$ for 15 min and stored at -20°C .

1.4.4 Fecal Sampling Fecal samples were collected on days 18 and 19 of each period. Samples were collected and weighed every 6 h, mixed thoroughly, and 10% of the total was taken. Twenty percent sulfuric acid (10 mL per 100 g feces) was added for nitrogen fixation. Samples were dried at 65°C to determine initial moisture, ground, and stored at -20°C .

1.5 Measurements and Methods

1.5.1 Nutrient Level Determination Crude protein (CP) content in TMR, Orts, and feces was determined by the Kjeldahl method. NDF content was analyzed using the detergent fiber method proposed by Van Soest. DM, OM, and ash contents were determined according to *Feed Analysis and Feed Quality Detection Technology* edited by Zhang Liying. Gross energy was measured using a PARR 6200 oxygen bomb calorimeter. The peNDF content in Orts was calculated as: $\text{peNDF} = \text{NDF} \times \text{physical effectiveness factor (pef)} (>1.18 \text{ mm})$.

1.5.2 Particle Size Determination TMR and Orts particle size were determined using a BX-4 portable particle separator for dairy cows, developed by the Dairy Cattle Research Center of China Agricultural University and Beijing Dairyland Technology Development Co., Ltd.

1.5.3 Plasma Biochemical Indicators Plasma alanine aminotransferase, aspartate aminotransferase, and alkaline phosphatase activities, as well as glucose, urea nitrogen, uric acid, and triglyceride concentrations were measured using kits from Wako Pure Chemical Industries, Ltd. (Japan) on a Hitachi 7020 automatic analyzer according to manufacturer instructions.

1.5.4 Milk Composition Determination Milk fat percentage, milk protein percentage, and lactose percentage were determined using a milk composition analyzer (78110, Foss).

1.5.5 Chewing Activity Measurement A video system with eight cameras was installed according to cow positions to record chewing activity for two consecutive days. Based on the obtained videos, eating and ruminating times were recorded at 5-min intervals over 24 h. Eating was considered terminated if cows did not resume feeding within 20 min after stopping, and rumination was considered ended if cows did not start ruminating within 5 min after a rumination bout. Chewing time was expressed as the sum of eating time and ruminating time.

1.6 Data Processing

Raw data were organized in Excel spreadsheets and analyzed using the GLM procedure of SAS 8.2 software for ANOVA and Duncan's multiple comparisons. Differences were considered significant at $P < 0.05$ and trends at $0.05 > P > 0.10$.

Results

2.1 Nutrient Apparent Digestibility

As shown in , different TMR particle sizes had no significant effects on DM, OM, peNDF, NDF, and N intakes ($P > 0.05$), but significantly affected whole-tract apparent digestibility of DM, OM, NDF, and N ($P < 0.05$). Compared with MLH and LH groups, FH and MFH groups showed significantly higher DM apparent digestibility ($P < 0.05$), with no significant differences between FH and MFH groups or between MLH and LH groups ($P > 0.05$). OM apparent digestibility in FH group was significantly higher than in LH group ($P < 0.05$), and MFH group was significantly higher than MLH and LH groups ($P < 0.05$), with no significant differences among FH vs. MFH, MLH vs. LH, or FH vs. MLH ($P > 0.05$). FH and MFH groups exhibited significantly higher NDF apparent digestibility compared to MLH and LH groups ($P < 0.05$), with no significant differences between FH and MFH or between MLH and LH ($P > 0.05$). N apparent digestibility in FH and MFH groups was significantly higher than in LH group ($P < 0.05$), with no significant differences among FH, MFH, and MLH groups or between MLH and LH groups ($P > 0.05$).

