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Dietary protein level and corn processing method: Intake, digestibility, and feeding behavior of lactating dairy cows☆

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ABSTRACT

The effects of corn processing and dietary protein level and their interaction on intake, digestibility, and feeding behavior in dairy cow was examined using eight multiparous Holstein dairy cows in mid-lactation (105 ± 9 days in milk and 47.2 ± 3 kg/day milk production at the start of the experiment) that were placed in a replicated 4 × 4 Latin square with a 2 × 2 factorial arrangement of treatments. Experimental diets contained either finely ground corn (FGC) or steam-flaked corn (SFC) based on either low protein (LP, 14.8%) or high protein (HP, 16.2%) content. Diets contained 40% forage (corn silage and alfalfa hay) and 40% corn grain. Dry matter intake did not differ between HP and LP diets. In contrast, cows fed LP had greater total tract digestibility compared with that for HP-fed cows. Cows fed LP had greater chewing time and lower chewing rate (g of DM/min) compared to those for cows fed HP. Cows receiving SFC had a lower intake of nutrients and tended to have greater ADF and starch digestibility than cows fed FGC. There was an interaction between corn processing and level of protein with respect to the apparent total tract digestibility with cows fed FGC with HP resulted in the lowest digestibility. Steam-flaked corn had lower density and greater moisture and mean particle size than the FGC. In comparison with FGC, SFC did not pass through the 8-mm sieve and caused significant increase in physical effectiveness factor (pef) and physically effective fiber (peNDF) in SFC diets compared to that for FGC diets. Cows fed SFC sorted against longer particles ($P = 0.04$) to a greater extent than cows fed FGC. Dietary protein level had no detectable effect on sorting index. Chewing time did not differ for cows fed SFC or FGC; however, cows fed SFC had lower chewing and rumination rate (g of DM/min). Chewing time per kg of DM and CP were greater and per kg of peNDF were lower in cows fed SFC rather than cows fed FGC. Results indicated that corn processing and dietary protein level may interact to affect nutrient digestibility, but did not affect the feeding and chewing behavior of lactating cows under our experimental conditions. Results also showed that dietary peNDF content and chewing activity can be effectively manipulated by steam flaking of corn, and cows fed SFC had greater peNDF and energy intake despite lower DMI.

1. Introduction

High-producing dairy cows require greater amounts of energy and protein in order to meet their nutrient requirements. Use of higher level of concentrate in the ration may however result in lowering the forage inclusion level and dietary physical fiber, which can be harmful to the health of the cows (Beauchemin and Yang, 2005).

Carbohydrates and protein are 2 main nutrients in the diet of dairy cows. The proper balance between carbohydrates and protein could increases the performance, enhance the efficiency and reduce the environmental pollution (Santos et al., 1998, 1999). Milk yield is maximized with greater dietary protein content (NRC, 2001), but diets must be formulated to maintain milk production as well as to improve nitrogen utilization efficiency. Careful management of dietary protein is necessary to maximize the benefit and minimize the potential threat of environmental pollution (Mutsvangwa et al., 2016). Optimization of rumen microbial production can be a more effective method than using higher percentages of CP. The rate of carbohydrate fermentation in the rumen is one of the major factors affecting rumen microbial production (Aldrich et al., 1993). Corn grain is commonly used to increase the

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energy density of diets because of its high starch content. As the whole grain is almost completely resistant to microbial digestion in the rumen, different methods of grinding or steam flaking have been used to enhance ruminal carbohydrate availability for improved performance and feed efficiency in dairy cattle (Zhong et al., 2008; Cooke et al., 2009; Ferraretto et al., 2013). Steam flaking of corn can increase ruminal digestion of starch and boost the microbial protein synthesis (Bernard et al., 2004), provided the level of physically effective fiber is sufficient to prevent acidosis (Allen, 2000; Beauchemin and Yang, 2005). Several experiments examined the effect of dietary protein (Broderick, 2003; Mutsvangwa et al., 2016) or corn processing (Zhong et al., 2008; Cooke et al., 2009) on dairy cow performance. For instance, Mutsvangwa et al. (2016) observed that dietary CP content had no effect on DMI. However, Broderick (2003) reported a linear increase in DMI with increased dietary CP. Cooke et al. (2009) and Harvatine et al. (2002a) reported that feeding steam flaked corn (SFC), instead of finely ground corn (FGC), decreased DMI, whereas Zhong et al. (2008) and Bernard et al. (2004) reported a greater DMI for cows fed SFC compared to those fed FGC.

The increase of dietary protein decreased ruminal fiber digestion (Reynal and Broderick, 2005) or DMI (Broderick, 2003). Corn flaking can affect DMI (Cooke et al., 2009) or increase particle size (Harvatine et al., 2002b); which in turn could affect chewing activity. Feeding behavior may be improved by the source (Oba and Allen, 2003) or processing (Harvatine et al., 2002b) of grain. Although the effect of corn flaking and dietary protein level on DMI has been extensively investigated, few experiments have evaluated the impacts of interaction between corn flaking and dietary protein level on feeding behavior, DMI and digestibility. As each of the dietary protein levels and corn flaking affect DMI and digestibility, we assumed that their interaction might also affect DMI, digestibility and feeding behavior. Because of this, our hypothesis for the present study was that corn flaking and protein level may interactively change the intake, digestibility and feeding behavior of high producing dairy cow. To our knowledge, the interaction between dietary protein and corn processing on intake, digestibility and feeding behavior of high producing dairy cows has not been studied. Hence, the specific objective of this experiment was to determine the effects of, and interactions between, corn processing and dietary protein level on the DMI, digestibility and feeding and chewing behavior in mid-lactation Holstein cows.

2. Material and methods

All animal procedures were conducted under protocols approved by the Animal Care and Use Committee of the Iranian Council of Animal Care (1995). The experiment was conducted from December 2014 to February 2015, in Lavark at the Farm Animal Research and Teaching Unit of Isfahan University of Technology (Isfahan, Iran). To calculate the temperature-humidity index (**THI**), ambient temperature (**T_{db}**, °C) and relative humidity (**RH**, %) were recorded using a temperature and humidity data-logger (ST-172; Fotronic Co., Melrose, MA) every 15 min:

$THI = (1.8 \times T_{db} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26.8)]$ (Dikmen and Hansen, 2009). The average THI, T_{db} and RH for entire experimental period were 50, 8.2 °C and 51%, respectively.

