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Substitution of wheat straw with sugarcane bagasse in low-forage diets fed to mid-lactation dairy cows: Milk production, digestibility, and chewing behavior

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ABSTRACT

Sugarcane bagasse (SB) is a low-quality roughage source that is often plentiful during times of forage shortage. It is generally less costly compared with other conventional sources of forage. We hypothesized that SB could be used as a source of roughage for dairy cattle by replacing wheat straw (WS), another low-quality forage. This study evaluated the effects of replacing WS with SB in diets offered to mid-lactation dairy cows on milk production and fatty acid profile, intake, digestibility, chewing activity, and ruminal fermentation. Nine multiparous Holstein cows averaging (mean ± standard deviation) 105 ± 12 d in milk, 42.1 ± 2.9 kg of milk/d, and 617 ± 59 kg of body weight were used in a replicated 3 × 3 Latin square with 21-d periods. Treatments were (% of dietary dry matter, DM): (1) 0SB, diet containing 0% SB and 27% WS, (2) 9SB, diet containing 9% SB and 18% WS, and (3) 18SB, diet containing 18% SB and 9% WS. Sugarcane bagasse had greater organic matter (OM; 94.1 vs. 85.1% of DM), neutral detergent fiber (NDF; 86.2 vs. 76.4% of DM), acid detergent fiber (ADF; 62.9 vs. 45.2% of DM), and lignin (19.9 vs. 10.3% of DM) concentration, but less crude protein (CP; 2.63 vs. 3.72% of DM) concentration than WS. Sugarcane bagasse also had greater physically effective NDF (total dietary NDF multiplied by % of TMR on the 8-mm + 19-mm sieves, peNDF_8; 63.2 vs. 40.6% of DM) and undegraded NDF after 288 h of incubation (uNDF_{288}; 35.5 vs. 21.2% of DM) contents than WS. The undegraded NDF after 30 h of incubation (uNDF_{30}) content was similar for all diets; however, peNDF_8 concentration and proportion of long particles (retained on a 19-mm sieve) increased linearly as SB inclusion in the diets increased. Cows increasingly sorted against long particles as SB replaced WS. Intakes of DM (26.53 kg/d) and NDF (8.58 kg/d) did not differ among the treatments, but intakes of OM and CP decreased, whereas ADF and uNDF_{288} intakes increased with SB inclusion level. Total-tract digestibilities of OM, CP, and NDF decreased linearly as SB replaced WS. Milk yield (37.0 kg/d), energy-corrected milk yield (ECM; 38.2 kg/d), feed efficiency (1.44 kg ECM yield/kg DM intake), and milk composition (fat, 3.89%; true protein, 2.90%) did not differ among diets. Increasing SB concentration of the diet linearly increased rumination time, but ruminal pH (ruminocentesis, 4 h after feeding) decreased. Total volatile fatty acid concentration increased linearly, whereas acetate: propionate decreased linearly, as SB replaced WS. The results indicate that replacement of WS with increasing levels of SB in low-forage diets with similar uNDF_{30} concentrations did not affect performance of mid-lactation dairy cows. We conclude that SB can be used as a fiber source in diets fed to dairy cows in mid-lactation; however, the decrease in total-tract digestibility of diets may decrease lactational performance when fed to high-producing dairy cows.

Key words: wheat straw, sugarcane bagasse, undegradable neutral detergent fiber, byproduct

INTRODUCTION

Providing adequate fiber to meet the needs of dairy cows is critical to maintaining rumen function, milk fat concentration, and animal performance. Two forage sources commonly used in dairy cow diets worldwide are corn silage and alfalfa hay or silage. These forages are highly digestible and therefore maintain high intake and milk production (Wang et al., 2014; Ferraretto et al., 2015). However, availability of high-quality forages is sometimes limited because of unfavorable weather conditions, or shortage of land or water, particularly in arid regions of the world. Consequently, crop byproducts and other roughage sources are often used in dairy cow rations.