2.2 Particle Size Distribution of Orts

As shown in , TMR particle size significantly affected the DM proportions of particles 19.00 mm, 8.00- $<$ 19.00 mm, and 1.18- $<$ 8.00 mm, as well as NDF proportions of particles 19.00 mm and 1.18- $<$ 8.00 mm in orts ($P < 0.05$). As TMR particle size increased, the NDF proportion of particles 8.00- $<$ 19.00 mm in orts tended to increase ($0.05 > P > 0.10$). The DM proportion of particles 19.00 mm in orts was significantly lower in FH group than in the other three groups ($P < 0.05$), with no significant differences among MFH, MLH, and LH groups ($P > 0.05$). The DM proportions of particles 8.00- $<$ 19.00 mm and 1.18- $<$ 8.00 mm in orts were significantly higher in FH group than in the other three groups ($P < 0.05$), with no significant differences among MFH, MLH, and LH groups ($P > 0.05$). The NDF proportion of particles 19.00 mm in orts was significantly lower in FH group than in the other three groups ($P < 0.05$), with no significant differences among MFH, MLH, and LH groups ($P > 0.05$). The NDF proportion of particles 1.18- $<$ 8.00 mm in orts was significantly higher in FH group than in the other three groups ($P < 0.05$), with no significant differences among MFH, MLH, and LH groups ($P > 0.05$). The NDF proportion of particles 8.00- $<$ 19.00 mm in orts tended to be higher in FH group than in the other three groups ($0.05 > P > 0.10$).

2.3 Chewing Activity

As shown in , TMR particle size had no significant effects on daily eating, ruminating, and chewing times, nor on eating, ruminating, and chewing times per kilogram of DM or NDF ($P>0.05$).

2.4 Milk Yield and Composition

As shown in , TMR particle size had no significant effects on milk yield, milk fat percentage and yield, lactose percentage and yield, or milk protein percentage and yield ($P>0.05$).

2.5 Plasma Biochemical Indicators

As shown in , TMR particle size had no significant effects on plasma alanine aminotransferase, aspartate aminotransferase, and alkaline phosphatase activities, or on glucose, urea nitrogen, uric acid, and triglyceride concentrations ($P>0.05$).

Discussion

3.1 Effects of Different TMR Particle Sizes on Nutrient Intake and Apparent Digestibility in Dairy Cows

This experiment used a Latin square design with TMR particle size as the sole treatment. As TMR particle size decreased with increased forage mixing time, DM intake did not significantly increase, consistent with findings by Beauchemin et al. [9], Yang et al. [17], and Soita et al. [18]. Belyea et al. [19] suggested that for cows fed forage-only diets, reduced particle size increases intake, whereas for cows fed mixed forage-concentrate diets, particle size does not affect intake because rumen fill is no longer the limiting factor for DM intake, and metabolic factors become the primary limitation. Rode et al. [20] proposed that only long forage affects intake, while chopped forage or meal does not. However, more studies [5-7,21,22] have shown that reduced particle size increases intake. Allen [22] demonstrated that feed intake and nutrient supply are limited by rumen fill and digesta outflow rate, and reduced particle size decreases forage effects on rumen fill while increasing outflow rate, enabling greater feed intake.

Shaver et al. [23] and Beauchemin et al. [24] noted that when dairy cows consume low-quality, high-fiber diets, reduced forage particle size increases DM intake, whereas with more balanced diets, forage particle size has minimal impact on DM intake. The lack of significant effect observed in this experiment may be attributed to two factors: first, the experimental TMR was well-balanced with diverse ingredients, a concentrate-to-forage ratio of 55.03:44.97 (with cottonseed as concentrate), and high-quality forage (imported alfalfa and Northeast *Leymus chinensis*, corn silage), making the effect of particle size reduction on DM intake insignificant; second, in experiments showing significantly increased intake with reduced particle size, such as Yansari et al. [5] (pef >1.18 mm range: 0.46-

0.71) and Einarson et al. [6] (pef >1.18 mm range: 0.776–0.952), the pef range in this experiment (0.83–0.90) was relatively narrow due to TMR mixer power and blade characteristics, possibly contributing to the non-significant effect of particle size reduction on DM intake.