2.1. Experimental design, cow management, and treatments

Eight multiparous Holstein cows from the research herd at Isfahan University of Technology were used in a replicated 4 × 4 Latin square design. Within each square, cows were randomly assigned in a sequence to four diets. Each period lasted 21 days, with the first 14 days for adaptation and the last 7 days for sampling and data collection. At the start, cows averaged 105 ± 9 DIM, 47.2 ± 3 kg milk/day, and 614 ± 43 kg of BW (mean ± SEM). Throughout the experiment, each cow was housed in a box stall (4 × 4 m) of a roofed barn with open sides. Each box stall was bedded with clean wood shavings, refreshed twice daily, to minimize the risk of mastitis. Each box had a concrete feed bunk and automatic water troughs.

Table 1
Ingredients and chemical composition of experimental diets on DM basis.

Item	SFC[a] HP	SFC[a] LP	FGC HP	FGC LP
Alfalfa hay	15.44	15.45	15.44	15.45
Corn silage	23.17	23.17	23.17	23.17
Ground corn grain	0	0	39.38	39.40
Flake corn grain	39.38	39.40	0	0
Soybean meal, 44% CP	11.66	8.11	11.66	8.11
Fish meal	3.01	2.32	3.01	2.32
Lignosulfonate treated soybean meal[b]	2.05	4.44	2.05	4.44
Urea	0.31	0.08	0.31	0.08
Beet pulp	1.12	3.17	1.12	3.17
Calcium salts of fatty acids[c]	1.74	1.74	1.74	1.74
Sodium bicarbonate	0.69	0.70	0.69	0.70
Magnesium oxide	0.31	0.31	0.31	0.31
Dicalcium phosphate	0.12	0.12	0.12	0.12
Salt	0.08	0.08	0.08	0.08
Mineral and vitamin premix[d]	0.93	0.93	0.93	0.93
Chemical composition				
DM, % of diet	55.52	55.54	56.32	56.01
NE_L[e], Mcal/kg DM	1.76	1.76	1.62	1.62
OM	92.40	92.49	92.53	92.86
CP	16.12	14.75	16.28	14.88
RUP[e]	7.46	7.56	7.22	7.35
RDP[e]	8.66	7.19	9.06	7.53
NDF	31.78	31.76	30.86	30.94
ADF	14.42	14.33	13.70	13.89
Starch	28.3	27.3	27.5	28.3
Ether extract	4.65	4.64	4.69	4.66
NFC[f]	39.84	41.34	40.68	42.37

[a] SFC = steam flake corn; FGC = finely ground corn; HP = high protein; LP = low protein.
[b] Sanadam Pars Co., Tehran, Iran.
[c] Nutracor, Wawasan, Malaysia. Composition: Ash 13%, Moisture 3%, Calcium 9%, Crude fat 85% (C12:0, 0.2%; C14:0, 1.2%; C16:0, 47%; C18:0, 5%; C18:1, 38%; C18:2, 8%).
[d] Composition: 195 g/kg of Ca, 21 g/kg of Mg, 2.2 g/kg of Mn, 0.3 g/kg of Zn, 0.3 g/kg of Cu, 0.12 g/kg of I, 0.1 g/kg of Co, 600,000 IU/kg of vitamin A, 200,000 IU/kg of vitamin D, and 0.2 g/kg of vitamin E, 0.025 g/kg of Se.
[e] Calculated from NRC (2001).
[f] Nonfibrous carbohydrates [NFC = OM − (NDF + CP + EE)] where EE = ether extract.

A 2 × 2 factorial arrangement of treatments was employed to provide two protein levels (low protein, LP = 14.8% or high protein, HP = 16.2%) each with two processing methods of corn (finely ground corn, FGC or steam-flaked corn, SFC). The treatments consisted of: steam-flaked corn with high level of protein (**SFC-HP**), steam-flaked corn with a low level of protein (**SFC-LP**), finely ground corn with a high level of protein (**FGC-HP**), and finely ground corn with a low level of protein (**FGC-LP**, Table 1). Chemical compositions of the experimental TMR are presented in Table 1. Diets contained 40% corn either finely ground or steam-flaked. The forage to concentrate ratio was 40:60 on a DM basis. Corn silage and chopped alfalfa were the forage components.

Before feeding, alfalfa was chopped to a theoretical length of 30 mm using a harvesting machine with screen size regulator (Golchin Trasher Hay Co., Isfahan, Iran). Corn silage was sampled on a weekly basis for DM content, and its inclusion in diets was adjusted accordingly. Diets were formulated to meet or exceed the Cornell Net Carbohydrate and Protein System (version 5.0) nutrient allowance for a lactating dairy cow weighing 620 kg and producing 47 kg/day of milk with 3.0% milk protein and 3.2% fat and consuming 25.5 kg of DMI and were 100 DIM. Diets were supplied twice daily at 0930 h and 1730 h, and orts were weighed daily, before feeding, and feed offered was adjusted daily to about 10% in excess.

2.2. Corn processing techniques

Corn grain (40% of diet as DM basis) from one source (Chavdane Co., Isfahan, Iran) was used throughout the experiment. Finely ground corn was processed through a conventional on-farm hammer mill with 3-mm screen (Isfahan Dasht, model 5543 GEN, Isfahan, Iran). Optimal flake density of steam-flaked corn grain appears to be approximately 360 g/L (Theurer et al., 1999), and we used this density for the current study. Corn flaking followed method described by Plascencia and Zinn (1996) at a commercial feed processing complex (Chavdane Co., Isfahan, Iran). Corn grains were screened and steamed (boiler pressure: 80 psi) for 30 min at 99 °C in a stainless steel chamber and subsequently rolled between preheated, corrugated rollers (46 cm × 90 cm). The gap between the two rollers was adjusted to produce the flake density of about 360 g/L, and grains flaked during the adjustment period were discarded. Density (kg per liter) was determined after rolling and before cooling. The steamed corn was dried immediately in a horizontal drier. Flake thickness (mm) and processing index (PI, %) were determined according to the method of Zinn and Barajas (1997) and Yang et al. (2000), respectively.

Particle size of each processed corn type was determined by dry sieving with a Ro-Tap sieve shaker equipped with sieves (W. S. Tyler, Inc., Mentor, OH) arranged in the descending mesh size (4.75, 2.36, 1.18, 0.85, 0.60, 0.30, 0.15,0.075 mm, and pan). Duplicate samples of ground and steam-flaked corns (100 g) were placed on the top screen and shaken for 10 min. The amount of grain held on each screen was weighed and used to calculate mean particle size. Geometric mean diameter and standard deviation of steam-flaked and ground corns were determined according to the procedure of the American Society of Agricultural Engineers (2006).