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For example, wheat straw (**WS**) is a crop byproduct that is abundantly available, with an estimated 750 million metric tonnes produced annually worldwide (FAOSTAT, 2016). However, the low digestibility and low nutritive value (NDF and CP about 80 and 2.5% of DM, respectively) of WS may compromise DMI, and consequently milk production of high-producing dairy cows (Eastridge et al., 2009; Wang et al., 2014). Despite its low digestibility, WS is sometimes included in dairy diets as a source of physically effective fiber (**peNDF**; Kahyani et al., 2019a,b).

Sugarcane (*Saccharum officinarum* L.) is a perennial plant with high potential DM yield that is widely used in the production of sugar and ethanol in tropical and subtropical climates. An important byproduct from sugarcane processing is sugarcane bagasse (**SB**; Costa et al., 2015). Sugarcane bagasse is often plentiful during times of forage shortage and it is generally less costly compared with other conventional sources of forage (Daniel et al., 2014; de Almeida et al., 2018). However, SB has low nutritive value; its NDF concentration is >80% of DM and its CP concentration is about 1.5% of DM. Therefore, when incorporating SB in dairy cow diets it is necessary to include a high proportion of concentrate to meet the digestible energy and CP requirements of the animals (Sá Neto et al., 2014). Alternatively, SB may be a source of peNDF, and used similarly to WS in dairy cow diets.

Most of the work to evaluate SB as a livestock feed has been conducted with beef cattle. Leme et al. (2003) substituted SB for corn grain and citrus pulp in the diet of beef cattle, with soybean meal inclusion to compensate for the low CP concentration of SB. Pate (1981) replaced shelled corn and citrus pulp with SB, and increased the inclusion of cottonseed meal to maintain dietary CP concentration. In both experiments, ADG decreased with increasing SB inclusion in diets.

Although studies indicate that SB can be used as a source of roughage for beef cattle, only limited information is available that compares SB to other fiber sources for dairy cows (Corrêa et al., 2003; Sá Neto et al., 2014; de Almeida et al., 2018). de Almeida et al. (2018) reported that diets with increasing concentrations of SB (45 to 60% of DM), with SB replacing spineless cactus, decreased DMI and milk yield of low-producing dairy cows. Freitas et al. (2018) noted that replacing spineless cactus with SB comprising 30 to 54% of dietary DM reduced milk yield from 22 to 16 kg/d. Corrêa et al. (2003) also reported that using SB silage instead of corn silage decreased DMI and milk yield. The decrease in DMI and milk yield of cows observed in those studies can be attributed mainly to high inclusion level, and increased NDF and undegraded NDF (**uNDF**) concentrations of the diets, and a decrease in total-tract digestibility because SB replaced higher quality fiber sources.

Given that the composition of WS is similar to that of SB, we hypothesized that partially replacing WS with SB in a low-forage diet would maintain DMI and performance of mid-lactation dairy cows. Therefore, the objective of the present study was to investigate the effects of partial replacement of WS with SB on performance, digestibility, chewing activity, and ruminal fermentation of dairy cows in mid-lactation.

MATERIALS AND METHODS

All animal procedures were conducted with protocols approved by the Animal Care and Use Committee of the Iranian Council of Animal Care (1995). The experiment was conducted from September to November 2018, at the Farm Animal Research and Teaching Unit of Isfahan University of Technology (Isfahan, Iran).

Crop Byproducts and In Situ NDF Degradability

A threshing machine (designed to separate cereal grains from straw) with a 10-mm theoretical length of cut (Golchin Trasher Hay Co., Isfahan, Iran) was used to finely chop the WS. The purchased SB had about 46% DM; it was kept for 3 to 4 d in a warm open environment before feeding to the cows. The chemical composition of the WS and SB is presented in Table 1, with the physical properties presented in Table 2.