Mertens [25] found that reduced TMR particle size increases surface area for microbial attachment, promoting faster rumen fermentation and digestion, while also increasing outflow rate and reducing digesta retention time, negatively affecting nutrient digestion. Conversely, Yansari et al. [5] and Einarson et al. [6] reported that reduced particle size decreased rumen pH and microbial digestion capacity. Thus, particle size effects on digestibility are multifaceted, with final digestibility representing a combination of multiple factors.

This experiment demonstrated that reduced TMR particle size through increased forage mixing time significantly affected apparent digestibility of DM, OM, NDF, and N, with the two longest mixing time groups showing significantly higher whole-tract apparent digestibility of DM and NDF than the two shortest mixing time groups. The shortest mixing time group had lower N apparent digestibility than the other three groups, and OM whole-tract apparent digestibility also differed among groups. Yang et al. [17] found that reduced particle size did not affect OM digestibility in the rumen or whole tract, decreased NDF digestibility in both rumen and intestine, and reduced whole-tract N apparent digestibility. Yansari et al. [5] reported that reduced particle size did not affect apparent digestibility of DM, OM, or N but decreased NDF apparent digestibility. Belyea et al. [19], Shaver et al. [23], and Grant et al. [26] indicated that reduced particle size decreases fiber digestibility due to increased intake and faster outflow rate. The discrepancy between our results and international studies may stem from two factors: first, reduced particle size in this experiment did not affect intakes of DM, OM, NDF, peNDF, or N, preventing the digestibility decline associated with increased nutrient intake; second, the relatively narrow pef range (0.83–0.90) in this experiment may have resulted in less pronounced effects on rumen acidity and outflow rate compared to effects on microbial digestion.

3.2 Effects of Different TMR Particle Sizes on Chewing Activity in Dairy Cows

Numerous studies [7,27,28] have demonstrated that dietary NDF content and particle size are important factors affecting dairy cow chewing activity. Beauchemin et al. [9] and Krause et al. [28] found that reduced particle size did not affect eating time but decreased ruminating time. Yansari et al. [5] reported that reduced particle size decreased total chewing, ruminating, and eating times. Notably, in Yansari et al. [5], reduced particle size increased DM intake but decreased peNDF intake, whereas in Beauchemin et al. [9], reduced particle size did not affect DM intake but decreased peNDF intake. peNDF intake may be an important indicator reflecting ruminating activity. While increased DM and peNDF intake certainly increases ruminating activity, eating time may not be

affected.

In this experiment, multiple indicators including daily eating, ruminating, and chewing times (eating + ruminating), as well as eating, ruminating, and chewing times per kilogram of DM or NDF, were unaffected by TMR particle size, consistent with Clark et al. [29]. Additionally, reduced TMR particle size through increased mixing time did not affect DM, NDF, or peNDF intakes, which may explain the lack of significant differences in chewing activity indicators.

3.3 Effects of Different TMR Particle Sizes on Milk Yield and Composition in Dairy Cows

Generally, TMR particle size affects milk yield through its influence on feed intake and digestibility. Multiple studies [6,7,10,27,30,31] have shown that reduced particle size does not significantly affect milk yield, and in these experiments, DM intake increased. The lack of improved milk yield despite increased intake may be attributed to decreased nutrient digestibility. Beauchemin et al. [9] found that reduced particle size did not significantly affect DM intake or milk yield. Notably, Yansari et al. [5] reported that reduced particle size significantly increased DM intake without affecting DM or N apparent digestibility, yet milk yield did not significantly improve. In this experiment, reduced TMR particle size through increased mixing time did not significantly affect nutrient intake but significantly affected apparent digestibility of DM, OM, NDF, and N, while milk yield did not differ significantly among groups. In practice, factors affecting milk yield are more complex than those affecting intake and digestibility, with multiple variables including diet formulation, feeding management, housing comfort, weather changes, and milking management all influencing milk yield.