2.3. Sampling, measurements, and analyses

Amounts of fresh TMR and refusal were recorded and sampled daily by cow. The samples were refrigerated until the end of the collection period, at which time they were combined by cow, sub-sampled and then stored at −20 °C for later analysis. Feed and orts samples were dried at 60 °C in a forced-air oven for 48 h and DM results were adjusted to 100 °C according to AOAC International (2002; method 925.40). The weight of TMR offered and orts was recorded and sampled daily. After drying feed and orts samples, the DM% of TMR and orts was determined. The fresh weight of TMR and orts of each day was multiplied on DM% to change the weight of them on DM basis. The amount of DMI was calculated from the difference between the offered TMR and the orts (DM basis). All feed and orts samples were ground using a Wiley mill with a 1-mm screen (Wiley mill, Arthur H. Thomas) and analyzed for NDF (using heat-resistant alpha-amylase, 100 μL/ sample) and ADF, according to Van Soest et al. (1991) with the Ankom Fiber Analyzer system (Ankom Technology, Macedon, NY), starch (Zhu et al., 2016), and DM (method 925.40), ash (method 942.05), CP (method 2001.11), and ether extract (**EE**; method 920.39) according to AOAC (2002). Organic matter was calculated as OM = (100% ash). Fecal grab samples were taken from each cow for 4 consecutive days (the first 4 days of each sampling period) at 9-h intervals at 1100, 2000, 0500, 1400, 2300, 0800, 1700, and 0200 h. The samples were composited by cow and kept at −20 °C until analysis. These samples were dried in a forced-air oven at 60 °C for 72 h, ground to pass through a 1-mm screen, and analyzed for starch, DM, ash, ADF, NDF and CP, as described above. Apparent total-tract digestibility of nutrients was determined using acid-insoluble ash as an internal marker (Van Keulen and Young, 1977).

2.4. Particle size distribution

On day 16 and 17 of each experimental period, PS distributions of the samples at 0, 2, 8 and 24 h post-feeding were determined on as fed basis (in duplicate) using the Penn State Particle Separator (**PSPS**) with 2 sieves (19 and 8 mm; Lammers et al., 1996), and also using the modified PSPS with an additional 1.18-mm sieve (19, 8, and 1.18 mm; Kononoff et al., 2003). The DM of particles retained on each fraction was determined by oven drying at 60 °C for 48 h. The physical effectiveness factor (**pef**) was determined as the DM proportion of particles retained on two sieves ($\mathbf{pef}_{>8}$; Lammers et al., 1996) and on three sieves ($\mathbf{pef}_{>1.18}$; Kononoff et al., 2003) of the PSPS, respectively. The physically effective NDF of two ($\mathbf{peNDF}_{>8}$) and three sieves ($\mathbf{peNDF}_{>1.18}$) were calculated as ration NDF multiplied by the corresponding pef. Actual intake of peNDF, with both systems, was then calculated after adjustment for this value in orts. Geometric mean PS was calculated as described by the American Society of Agricultural Engineers (ASAE, 1995, method S424.1).

2.5. Chewing activity and sorting activity

Eating and ruminating behaviors were monitored visually for a 24-h period on day 19 of each period using sheet scale scoring. In this method, individuals (3 persons) are instructed before recording on detection of various behaviors such as eating and ruminating. Then, a specific sign is assigned for each behavior. Therefore, the variation in detection of cow's behaviors is reduced among individuals assigned. Chewing activity were noted every 5 min, and each activity (i.e., eating, ruminating, resting) was assumed to persist for the entire 5 min. Total chewing time was determined as the sum of total eating and ruminating times. Activities per kg of nutrient ingested, such as DM, NDF, $\mathrm{peNDF}_{>8}$ and $\mathrm{peNDF}_{>1.18}$ were calculated by dividing total time spent for chewing, eating or ruminating on day 19 intake. A period of chewing was defined as at least 5 min of chewing activity followed by at least 5 min without chewing activity. Rate of DMI was calculated as the ratio of DM ingested and duration of the meal.

The sorting index was calculated as the ratio of actual intake to expected intake for particles retained on each sieve of the PSPS (Leonardi and Armentano, 2003). The predicted intake of an individual fraction was calculated as the product of the DMI of the total diet multiplied by the DM percentage of that fraction in the TMR fed. Sorting index of 100 indicates no sorting, >100 indicates sorting for particles, and <100 indicates sorting against particles.

2.6. Statistical analysis

Normality of distribution and homogeneity of variance for residuals were tested using PROC UNIVARIATE (SAS Institute, 2002). Data were subjected to the MIXED MODEL procedure of SAS (SAS Institute, 2002). The model included period, treatment, square, and the relevant interactions as fixed effects, and cow as a random effect. The REML method was used to estimate least squares means, and the Kenward-Roger method was used to calculate denominator degrees of freedom. Effects were declared significant at $P \le 0.05$ and trends were discussed at $P \le 0.10$. Means were compared using the Tukey multiple comparison test.

3. Results

3.1. Diet composition

Diets did not differ in DM, ADF and NDF content (Table 1). The mean concentrations of DM, ADF, and NDF for diets were 55.8%, 14.0%, and 31.3% of DM, respectively. The mean protein content of HP diets was 9.4% greater than LP diets (16.2% vs 14.8% of DM). The NFC content of the HP diets was lower than for LP diets (40.3% vs 41.8% of DM). There were no differences detected between FGC and SFC diets in chemical composition.

Table 2
Particle size distribution of processed corn.

Sieve opening, mm	Steam-flaked corn	Ground corn	SEM	P
4.75	86.28	0	0.25	< 0.01
2.36	12.83	1.95	0.44	< 0.01
1.18	0.40	8.16	0.03	< 0.01
0.85	0.045	13.28	0.43	< 0.01
0.60	0.03	20.88	0.90	< 0.01
0.30	0.07	38.75	1.76	< 0.01
0.15	0.32	16.50	2.68	0.05
0.075	0.02	0.48	0.10	0.09
Pan	0	0	0	0
Mean particle size, mm	4.25	0.41	0.01	< 0.01
Standard deviation, mm	1.39	11.41	0.35	< 0.01
DM, %	86.00	88.99	0.73	0.10
Density, g/L	367	643	0.98	< 0.01
Processing index[a], %	41.99	73.57	0.11	< 0.01
Flake thickness, mm	1.56 ± 0.32	–	–	–

[a] Processing index is the volume weight of the corn after processing, expressed as a percentage of its volume weight before processing (Yang et al., 2000).

3.2. Physical characteristics of corn grain

Dry matter content of SFC tended to be reduced by about 3%, as compared with that for the FGC (86% vs 89%, $P = 0.10$, Table 2). Steam-flaked corn had lower PI (42% vs 73%, $P < 0.01$) and density (367 vs 643 g/L, $P < 0.01$) than the ground corn. Flake thickness averaged 1.56 ± 0.32 mm. Mean particle size (**MPS**) of the steam-flaked corn was greater than that of the ground corn, as expected (4.25 vs 0.41 mm, $P < 0.01$). Using SFC, rather than FGC, in the concentrate of dairy cows increased the MPS of the concentrate. In the current study, the concentrate containing SFC had higher MPS (6.67 vs 3.90 mm, $P < 0.01$) and lower density (552 vs 691 g/L, $P < 0.01$), as compared with the concentrate containing FGC.