An in situ study was conducted to measure uNDF in WS, SB, and TMR, according to the method described by Kahyani et al. (2019a,b). For the incubations, 2 nonlactating Holstein ruminally cannulated dairy cows were offered a high-forage TMR diet (25% SB, 50% WS, 25% concentrate mix; DM basis) as recommended by Krizsan and Huhtanen (2013). The cows received this diet for 2 wk before starting the incubation. Dried samples (60°C for 48 h) of WS, SB, and TMR were ground using a Wiley mill (Arthur H. Thomas, Philadelphia, PA) to pass a 1-mm sieve, and 0.5 g of each feed was weighed into Ankom F57 bags (5 × 4 cm; Ankom Technology, Macedon, NY) with pore size of 25 μm (Kahyani et al., 2019a,b). Samples were incubated in triplicate within each cow for 6, 12, 24, 30, 48, 72, and 288 h. Triplicate empty bags (blanks) were also incubated and removed at each time to correct for possible infiltration of NDF into the sample bags. After removal, the bags were soaked in cold water and washed in a washing machine for 12 min, and then transferred to a forced ventilation oven (60°C) for 48 h. The equation used to correct for blanks in the calculation of NDF residue at each time point was as follows (Kahyani et al., 2019a,b):

Table 1. Chemical characteristics of the roughage sources [mean (SD)]

Item, % of DM, unless otherwise stated	Wheat straw	Sugarcane bagasse
DM, % as fed	96.4 (0.1)	95.5 (0.02)
OM	85.1 (0.42)	94.1 (0.20)
CP	3.72 (0.35)	2.63 (0.42)
NDF	76.4 (1.66)	86.2 (1.00)
ADF	45.2 (0.68)	62.9 (0.53)
ADL	10.3 (0.94)	19.9 (0.90)
Ether extract	0.97 (0.09)	0.80 (0.15)
Ash	14.9 (0.42)	5.94 (0.20)
Acid-insoluble ash	6.98 (0.33)	2.69 (0.09)
NFC[1]	4.01 (0.78)	4.43 (1.02)
NE_L,[2] Mcal/kg of DM	0.50	0.49

[1] Nonfiber carbohydrates [NFC = OM – (NDF + CP + EE)], where EE = ether extract.

[2] Calculated from NRC (2001).

$$\text{NDF residue (g/g of DM)} = [(\text{bag weight} + \text{residue}) - (\text{bag weight} \times \text{bag correction factor})]/[(\text{bag weight} + \text{sample}) - \text{bag weight}].$$

The bag correction factor represents the average fractional weight change of 3 blank bags following the NDF washing procedure. The $\mathbf{uNDF_{30}}$, $\mathbf{uNDF_{72}}$, and $\mathbf{uNDF_{288}}$ were undegraded NDF after 30-, 72-, and 288-h of incubation, with $uNDF_{288}$ considered undegradable NDF. Potentially degradable NDF ($\mathbf{pdNDF_{288}}$) was calculated as the difference between total NDF and $uNDF_{288}$ (Lopes et al., 2015a). The uNDF and pdNDF are presented as % of DM.

Cows, Management, and Treatments

Nine multiparous Holstein cows with 105 ± 12 DIM, 42.1 ± 2.9 kg of milk/d, 617 ± 59.5 kg of BW, and a BCS of 2.9 ± 0.3 (mean ± SEM, using a 5-point scale where 1 = emaciated and 5 = obese; Edmonson et al., 1989) at the beginning of the experiment were used. The cows were individually housed in box stalls (4 × 4 m) within a roofed barn with open sides. Clean wood shavings were used as bedding, and refreshed twice daily. Cows had continuous access to concrete feed bunks and automatic water troughs. The cows were moved to the box stalls 2 wk before the start of the experiment to allow them to adapt to the pen. At the end of the

Table 2. Physical attributes and NDF degradation characteristics of the roughage sources