Shaver et al. [23], Armentano et al. [32], and Mertens [25] suggested that reduced fiber digestibility, decreased rumen pH, reduced ruminating and chewing times, and decreased acetate-to-propionate ratio associated with reduced particle size ultimately affect milk fat and protein percentages. Armentano et al. [32] considered milk fat percentage a good indicator of rumen fermentation status, rumen pH, and peNDF content for mid-lactation cows. This experiment did not observe effects of reduced TMR particle size through increased mixing time on milk composition, consistent with Krause et al. [30], Beauchemin et al. [9], Calberry et al. [27], and Einarson et al. [6]. However, Yansari et al. [5] found that reduced particle size significantly decreased NDF and peNDF intake, significantly increased DM intake, did not affect DM or N apparent digestibility, but decreased NDF apparent digestibility, resulting in non-significant effects on milk yield but decreased milk fat percentage and increased milk protein percentage. Despite controversial findings, the conclusion that reduced particle size and decreased peNDF intake reduce milk fat percentage is widely accepted. Mertens [25] and Beauchemin et al. [33] suggested that particle size effects on milk fat percentage are more readily observed when dietary NDF content (19.7%) is below the minimum requirement of NRC (1989).

Three factors may explain the lack of milk composition changes in this experiment: first, the relatively short experimental period (19 days per period) and small number of animals (4 cows); second, the inclusion of alfalfa (18.28%) in the experimental TMR, which has buffering effects; and third, the presence of cottonseed in the diet, which directly affects milk fat percentage.

3.4 Effects of Different TMR Particle Sizes on Plasma Biochemical Indicators in Dairy Cows

Few studies have investigated TMR particle size effects on plasma biochemical indicators in dairy cows. Bhandari et al. [34] found that reducing alfalfa and corn silage length did not affect plasma glucose and urea concentrations, and Bhandari et al. [15] similarly reported no significant differences in plasma glucose and urea concentrations after reducing alfalfa and oat lengths, consistent with our results. Kahn [35] considered normal plasma glucose and urea concentrations in dairy cows to be 2.4–4.2 mmol/L and 2.8–8.8 mmol/L, respectively. Plaizier [36] found that replacing alfalfa silage with chopped alfalfa to reduce TMR particle size increased plasma glucose concentration and decreased plasma urea concentration, but these differences were primarily attributed to feed type rather than particle size. In this experiment, reduced particle size did not affect intakes of DM, OM, NDF, peNDF, or N, which may explain the lack of significant differences in plasma indicators.

Conclusion

This study demonstrates that moderately extended forage mixing time significantly affects TMR particle size and improves nutrient digestibility. Under the conditions of this experiment, the suitable TMR particle size distribution is as follows: DM proportions of 19.00 mm, 8.00–<19.00 mm, 1.18–<8.00 mm, and <1.18 mm should be 45.20%, 25.50%, 16.55%, and 12.75%, respectively. The optimal mixing times for alfalfa and *Leymus chinensis* in TMR are 9 min and 15 min, respectively.

References

- [1] Kong QB, Zhang XM. Effects of alfalfa hay cutting length on nitrogen balance and energy metabolism in Holstein heifers [J]. *Chinese Journal of Animal Nutrition*, 2008, 20(4): 429–434.
- [2] He M. Effects of different particle sizes of roughage in TMR on chewing behavior and rumen fermentation in dry cows [D]. Master's thesis. Beijing: China Agricultural University, 2005.
- [3] Li SL, Chen P, Zheng BW. How to improve milk yield and quality by improving feed conversion efficiency in dairy cows [C]//Progress in Feed Nutrition Research—Proceedings of the 5th National Symposium on Feed Nutrition. Beijing: Chinese Association of Animal Nutrition and Feed Science, 2006: 210–

216.