3.3. Diet particle length and effective fiber

Physical characteristics of the TMR offered, orts and TMR consumed are shown in Table 3. There were no treatment interactions detected in physical characteristics of diets. A greater proportion of particles retained on 8-mm sieve of the PSPS for HP tended to be greater when compared with LP diets of the offered (33.4% vs 31.9%, $P = 0.06$) and consumed (33.2% vs 31.4%, $P = 0.06$) TMR. Consequently, $pef_{>8}$ (41.3% vs 39.3%, $P = 0.03$), $peNDF_{>8}$ (12.6% vs 12.0%, $P = 0.05$) and MPS (4.9 vs 4.7 mm, $P = 0.04$) were increased in HP diets. Protein level had no detectable effect on particle distributions of orts. However, particle distributions of orts differed from those of the offered TMR. The proportion of particles retained on 19- and 1.18-mm sieves of the PSPS were respectively higher and lower for orts than for the offered TMR, indicating the preferential consumption of shorter feed particles by cows. Averaged over different protein level, the $pef_{>8}$, $peNDF_{>8}$ and MPS of the orts increased by 41%, 86% and 65%, respectively, compared with the diets offered.

Proportion of particles on the pan was lower ($P < 0.01$) in SFC diets compared with FGC diets; however, the proportions of particles in 8-mm sieve, pef, MPS, and peNDF ($P < 0.01$) were higher in offered and consumed SFC diets compared with FGC diets (Table 3). In comparison with FGC, SFC remained on 8-mm sieve indicating increase in pef and peNDF ($P < 0.01$).

Particle distributions of orts differed from those of the offered TMR. The proportion of particles retained on the 19-mm sieve was higher and proportion of particles retained on the 8- and 1.18-mm sieves and pan were lower for orts than for those offered SFC, and cows fed SFC diets had lower intake of 19-mm particles. However, the proportion of particles retained on the 19- and 8-mm sieves were higher and proportion of particles retained on the 1.18-mm sieve and pan were lower for orts than for those offered FGC, and cows fed FGC diets had lower intake of particles > 19 and > 8 mm.

3.4. Sorting behavior

There was no significant interaction between corn processing and protein level on sorting index detected (Table 4). Dietary protein level had no effect on sorting index either. Cows on HP diets ate more $peNDF_{>8}$ than cows in LP diets (3.1 vs 2.8 kg/day, $P = 0.03$), because HP diets had more $peNDF_{>8}$ compared with LP diets.

The proportion of orts particles on the 19-mm sieve in SFC diets was more than FGC diets (29.3% vs 21.8%, $P = 0.01$), cows fed SFC sorted against longer particles (82.2% vs 94.9%, $P = 0.04$) and sorted for medium-length particles on the 8-mm (100.5% vs 96.3%, $P < 0.01$) and 1.18-mm (103% vs 102%, $P = 0.03$) sieve of the PSPS to a greater extent than cows fed FGC. Regardless of the dietary treatment, cows sorted, to a similar extent, for particles on the pan. Cows fed FGC had higher intake of particles retained on the 19-mm (by 10.7%, 2.3 vs 2.0 kg/day, $P = 0.02$), 1.18-mm (by 8%, 10.4 vs 9.7 kg/day, $P < 0.01$) sieve and pan (by 216%, 9.5 vs 3.0 kg/day, $P < 0.01$) and lower intake of particles retained on the 8-mm sieve (by 102%, 5.8 vs 11.6 kg/day, $P < 0.01$) compared with cows fed SFC.

3.5. Nutrient intake and digestibility

The interaction between corn processing and dietary level was significant for starch intake ($P = 0.02$; Table 5), with cows fed FGC-LP having greatest starch intake (8.25 kg/day) while those fed SFC-LP diet lowest starch intake (7.41 kg/day). Dietary protein level had no effects on DMI (Table 5). Protein level had no effects on diurnal pattern of DMI and feeding rate. Cows fed HP diets showed greater ($P \leq 0.03$) intakes of protein (4.5 vs 4 kg/day) and $peNDF_{>8}$ (3.1 vs 2.8 kg/day) than cows fed LP diets (Table 6).

Total-tract digestibility of DM (69.7% vs 66.9%, $P < 0.01$), OM (72.0% vs 69.4%, $P = 0.01$), ADF (by 18.2%, 43.4% vs 36.7%, $P = 0.01$) and NDF (by 13.3%, 49.0% vs 43.2%, $P = 0.01$) was greater in LP than HP diets (Table 5; $P < 0.05$). Digestibility of CP and starch was not however affected by the dietary protein level. Interactions between corn processing and the dietary level of CP on the total-tract digestibility of DM, OM, ADF and NDF were detected ($P = 0.01$). The FGC-HP had lower digestibility compared to the other diets.

Dry matter intake was greater for cows fed FGC than that for cows fed SFC diets (28.0 vs 26.4 kg/day, $P < 0.01$; Table 5). Cows fed FGC diets had greater intakes ($P < 0.01$) of OM (26.0 vs 24.4 kg/day), NDF (8.5 vs 8.1 kg/day) and CP (4.4 vs 4.1 kg/day). Starch intake was greater in FGC than SFC (7.63 vs 8.17 kg/day, $P < 0.01$). Cows fed the SFC diets consumed more NE_L than cows fed the FGC diets (46.4 vs 45.4 Mcal/day, $P = 0.05$). Corn processing have influenced DMI in different time after morning feeding. The DMI during 0–2 h post feeding was not significantly affected by corn processing (6.7 kg). Cows fed SFC had 18.8% lower DMI (6.07 vs 7.21 kg) and feeding rate (16.86 vs 20.04 g DM/min) than cows fed FGC during 2–8 h post feeding ($P < 0.01$, Table 6).

The apparent total-tract digestibility of DM ($\bar{x} = 68.3\%$), OM ($\bar{x} = 70.7\%$), protein ($\bar{x} = 60.3\%$) and NDF ($\bar{x} = 46.1\%$) did not significantly differ by corn processing. The SFC diets tended to have greater total-tract digestibility of ADF (by 11%, 42.2% vs 37.9%, $P = 0.08$) and starch (by 1.1%, 98% vs 96.9%, $P = 0.10$) than FGC diets.