Item	Wheat straw	Sugarcane bagasse	SEM	*P*-value
Particle size distribution, % DM retained on sieve				
19 mm	2.6	24.9	2.04	<0.01
8 mm	50.5	48.4	1.24	0.16
1.18 mm	41.2	23.6	1.99	<0.01
Pan	5.7	3.1	0.60	0.01
$peNDF_8$,[1] % of DM	40.6	63.2	2.11	<0.01
$peNDF_{1.18}$,[1] % of DM	72.1	83.5	0.48	<0.01
GMPS,[2] mm	6.6	10.7	0.67	<0.01
SDPS,[2] mm	2.23	2.37	0.03	0.02
NDF degradation characteristics (% of DM)				
$uNDF_{30}$[3]	54.2	65.1	0.68	<0.01
$uNDF_{30}$, % of NDF	70.8	75.6	0.88	<0.01
$pdNDF_{30}$[4]	22.2	21.1	0.68	0.16
$uNDF_{72}$	35.3	45.8	2.03	<0.01
$uNDF_{72}$, % of NDF	46.2	53.2	2.40	0.04
$pdNDF_{72}$	41.1	40.4	2.04	0.73
$uNDF_{288}$	21.2	35.5	0.80	<0.01
$uNDF_{288}$, % of NDF	27.7	41.4	0.94	<0.01
$pdNDF_{288}$	55.2	50.7	0.71	<0.01

[1] $peNDF_8$ and $peNDF_{1.18}$ = physically effective NDF determined as NDF concentration (% of DM) of forage or TMR multiplied by corresponding physical effectiveness factors (pef_8 and $pef_{1.18}$), respectively, determined by sieving fresh sample.

[2] Geometric mean of particle size (GMPS) and standard deviation of particle size (SDPS) were calculated as described by the American Society of Agricultural Engineers (ASABE, 2003, method S319.3).

[3] uNDF = NDF residue after 30-, 72-, or 288-h in situ incubation.

[4] pdNDF = potentially degradable NDF after 30-, 72-, or 288-h in situ incubation.

Table 3. Ingredients and chemical composition of experimental diets

Item, % of DM, unless otherwise stated	Treatment[1] 0SB	9SB	18SB
Ingredient			
Wheat straw	27.40	18.40	9.32
Sugarcane bagasse	0.00	9.04	18.10
Ground corn grain	21.80	21.80	21.80
Ground barley grain	19.20	19.20	19.20
Soybean meal, 44% CP	15.00	15.00	15.00
Meat meal	4.80	4.80	4.80
Beet pulp	3.24	3.24	3.24
Fat powder[2]	3.20	3.20	3.20
Molasses	2.00	2.00	2.00
Fish meal	1.00	1.00	1.00
Sodium bicarbonate	1.16	1.16	1.16
Vitamin supplement[3]	0.32	0.32	0.32
Mineral supplement[4]	0.32	0.32	0.32
Calcium carbonate	0.28	0.28	0.28
Salt	0.12	0.12	0.12
Magnesium oxide	0.04	0.04	0.04
Chemical composition, mean (SD)			
DM	50.70 (0.01)	50.54 (0.02)	50.10 (0.04)
OM	92.69 (0.23)	93.19 (0.01)	93.30 (0.07)
CP	16.79 (0.87)	16.60 (1.10)	16.20 (0.43)
NDF	31.19 (0.00)	32.30 (0.96)	33.40 (0.60)
Forage NDF	23.29 (0.23)	24.40 (0.31)	25.59 (0.28)
ADF	15.79 (1.03)	16.51 (0.74)	19.60 (0.83)
Ether extract	5.75 (0.17)	6.32 (0.12)	6.22 (0.23)
NFC[5]	38.49 (0.44)	39.30 (0.92)	40.09 (0.77)
Starch	26.69 (0.90)	27.00 (0.16)	27.69 (0.33)
Acid-insoluble ash	1.23 (0.02)	1.15 (0.01)	1.14 (0.06)
NE_L,[6] Mcal/kg of DM	1.68	1.68	1.68

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] Extima 100, Erafeed, Selangor, Malaysia. Composition: moisture, 0.5%; crude fat, 99.5% (C14:0, 0–3%; C16:0, 80%; C18:0, 5–10%; C18:1, 8–12%).