- [4] Zhang Q. Effects of PeNDF level in TMR on rumen fermentation and milk performance in dairy cows [D]. Master's thesis. Yangzhou: Yangzhou University, 2010.
- [5] YANSARI AT, VALIZADEH R, NASERIAN A, et al. Effects of Alfalfa particle size and specific gravity on chewing activity, digestibility and performance of Holstein dairy cows [J]. *Journal of Dairy Science*, 2004, 87(11): 3912-3924.
- [6] EINARSON MS, PLAIZIER JC, WITTENBERG KM. Effects of barley silage chop length on productivity and rumen conditions of lactating dairy cows fed a total mixed ration [J]. *Journal of Dairy Science*, 2004, 87(9): 2987-2996.
- [7] KONONOFF PJ, HEINRICHS AJ. The effect of corn silage particle size and cottonseed hulls on cows in early lactation [J]. *Journal of Dairy Science*, 2003, 86(7): 2438-3451.
- [8] ALAMOUTI AA, ALIKHANI AM, GHORBANI GR, et al. Effects of inclusion of neutral detergent soluble fibre sources in diets varying in forage particle size on feed intake, digestive processes, and performance of mid-lactation Holstein cows [J]. *Animal Feed Science and Technology*, 2009, 154(1/2): 9-23.
- [9] BEAUCHEMIN KA, YANG WZ, RODE LM. Effects of particle size of Alfalfa-Based dairy cow diets on chewing activity, ruminal fermentation, and milk production [J]. *Journal of Dairy Science*, 2003, 86(2): 630-643.
- [10] YANG WZ, BEAUCHEMIN KA. Effects of physically effective fiber on chewing activity and ruminal pH of dairy cows fed diets based on barley silage [J]. *Journal of Dairy Science*, 2006, 89(1): 217-228.
- [11] YANG WZ, BEAUCHEMIN KA. Effects of physically effective fiber on digestion and milk production by dairy cows fed diets based on corn silage [J]. *Journal of Dairy Science*, 2005, 88(3): 1090-1098.
- [12] BEAUCHEMIN KA, YANG WZ. Effects of physically effective fiber on intake, chewing activity, and ruminal acidosis for dairy cows fed diets based on corn silage [J]. *Journal of Dairy Science*, 2005, 88(6): 2117-2129.
- [13] KAHYANI A, GHORBANI GR, KHORVASH M, et al. Effects of alfalfa hay particle size in high-concentrate diets supplemented with unsaturated fat, chewing behavior, total-tract digestibility, and production dairy cows [J]. *Journal Dairy Science*, 2013, 96(11): 7110-7119.
- [14] LEONARDI C, ARMENTANO LE. Effect of quantity, quality and length of alfalfa hay on selective consumption by dairy cows [J]. *Journal of Dairy Science*, 2003, 86(2): 557-564.
- [15] BHANDARI SK, LI S, OMINSKI KH, et al. Effects of the chop lengths of alfalfa silage and oat silage on feed intake, milk production, feeding behavior, and rumen fermentation of dairy cows [J]. *Journal of Dairy Science*, 2008, 91(5): 1942-1958.