3.6. Chewing activity

Eating (349.9 vs 355.9 min/day, $P = 0.06$) and rumination (475.6 vs 497.5 min/day, $P = 0.08$) time tended to be lower and chewing time was lower (862 vs 817.5 min/day, $P < 0.01$) for cows fed HP diets than cows fed LP diets (Table 7). However, there were no treatment

Table 3
Least square means of particle distribution, physical effectiveness factor (pef), and physically effective fiber (peNDF) contents of the diets and orts containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
TMR offered								
% DM retained on screens								
19 mm	9.56	9.35	9.43	9.12	0.33	0.46	0.29	0.83
8 mm	44.68	43.01	22.12	20.71	0.80	< 0.01	0.06	0.87
1.18 mm	34.96	36.37	36.11	36.90	0.51	0.11	0.04	0.55
Pan	10.77	11.26	32.31	33.26	0.52	< 0.01	0.16	0.64
$pef_{>8}$[b]	54.25	52.37	31.56	29.83	0.68	< 0.01	0.01	0.91
$pef_{>1.18}$	89.21	88.74	67.67	66.74	0.52	< 0.01	0.16	0.64
$peNDF_{>8}$,[b]% of DM	17.23	16.63	9.72	9.20	0.25	< 0.01	0.04	0.87
$peNDF_{>1.18}$,[b]% of DM	28.35	28.19	20.87	20.73	0.30	< 0.01	0.62	0.97
MPS[c], mm	6.57	6.36	3.63	3.48	0.07	< 0.01	0.02	0.68
SDPS[c], mm	2.68	2.70	3.33	3.31	0.01	< 0.01	0.94	0.38
Orts								
% DM retained on screens:								
19 mm	30.03	28.66	23.67	19.99	3.08	0.01	0.36	0.67
8 mm	41.32	38.53	28.08	27.87	1.76	< 0.01	0.29	0.36
1.18 mm	22.75	25.61	27.97	30.29	2.03	< 0.01	0.13	0.87
Pan	28.35	28.19	20.87	20.73	0.30	< 0.01	0.62	0.97
$pef_{>8}$	71.36	67.19	51.76	47.94	3.21	< 0.01	0.16	0.94
$pef_{>1.18}$	94.11	92.80	79.74	78.24	1.52	< 0.01	0.37	0.95
$peNDF_{>8}$, % of DM	30.77	29.15	20.33	18.47	2.43	< 0.01	0.36	0.94
$peNDF_{>1.18}$, % of DM	40.10	39.43	31.05	29.82	2.11	< 0.01	0.57	0.86
MPS, mm	10.67	10.23	6.46	5.84	0.74	< 0.01	0.43	0.89
SDPS, mm	2.61	2.64	3.48	3.43	0.06	< 0.01	0.86	0.49
TMR consumed (adjusted for particle size of orts)								
% DM retained on screens:								
19 mm	7.71	7.80	8.38	7.84	0.50	0.35	0.55	0.41
8 mm	44.98	43.16	21.48	19.72	0.90	< 0.01	0.06	0.97
1.18 mm	36.09	37.35	36.79	37.85	0.58	0.32	0.06	0.87
Pan	11.20	11.68	33.34	34.47	0.55	< 0.01	0.16	0.55
$pef_{>8}$	52.69	50.96	29.86	27.70	0.84	< 0.01	0.03	0.80
$pef_{>1.18}$	88.79	88.32	66.65	65.52	0.55	< 0.01	0.16	0.55
$peNDF_{>8}$, % of DM	16.22	15.65	9.00	8.38	0.29	< 0.01	0.05	0.93
$peNDF_{>1.18}$, % of DM	27.34	27.12	20.12	19.84	0.31	< 0.01	0.44	0.93
MPS, mm	6.30	6.13	3.47	3.28	0.08	< 0.01	0.04	0.93
SDPS, mm	2.65	2.67	3.27	3.25	0.02	< 0.01	0.97	0.28

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).
[b] $pef_{>8}$ and $pef_{>1.18}$ = physical effectiveness factor determined as the proportion of particles retained on 2 sieves (Lammers et al., 1996) and on 3 sieves (Kononoff et al., 2003), respectively; $peNDF_{>8}$ and $peNDF_{>1.18}$ = physically effective NDF determined as NDF content of forage or TMR multiplied by $pef_{>8}$ and $pef_{>1.18}$, respectively.
[c] Mean particle size (MPS) and standard deviation of particle size (SDPS) were calculated as described by the American Society of Agricultural Engineers (ASAE, 1995, method S424.1).

Table 4
Least squares means of sorting activity and particle size intake of high producing dairy cows (n = 8) fed diets containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
Sorting index, %								
19 mm	80.02	84.02	88.64	87.24	3.60	0.04	0.63	0.32
8 mm	100.65	100.32	96.94	95.75	0.84	< 0.01	0.38	0.62
1.18 mm	103.30	102.71	101.88	102.27	0.63	0.03	0.81	0.24
Pan	104.01	103.75	103.17	103.92	0.72	0.57	0.68	0.40
Intake, kg/day								
19 mm	2.05	2.04	2.34	2.19	0.15	0.02	0.40	0.47
8 mm	11.99	11.26	6.01	5.51	0.32	< 0.01	0.07	0.74
1.18 mm	9.64	9.71	10.31	10.59	0.24	< 0.01	0.41	0.61
Pan	3.00	3.02	9.35	9.71	0.24	< 0.01	0.34	0.39
$peNDF_{>8}$	4.02	3.69	2.19	1.94	0.15	< 0.01	0.03	0.76
$peNDF_{>1.18}$	8.29	8.19	6.39	6.39	0.13	< 0.01	0.68	0.67

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).

interactions detected on chewing activity. Increased chewing time in cows fed LP diets may have been related to increased level of beet pulp in LP diets, which was used instead of soybean meal. Because of greater chewing time and similar DMI, cows fed LP diets had greater eating, rumination and chewing time per kg of nutrients compared with those for cows fed HP diets.