[3] Composition: 1,500,000 IU/kg vitamin A; 250,000 IU/kg vitamin D_3; 15,000 IU/kg vitamin E, 0.5 g/kg Cu; 0.008 g/kg Se; 1.5 g/kg Mn; 2 g/kg Zn; 0.2 g/kg biotin; and 3 g/kg monensin.

[4] Composition: 245 g/kg Ca; 55 g/kg Mg; 13.5 g/kg Mn; 18 g/kg Zn; 4.5 g/kg Cu; 0.02 g/kg I; 0.1 g/kg Co; and 0.072 g/kg Se.

[5] Nonfiber carbohydrates [NFC = OM – (NDF + CP + EE)], where EE = ether extract.

[6] Calculated from NRC (2001).

2 wk, milk production, BW, and BCS were recorded and used to allocate 3 cows to each of 3 groups. Within each group, the cows were randomly allocated to 1 of 3 treatment sequences. The experimental design was a replicated (3 blocks) 3 × 3 Latin square, with 3 dietary treatments and 3 experimental periods. Each period lasted 21 d with the first 16 d for adaptation and the last 5 d for sampling and data collection. The dietary treatments were (1) 0SB, diet containing 0% SB and 27% WS, (2) 9SB, diet containing 9% SB and 18% WS, and (3) 18SB, diet containing 18% SB and 9% WS.

The ingredient and chemical composition of diets are shown in Table 3. All diets contained 3.24% beet pulp (DM basis), with no other forage source other than WS or SB offered. Thus, all diets had 27:73 forage to concentrate ratio (DM basis) and differed only by proportion of SB and WS. Diets were offered twice daily at 1000 and 1700 h, and orts were removed and weighed daily. Feed offered was adjusted daily to ensure 10% excess. All diets were formulated with the Cornell Net Carbohydrate and Protein System (version 5.0) to contain similar NE_L concentrations and to meet the requirements of a multiparous cow producing 42 kg of milk/d with 3% true milk protein and 3.2% fat assuming a DMI of 25 kg/d.

Feed Sampling and Analyses

During the sampling period, the amount of TMR offered and refused was recorded to determine DMI. Samples of TMR were collected at feeding and refusals were collected before morning feeding during the last 5 d of each period and composited (by cow for orts), and stored at −20°C for later analysis. The TMR and orts

Table 4. Physical properties and NDF degradation characteristics of experimental diets

Item	Treatment[1]			SEM	*P*-value[2]	
	0SB	9SB	18SB		L	Q
Particle size distribution, % DM retained on sieve						
19 mm	1.4	5.9	7.0	0.13	<0.01	<0.01
8 mm	25.8	24.2	22.4	0.79	0.09	0.90
1.18 mm	51.0	48.3	50.2	0.47	0.33	0.06
Pan	21.8	21.5	20.4	0.39	0.14	0.55
peNDF$_8$,[3] % of DM	8.54	9.74	9.81	0.257	0.07	0.22
GMPS,[4] mm	3.73	3.95	4.20	0.101	0.09	0.92
SDPS,[4] mm	2.61	2.75	2.80	0.048	0.10	0.51
NDF degradation characteristics (% of DM)						
uNDF$_{30}$[5]	22.1	22.7	23.5	0.57	0.16	0.93
uNDF$_{30}$, % of NDF	68.0	69.7	71.6	1.59	0.19	0.98
pdNDF$_{30}$[6]	9.31	9.59	9.92	0.576	0.49	0.97
uNDF$_{288}$	8.00	9.21	11.5	0.151	<0.01	0.05
uNDF$_{288}$, % of NDF	23.1	26.3	32.1	0.34	<0.01	0.03
pdNDF$_{288}$	23.4	23.1	21.9	0.15	<0.01	0.08

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] L = linear effect; Q = quadratic effect.