- [16] Feng YL, Lu ZN. Nutritional Requirements of Dairy Cows and Feed Composition [M]. 3rd ed. Beijing: China Agriculture Press, 2007.
- [17] YANG WZ, BEAUCHEMIN KA, RODE LM. Effects of particle size of alfalfa-based dairy cow diets on site and extent of digestion [J]. *Journal of Dairy Science*, 2002, 85(8): 1958-1968.
- [18] SOITA HW, CHRISTENSEN DA, MCKINNON JJ. Influence of particle size on the effectiveness of the fiber in barley silage [J]. *Journal of Dairy Science*, 2000, 83(10): 2295-2300.
- [19] BELYEA RL, MARTIN PJ, SEDGWICK HT. Utilization of chopped and long alfalfa by dairy Heifers [J]. *Journal of Dairy Science*, 1985, 68(5): 1297-1301.
- [20] RODE LM, WEAKLEY DC, SATTER LD. Effect of forage amount and particle size in diets of lactating dairy cows on site of digestion and microbial Protein synthesis [J]. *Canadian Journal of Animal Science*, 1985, 65(1): 101-111.
- [21] JASTER EH, MURPHY MR. Effects of varying particle size of forage on digestion and chewing behavior of dairy heifers [J]. *Journal of Dairy Science*, 1983, 66(4): 802-810.
- [22] ALLEN MS. Effects of diet on short-term regulation of feed intake by lactating dairy cattle [J]. *Journal of Dairy Science*, 2000, 83(7): 1598-1624.
- [23] SHAVER RD, NYTES AJ, SATTER LD, et al. Influence of feed intake, forage physical form, and forage fiber content on Particle size of masticated forage, ruminal digesta and feces of dairy cows [J]. *Journal of Dairy Science*, 1988, 71(6): 1566-1567.
- [24] BEAUCHEMIN KA, RODE LM, ELIASON MV. Chewing activities and milk production of dairy cows fed alfalfa as hay, silage, or dried cubes of hay or silage [J]. *Journal of Dairy Science*, 1997, 80(2): 324-333.
- [25] MERTENS DR. Creating a system for meeting the fiber requirements of dairy cows [J]. *Journal of Dairy Science*, 1997, 80(7): 1463-1481.
- [26] GRANT RJ, COLENBRANDER VF, MERTENS DR. Milk fat depression in dairy cows: role of particle size of alfalfa hay [J]. *Journal of Dairy Science*, 1990, 73(7): 1823-1833.
- [27] CALBERRY JM, PLAIZIER JC, EINARSON MS, et al. Effects of replacing chopped alfalfa hay with alfalfa silage in a total mixed ration on production and rumen conditions of lactating dairy cows [J]. *Journal of Dairy Science*, 2003, 86(11): 3611-3619.
- [28] KRAUSE KM, COMBS DK, BEAUCHEMIN KA. Effects of forage particle size and grain fermentability in midlactation cows. II. Ruminant pH and chewing activity [J]. *Journal of Dairy Science*, 2002, 85(8): 1947-1957.

- [29] CLARK PW, ARMENTANO LE. Influence of particle size on the effectiveness of the fiber in corn silage [J]. *Journal of Dairy Science*, 1999, 82(3): 581-588.
- [30] KRAUSE KM, COMBS DK, BEAUCHEMIN KA. Effects of forage particle size and grain ferment ability in midlactation cows. I. Milk production and diet digestibility [J]. *Journal of Dairy Science*, 2002, 85(8): 1936-1946.
- [31] YANG WZ, BEAUCHEMIN KA, RODE LM. Effects of grain processing, forage to concentrate ratio, and forage particle size on rumen pH and digestion by dairy cows [J]. *Journal of Dairy Science*, 2001, 84(10): 2203-2216.
- [32] ARMENTANO L, PEREIRA M. Measuring the effectiveness of fiber by animal response trials [J]. *Journal of Dairy Science*, 1997, 80(7): 1416-1425.
- [33] BEAUCHEMIN KA, FARR BI, RODE LM, et al. Effects of alfalfa silage chop length and supplementary long hay on chewing and milk production of dairy cows [J]. *Journal of Dairy Science*, 1994, 77(5): 1326-1339.
- [34] BHANDARI SK, OMINSKI KH, WITTENBERG KM, et al. Effects of chop length of alfalfa and corn silage on milk production and rumen fermentation of dairy cows [J]. *Journal of Dairy Science*, 2007, 90(5): 2355-2366.
- [35] KAHN CM. *The Merck veterinary manual* [M]. 9th ed. Rahway, NJ: Merck & Co Inc., 2005.
- [36] PLAIZIER JC. Replacing chopped alfalfa hay with alfalfa-silage in barley grain and alfalfa based total mixed rations lactating dairy cows [J]. *Journal of Dairy Science*, 2004, 87(8): 2495-2505.

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