Cows fed SFC had longer chewing time per kg of DM compared with that for cows fed FGC, because of similar chewing time/day and lower DM intake. However, cows fed FGC diets had longer chewing time per kg of peNDF because of lower peNDF compared with cows fed SFC

Table 5
Least squares means of nutrient intake and digestibility of high producing dairy cows (n = 8) fed diets containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
Intake, kg/day								
NE_L intake, Mcal/day	46.98	45.83	45.41	45.36	1.03	0.05	0.24	0.29
DM	26.69	26.04	28.03	28.00	0.57	< 0.01	0.26	0.30
OM	24.08	24.66	26.00	25.94	0.55	< 0.01	0.35	0.25
CP	4.36	3.87	4.59	4.19	0.13	< 0.01	< 0.01	0.66
NDF	8.23	7.99	8.47	8.47	0.22	< 0.01	0.35	0.33
ADF	3.70	3.56	3.74	3.77	0.12	0.26	0.60	0.43
Starch	7.85[b]	7.41[c]	8.10[ab]	8.25[a]	0.30	< 0.01	0.19	< 0.02
Apparent total tract digestibility, %								
DM	68.81[a]	69.06[a]	64.91[b]	70.37[a]	1.09	0.18	< 0.01	0.01
OM	71.10[a]	71.25[a]	67.60[b]	72.68[a]	1.07	0.27	0.01	0.01
CP	61.77	58.33	59.50	61.45	2.20	0.85	0.74	0.24
NDF	47.90[a]	47.49[a]	38.60[b]	50.54[a]	2.50	0.16	0.01	0.01
ADF	42.71[a]	41.70[a]	30.75[b]	45.15[a]	2.83	0.08	0.01	< 0.01
Starch	98.01	98.03	96.62	97.30	0.71	0.10	0.54	0.56

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).

Table 6
Least squares means of diurnal feed intake and feed rate of high producing dairy cows (n = 8) fed diets containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
DMI, hours after morning feeding (kg)								
0–2 h	7.02	6.88	6.56	6.26	0.62	0.33	0.68	0.88
2–8 h	6.00	6.13	7.28	7.14	0.44	< 0.01	0.99	0.66
0–8 h	13.03	13.02	13.85	13.39	0.43	0.18	0.59	0.62
8–24 h	14.17	13.59	13.75	14.54	0.53	0.52	0.79	0.10
0–24 h	26.69	26.04	28.03	28.00	0.57	< 0.01	0.26	0.30
DMI rate, hours after morning feeding (g of DM/min)								
0–2 h	58.60	57.34	54.72	52.23	5.23	0.33	0.68	0.88
2–8 h	16.67	17.05	20.23	19.85	1.24	< 0.01	0.99	0.67
0–8 h	27.16	27.13	28.85	27.91	0.89	0.18	0.60	0.62
8–24 h	14.77	14.16	14.33	15.15	0.55	0.51	0.79	0.10
0–24 h	18.53	18.08	19.46	19.44	0.46	< 0.01	0.26	0.30

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).

Table 7
Least squares means of chewing activity of high producing dairy cows (n = 8) fed diets containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
Eating								
Min/day	346	366	338	362	11.2	0.59	0.06	0.89
Min/DMI	13	14	12	13	0.5	0.01	0.01	0.94
Min/$peNDFI_{>8}$	75	85	128	144	5.2	< 0.01	0.01	0.56
Min/$peNDFI_{>1.18}$	46	50	59	64	2.1	< 0.01	0.01	0.91
Rumination								
Min/day	476	496	475	499	15.5	0.95	0.08	0.87
Min/DMI	18	19	17	18	0.8	0.03	0.05	0.68
Min/$peNDFI_{>8}$	104	116	179	198	6.1	< 0.01	0.01	0.53
Min/$peNDFI_{>1.18}$	63	68	83	88	3.2	< 0.01	0.04	0.96
Total Chewing Activity								
Min/day	822	862	813	862	19.3	0.75	< 0.01	0.79
Min/DMI	31	33	29	31	1.1	< 0.01	< 0.01	0.66
Min/$peNDFI_{>8}$	179	202	306	342	9.9	< 0.01	< 0.01	0.48
Min/$peNDFI_{>1.18}$	109	119	142	152	4.5	< 0.01	< 0.01	0.99

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).

diets. Eating, rumination and chewing time were not significantly different in cows fed SFC or FGC (Table 7).

3.7. Meal and rumination patterns

Because of similar DMI and lower eating, rumination and chewing time, cows fed HP diets had higher eating (80.5 vs 75.4 g DM/min, $P = 0.03$), rumination (58.3 vs 54.9 g DM/min, $P = 0.04$) and chewing (33.6 vs 31.5 g DM/min, $P < 0.01$) rate than cows fed LP diets (Table 8). Treatments interactions were not detected for meal and rumination patterns. Lower chewing rate in cows fed LP diets indicated they consumed diets slower than cows fed HP diets. Cows fed LP diets had longer chewing (30.5 vs 27.5 min, $P = 0.03$) and rumination (34.9 vs 30.7 min, $P = 0.01$) meal length than cows fed HP diets.

Because of similar eating and rumination time and higher DMI, cows fed FGC had greater eating (81.1 vs 74.8 g DM/min, $P = 0.01$) and rumination (58.0 vs 54.9 g DM/min, $P = 0.08$) rate; cows fed FGC consumed and ruminated their diets faster rather than cows fed SFC. Meal size per kg of $peNDF_{>8}$ (by 68%, 0.32 vs 0.19 kg, $P < 0.01$) and $peNDF_{>1.18}$ (by 31%, 0.54 vs 0.41 kg, $P < 0.01$) was greater in cows fed SFC diets than cows fed FGC, likely related to higher intake of peNDF. Rumination and chewing patterns were not affected by the corn processing (Table 8).

4. Discussion

Because of the greater energy value of the steam-flaked than the ground corn (NRC, 2001), estimated NE_L was greater for diets containing SFC than FGC. Other studies have shown that in comparison with FGC, SFC diets had greater NE_L in dairy rations (Zhong et al., 2008; Cooke et al., 2009).

Dry matter content of SFC was reduced by about 3% and tended to be significant, as compared with the FGC (86% vs 89%), likely because of the steaming in the flaking process. This moisture uptake was consistent with the range of 3% to 5%, as reported in past studies (Zinn, 1990; Plascencia and Zinn, 1996).

The SFC diets, compared with FGC diets, had lower proportion of particles on the pan and higher proportions of particles in 8-mm sieve, pef, MPS, and peNDF in offered and consumed diet (Table 2). Steam-flaked corn had higher MPS compared with FGC and remained in 8-mm sieve, but FGC almost entirely passed through the 8-mm sieve and remained in pan. The reason for the differences in particle size

Table 8
Least squares means of meal patterns of high producing dairy cows (n = 8) fed diets containing either high (HP) or low (LP) level of protein supplemented with either finely ground (FGC) or steam-flaked corn (SFC).