[3] peNDF$_8$ = physically effective NDF determined as NDF concentration of TMR multiplied by physical effectiveness factor (pef$_8$), calculated as the total DM retained on 8- and 19-mm sieves.

[4] Geometric mean of particle size (GMPS) and standard deviation of particle size (SDPS) were calculated as described by the American Society of Agricultural Engineers (ASABE, 2003, method S319.3).

[5] uNDF = NDF residue after 30- or 288-h in situ incubation.

[6] pdNDF = potentially degradable NDF after 30- or 288-h in situ incubation.

samples were dried at 60°C in a forced-air oven for 48 h and ground to pass a 1-mm sieve (Wiley mill, Arthur H. Thomas). All samples (duplicates) were analyzed for DM (AOAC International, 2002; method 925.40), CP (AOAC International, 2006, method 955.04), ash (AOAC International, 2006; method 942.05), ether extract (**EE**; AOAC International, 2006, method 920.39), starch (Zhu et al., 2016), and NDF (using heat-resistant α-amylase and sodium sulfite) and ADF sequentially according to Van Soest et al. (1991) with the Ankom Fiber Analyzer system (A200 model, Ankom Technology, Macedon, NY). The ADL was determined using AOAC International (2006) method 973.18, modified to use a 1.0-g sample in Ankom F57 bags (Ankom Technology). Nonfiber carbohydrates were calculated as NFC = OM − (NDF + CP + EE).

During the sampling period, forages, TMR, and individual refusals of each cow were sampled for particle size separation. All samples were frozen immediately at −20°C until subsequent analysis. After thawing, particle size distributions of representative subsamples were determined (in triplicate) on an as-fed basis using the Penn State Particle Separator (**PSPS**; Nasco, Fort Atkinson, WI) equipped with 3 sieves (19, 8, and 1.18 mm). After thawing, the DM retained on each sieve of the PSPS was determined by oven drying at 60°C for 48 h and the physical effectiveness factor (**pef**) was determined as the proportion of DM retained on 2 sieves (8 + 19 mm, **pef$_8$**; Lammers et al., 1996) and on 3 sieves (1.18 + 8 + 19 mm, **pef$_{1.18}$**; Kononoff et al., 2003) of the PSPS. The peNDF$_8$ and peNDF$_{1.18}$ concentrations were calculated by multiplying the NDF concentration of the feed (% of DM) by pef$_8$ and pef$_{1.18}$, respectively. Actual intakes of peNDF were calculated based on peNDF concentration of TMR and orts (thereby accounting for sorting). The geometric mean of particle size (**GMPS**) was calculated according to the ASABE (2003; method S319.3) procedure. Physical properties of experimental diets are presented in Table 4.

Digestibility and N Balance

Fecal samples were collected approximately every 8 h from d 16 to 18 so that 9 samples were taken from each cow each period. The samples were composited by cow and analyzed for nutrient digestibility using acid-insoluble ash (**AIA**) as an internal marker (Van Keulen and Young, 1977). The calculation of DM digestibility was as follows: DM digestibility (%) = 1 − (A/B) × 100, where A and B were the AIA concentrations in the feed and feces, respectively. The nutrient digestibilities (X) were calculated as X digestibility (%) = [1 − (A/B) × (XB/XA)] × 100, where XA and XB were the nutrient concentrations in the feed and feces, respectively. Intakes presented during the digestibility measurements account for chemical composition of both the TMR and orts.

The intake of N (g/d) was calculated by multiplying DMI by the N concentration of the diet. Predicted urine N, fecal N excretion, and N efficiency were calculated (Kohn et al., 2002) using the following equations:

$$\text{Predicted urine N (g/d)} = 0.0283 \times \text{MUN (mg/dL)} \times \text{BW (kg)},$$

$$\text{Predicted fecal N (g/d)} = \text{N intake (g/d)} - [\text{milk N (g/d)} + \text{predicted urine N (g/d)}],$$

$$\text{Apparent N efficiency (\%)} = [\text{milk N (g/d)}/\text{N intake (g/d)}] \times 100.$$