Item	SFC		FGC			Contrast[a]		
	HP	LP	HP	LP	SEM	Proc	CP	Proc × CP
Eating								
Bout/day	14.00	14.12	14.62	13.65	0.85	0.92	0.62	0.52
Min/bout	25.42	26.12	23.67	27.74	1.79	0.97	0.19	0.35
Interval, min	83.43	79.96	80.01	85.69	5.15	0.81	0.82	0.35
Rate, g of DM/min	77.73	71.83	83.20	79.04	3.19	0.01	0.03	0.69
Meal size, kg DM	1.94	1.86	1.97	2.12	0.12	0.26	0.76	0.35
Meal size, kg $peNDF_{>8}$	0.33	0.31	0.19	0.19	0.01	< 0.01	0.46	0.38
Meal size, kg $peNDF_{>1.18}$	0.55	0.52	0.40	0.43	0.02	< 0.01	0.87	0.33
Rumination								
Bout/day	15.62	15.00	16.00	14.73	0.91	0.93	0.17	0.64
Min/bout	31.01	34.08	30.48	35.79	2.45	0.68	< 0.01	0.43
Interval, min	59.56	60.13	58.65	64.43	3.47	0.61	0.34	0.43
Rate, g of DM/min	56.96	52.81	59.64	56.34	2.53	0.08	0.04	0.80
Meal size, kg DM	1.73	1.77	1.79	2.01	0.10	0.14	0.17	0.34
Meal size, kg $peNDF_{>8}$	0.30	0.29	0.17	0.18	0.01	< 0.01	0.92	0.55
Meal size, kg $peNDF_{>1.18}$	0.49	0.50	0.36	0.40	0.02	< 0.01	0.38	0.44
Total Chewing Activity								
Bout/day	29.50	29.50	30.75	28.24	1.32	0.99	0.31	0.31
Min/bout	28.31	29.62	26.81	31.48	1.70	0.89	0.03	0.21
Interval, min	24.36	22.56	23.57	23.58	1.25	0.93	0.48	0.48
Rate, g of DM/min	32.64	30.27	34.64	32.69	1.16	< 0.01	< 0.01	0.73
Meal size, kg DM	0.91	0.89	0.92	1.02	0.04	0.11	0.37	0.18
Meal size, kg $peNDF_{>8}$	0.15	0.14	0.09	0.09	0.006	< 0.01	0.41	0.34
Meal size, kg $peNDF_{>1.18}$	0.25	0.25	0.19	0.20	0.01	< 0.01	0.73	0.27

[a] Contrasts for Proc (corn processing effect), CP (protein level effect) and interaction (Proc × CP).

distribution of SFC and FGC treatments is likely the differences in their physical characteristics and particle size distribution. In agreement with these observations, Mathew et al. (2011) reported diets containing SFC had a lower proportion of particles smaller than 1.18-mm and a higher proportion of particles retained on the 8-mm screen and MPS compared with the FGC diets. In addition, SFC diets have a higher $peNDF_{>1.18}$ than the FGC diets (Mathew et al., 2011).

The 8-mm sieve collects particles that would probably make up the part of the rumen mat, and therefore provides dry matter that would require additional chewing by the cow. Because the remaining parts in the pan pass through the rumen, they likely have no major effect on stimulating the rumination (Heinrichs, 2013). Maulfair et al. (2011) reported that the critical size for increased resistance to rumen escape was particles larger than 1.18 mm in high producing dairy cows. The 8-mm particles may affect ruminal pH and chewing activity. White et al. (2017b) suggested that ruminal pH can be maintained by increasing the proportion of TMR (between 40% and 60%) retained on the 8-mm sieve.

Guidelines on TMRs for high producing dairy cows suggest 2%–8% of the particles in the upper sieve, 30%–50% in the middle and lower sieves, and no more than 20% in the pan (Heinrichs and Kononoff, 2002). In the current study, proportions of particles on different sieves in SFC diets are within the suggested range; however, FGC diets had lower proportion in 8-mm sieve (21.5%) and higher proportion in pan (32.9%; Table 3). Zebeli et al. (2012) recommended that average amounts of 31.2% $peNDF_{>1.18}$ or 18.5% $peNDF_{>8}$ in the diet (DM basis) are required to minimize subacute ruminal acidosis. Cows consuming SFC diets had marginally sufficient level of $peNDF_{>1.18}$ and $peNDF_{>8}$ (27.2% and 15.9% DM, respectively), whereas cows consuming FGC diets had lower level of $peNDF_{>1.18}$ and $peNDF_{>8}$ (20.8% and 9.5% DM, respectively) than the recommended levels by Zebeli et al. (2012).

Regardless of the dietary protein level, cows sorted, to a similar extent, against long particles (19- and 8-mm sieves) and sorted for short particles (1.18-mm sieve and pan). This was expected because some investigations noted cattle sort widely against long particles, regardless of the substrate constituting the bulk of the long particle fraction (Leonardi and Armentano, 2003).

Greater DMI and lower sorting index against 19-mm sieve resulted in greater intake from the 19-mm sieve in cows fed FGC compared with that for cows fed SFC (Table 4). White et al. (2017b) reported when high concentration of starch was fed, cattle preferred to consume larger particles of diet to prevent ruminal acidosis. In the current study, cows consumed 8 kg of starch per day, and cows fed FGC diets consumed more DM from 19-mm sieve to maintain rumen health and provide adequate peNDF. However, cows fed SFC received enough peNDF because of corn flaking and consumed less DM from 19-mm sieve. In SFC diets, 43% of DM remained in the 8-mm sieve and cows fed SFC diets had more DM from this sieve compared to that for cows fed FGC. In FGC 33% of diets remained in pan and cows fed FGC diets had more DM from pan compared to those fed SFC. Despite greater DMI in FGC treatments and because SFC diets had greater peNDF content compared to those for FGC treatments, cows in SFC consumed more $peNDF_{>8}$ (by 86%, 3.8 vs 2.0 kg/day, $P < 0.01$) and $peNDF_{>1.18}$ (by 28%, 8.2 vs 6.4 kg/day, $P < 0.01$) than cows in FGC diets. This observation indicates that in high producing dairy cows, consuming high DMI (> 24 kg/day), corn flaking could potentially increase the dietary $peNDF_{>8}$ and improve the rumen health without reducing the milk yield.

Dry matter intake was not different between different dietary protein levels (Table 5). In line with this observation, some studies reported that dietary CP content had no effect on DMI (Chibisa and Mutsvangwa, 2013; Mutsvangwa et al., 2016). Broderick (2003) however reported a linear increase in DMI when dietary CP was increased from 15.1% to 16.7% and 18.3%. Cows fed FGC-LP or SFC-LP diet had the greatest and lowest starch intake respectively, and the interaction between corn processing and dietary level was significant for starch intake. This decrease in starch intake in SFC-LP diet was probably because of a significant decrease in DMI in cows fed SFC and numerically lower starch content of SFC-LP.

Interactions between dietary CP level and corn processing on the total-tract digestibility were significant where the FGC-HP had lower digestibility than other diets (Table 5). According to Firkins et al. (2001), the level of dietary CP has a negative relationship with NDF and OM digestibility. Moreover, passage rate increases with greater RDP (Arroquy et al., 2004) or CP (Mutsvangwa et al., 2016), and higher passage rate reduces the rumen degradability. In SFC-HP, the higher ruminal starch digestibility may have provided more energy for microbial fermentation and increased microbial protein production (Bernard et al., 2004). Hence, rumen microbes may have used the dietary protein with higher efficiency and this could have reduced the effect of the higher CP on NDF and OM digestibility. In the current experiment, total-tract ADF digestibility tended (42.2% vs 37.9%, $P = 0.08$) to be greater in SFC than FGC diets; therefore, greater digestibility of fiber in SFC diets may have improved fiber digestibility of the SFC-HP diet.

Cows fed SFC had lower DMI especially in 2–8 h post morning feeding, however, they had greater peNDF and NE_L intake in comparison with cows fed FGC (Table 6). The increased peNDF and NE_L intake simultaneously has been difficult to achieve in high-producing cows and this combination could be helpful in high producing cows that typically consume large amounts of concentrate. The effects of corn processing on DMI have been inconsistent; feeding SFC decreased (Harvatine et al., 2002a; Cooke et al., 2009), increased (Yu et al., 1998; Bernard et al., 2004; Zhong et al., 2008), or had no effect (Mathew et al., 2011; Batistel et al., 2017) as compared with FGC on DMI. Greater particle size of SFC diets compared with FGC diets (6.46 vs 3.55 mm, Table 3) could enhance the rumen fill, resulting in increased ruminal distention. According to Allen (2000), distension stimulates stretch receptors in rumen wall and the signal from stretch receptors could reduce feed intake. In agreement with this notion, Cooke et al., (2008) also reported that the smaller particle size of FGC, compared with SFC, allowed faster passage of FGC and that this may have increased DMI for cows fed FGC. In a meta-analysis, White et al. (2017b) showed that DMI could decrease with increasing dietary MPS. Moreover, Firkins et al. (2001) indicated that DMI was negatively related to the extent of ruminal digestion of starch. Extent of ruminal starch digestion was greater with SFC than with ground (Bernard et al., 2004) or dry rolled (Theurer et al., 1999) corn. On the other hand, in accordance to Hepatic Oxidation Theory the increased digestibility of starch and ADF in SFC diets, compared with FGC diets may decrease the DMI (Allen, 2000).

Apparent total-tract starch digestibility typically is increased by steam flaking of corn in other studies (Yu et al., 1998; Mathew et al., 2011; Batistel et al., 2017). The higher total-tract starch digestibility in SFC were likely related to disruption of the protein matrix surrounding starch granules, which would increase surface area of corn and gelatinization of starch granules. The increase of starch gelatinization makes the access of ruminal microorganisms to amylose and amylopectin molecules easy and makes the starch more susceptible to the enzymatic hydrolysis (Yu et al., 1998).

Compared with cows fed FGC, cows fed SFC had longer chewing time per kg of DM (Table 7). One of the major factors that affect eating activity is physical processing of the diet (White et al., 2017a). Increased rumination times per kg of DM was likely related to the increased need for particle size reduction (Beauchemin et al., 2001), and cows fed SFC had lower DMI and higher rumination times per kg of DM. Intake of peNDF is the main contributing factor to rumination time (Mertens, 1997), and higher intake of peNDF in cows fed SFC likely caused the longer rumination time per kg of DMI. Rumination activity is more important than eating activity on reduction of food particle size and salivary secretion (Grant et al., 1990). Lower DMI and similar rumination time in cows fed SFC, as compared to cows fed FGC, supports the hypothesis that increased corn particle size through steam flaking can increase the peNDF and therefore stimulate the rumination. In agreement with these results, White et al. (2017b) noted that increasing MPS has similar effects on cattle performance, as does increasing forage NDF. Particles that remain in the rumen stimulate the rumination (Teimouri et al., 2004) and White et al. (2017a) reported particles between 3 mm and 5 mm remain in rumen and therefore stimulate chewing and rumination. Increased corn particle size though flaking process may have increased ruminal retention time, and resulted in higher rumination in cows fed SFC compared with that for cows fed FGC.

Similar to our observation, Harvatine et al. (2002b) reported that SFC reduced DMI compared with FGC. Cows did not differ in eating and rumination time (min/day), in contrast with our results; however, eating and rumination time per kg of DM was not different between cows fed SFC or FGC (Harvatine et al., 2002b). Beauchemin et al. (2001) and Yang et al. (2001) reported that increase in grain processing had no effect on eating time and eating time per kg of DMI. The kernel thickness (mm) in Beauchemin et al. (2001) report decreased from 2.38 to 1.87 mm while for Yang et al. (2001) it decreased from 1.60 to 1.36 mm.

Others reported that increased peNDF level, from 8.9% to 11.5%, in diets did not reduce DMI, resulting in greater rumination or chewing time (Beauchemin and Yang, 2005). In our experiment, increase in dietary peNDF, from 9.4% to 16.9%, reduced DMI by 6%, and did not increase chewing time. In pervious experiments, increased forage level or forage particle size larger than 19 mm, resulted in increased peNDF level (Teimouri et al., 2004). Particles retained on 19-mm sieve, compared with particles retained on 8-mm sieve, are more effective in stimulating rumination (Heinrichs and Kononoff, 2002). Greater peNDF > 8 intake (Table 4) and lower chewing time per kg of peNDF > 8 intake (Table 7) showed that cows with SFC chewed fiber more efficiently than cows with FGC. To our knowledge, no experiment has evaluated the effect of corn processing on peNDF and feeding behavior. The results of present study show that, independent of forage particle size or its inclusion level, steam flaking of corn can increase the particles retained on 8-mm sieve and in turn increase rumination and chewing time per kg of DM.

5. Conclusion

In this study, the level of protein had no effect on DMI, but digestibility was lower with HP diet. An interaction between CP level and corn processing method on digestibility was detected with HP diets with FGC having lower digestibility of DM and NDF than other diets. Cows fed SFC had lower DMI and tended to have higher fiber and starch digestibility than cows fed FGC. Cows fed LP diets had longer chewing time and lower chewing rate compared with those for cows fed HP diets. Steam flaking of corn increased pef and peNDF in SFC diets compared with that of FGC diets. Cows fed SFC had lower chewing and rumination rate but longer chewing time per kg of DM and CP than those for cows fed FGC. Results suggested that in lactation dairy cows with high DMI and low forage level, steam flaking of corn can potentially be used to increase dietary peNDF and stimulate rumination without any increase in forage inclusion level or length. The current study provides evidence that greater corn particle size increased MPS and peNDF of diets and is perhaps an important determining factor influencing DMI, digestibility, and chewing behavior. Compared with cows fed FGC, cows fed SFC simultaneously showed an increased peNDF and energy intake, and this could be helpful in high producing lactation cows.

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