Chewing Behavior and Sorting Activity

Eating and ruminating behaviors were monitored visually by 8 trained observers (1 every 3 h) for 24-h on d 20 of each period. Beforehand, the process and definition of each behavior were reviewed with the observers, and then they simultaneously recorded cow behaviors to ensure agreement among them. Activity of the cows was noted every 5 min and the behavior (i.e., eating, ruminating, idling) was assumed to persist for the entire 5 min. The total time spent performing each behavioral activity over 24 h was then expressed in minutes. Eating was defined as muzzle in or over the feed trough with the cow chewing or swallowing. Meals were later calculated as the sum of consecutive eating activity for at least 5 min, preceded and followed by at least 5 min without eating activity. Rumination was defined as regurgitation, chewing, and swallowing of a bolus. Rumination bouts were then calculated as a period of ruminating consecutive boluses, preceded and followed by at least 5 min without ruminating. Total chewing time was calculated as the sum of total eating and ruminating times, and eating, ruminating, and chewing activities per kilogram of DM, NDF, peNDF, and uNDF intake were calculated by dividing total chewing activity by the respective intake recorded on d 20. The rate of eating and ruminating were calculated as total time spent eating and rumination per day divided by DMI on d 20, respectively (Beauchemin and Yang, 2005). During milking, the cows walked to and from the milking parlor (20–30 min per round-trip) and were considered not to be chewing (i.e., idle).

Sorting of particles was determined from the actual intake of each fraction compared with the predicted intake of the same fraction had the diet been consumed as formulated (Leonardi and Armentano, 2003). A sorting index score was calculated for each fraction as the percentage of actual intake compared with the predicted intake. Values equal to 100% indicated no sorting, whereas values <100% indicated selective refusals (sorting against), and >100% indicated preferential consumption (sorting for).

Milk Yield and Components, BW, and BCS

The cows were milked 3 times daily at 0800, 1600, and 1200 h in a herringbone milking parlor. Milk yields were recorded and sampled during the 5 d of the sampling period and samples were preserved with potassium dichromate and stored at 4°C pending analysis. Milk samples were submitted to Ideh Sazan Rojan Alvand Co. (Alborz, Iran) for fat, true protein, lactose, SNF, TS, MUN, nonesterified fatty acids, BHB, and fatty acid analyses using Fourier-transform mid-infrared spectroscopy of CombiScope FTIR 600 HP (Delta Instruments, Drachten, the Netherlands).

The yields of 3.5% FCM, ECM, and milk energy were calculated according to the following NRC (2001) equations:

$$3.5\%\ \text{FCM} = 0.432 \times \text{milk yield} + 16.23 \times \text{fat yield},$$

$$\text{ECM} = 12.82 \times \text{fat yield} + 7.13 \times \text{true protein yield} + 0.323 \times \text{milk yield},$$

$$\text{Milk NE}_{\text{L}}\ (\text{Mcal/kg}) = 0.0929 \times \text{fat \%} + 0.0547 \times \text{true protein \%} + 0.0395 \times \text{lactose \%}.$$

Daily secretion of milk energy (Mcal/d) was computed as milk NE_{L} × milk yield. Feed efficiency was calculated as kilograms of ECM per kilogram of DMI.

The BW of each cow was measured at the start and end of each period, after the morning milking. Body condition was scored by 2 experienced evaluators using a 5-point scale where 1 = emaciated and 5 = obese at the beginning and end of each experimental period.

Ruminal pH and Fermentation

On the last day of each experimental period, approximately 4 h after the morning feeding, ruminal fluid (approximately 3 mL) was sampled from the ventral sac via rumenocentesis, the technique developed by Nordlund and Garrett (1994). The pH was measured immediately, using a portable digital pH meter (HI 8318, Hanna Instruments, Cluj-Napoca, Romania) and the samples were immediately frozen at −8°C. Before freezing, a subsample of ruminal fluid was acidified with 200 μL of 25% metaphosphoric acid per each mL of ruminal fluid. The ruminal fluid samples were thawed and analyzed for NH_3-N by the colorimetric phenol-hypochlorite method (Broderick and Kang, 1980). For VFA analysis, samples were thawed and centrifuged at 10,000 × g at 4°C for 20 min and analyzed using GC (0.25 × 0.32, 0.3 μm i.d. fused silica capillary, model no. CP-9002 Vulcanusweg 259 a.m., Chrompack, Delft, the Netherlands), as described by Bal et al. (2000).

Statistical Analyses

Data were analyzed as a replicated 3 × 3 Latin square design using Proc Mixed of SAS (version 9.0, SAS Institute Inc., Cary, NC). Square, period within square, and treatment were considered as fixed effects in the model, whereas cow within square was included as a random effect. Normality of distribution and homogeneity of variance for the residuals were tested using PROC UNIVARIATE. Values are reported as least squares means. Polynomial orthogonal contrasts were used to test linear and quadratic responses. Significance was declared at $P \leq 0.05$, and tendencies were noted if $0.05 < P \leq 0.10$.

RESULTS

Forages and Diets

Although a statistical analysis was not performed because the crop byproducts were from a single source, SB had numerically greater OM (94.1 vs. 85.1% of DM), NDF (86.2 vs. 76.4% of DM), ADF (62.9 vs. 45.2% of DM), and ADL (19.9 vs. 10.3% of DM) concentrations, and less CP (2.63 vs. 3.72% of DM) and AIA (2.69 vs. 6.98% of DM) concentrations than WS (Table 1). The NFC and predicted NE_L concentrations were approximately similar between SB and WS.

Physical properties and NDF characteristics of the roughage sources are presented in Table 2. The SB had greater $peNDF_8$ (63.2 vs. 40.6% of DM), $peNDF_{1.18}$ (83.5 vs. 72.1% of DM), GMPS (10.7 vs. 6.6 mm), $uNDF_{30}$ (65.1 vs. 54.2% of DM and 75.6 vs. 70.8% of NDF), $uNDF_{72}$ (45.8 vs. 35.3% of DM and 53.2 vs. 46.2% of NDF), and $uNDF_{288}$ (35.5 vs. 21.2% of DM and 41.4 vs. 27.7% of NDF) than WS. Consequently, SB contained less $pdNDF_{288}$ (50.7 vs. 55.2% of DM) compared with WS. A greater proportion of particles was retained on the 19-mm sieve (24.9 vs. 2.6%, $P < 0.01$) for SB compared with WS, and correspondingly a smaller proportion of particles was retained on the 1.18-mm sieve (23.6 vs. 41.2%, $P < 0.01$) and pan (3.1 vs. 5.7%, $P = 0.01$) for SB compared with WS. The proportion of particles retained on the 8-mm sieve was not different between roughages ($P = 0.16$).

With increasing SB proportion in the diet, $uNDF_{288}$ as a percentage of TMR DM and NDF increased linearly ($P < 0.01$; Table 4). The proportion of particles retained on the 19-mm sieve ($P < 0.01$) increased linearly as inclusion of SB in the diets increased. Furthermore, $peNDF_8$ ($P = 0.07$) and GMPS ($P = 0.09$) tended to increase linearly as SB replaced WS in the diets.

Intake, Sorting Activity, and Apparent Digestibility

The intake of DM on the 1.18-mm sieve was not different among treatments (Table 5). However, DMI of material on the 19-mm sieve increased and that on the 8-mm sieve decreased linearly ($P < 0.01$) with increasing SB level. The sorting index for particles retained on the 19-mm sieve decreased as WS was replaced with SB ($P < 0.01$), indicating sorting against the long particles provided by SB. In contrast, there was increased preference for small particles retained on the 1.18-mm sieve as proportion of SB in the diet increased ($P < 0.01$).

Average DM (26.53 kg/d), EE (1.62 kg/d), starch (7.21 kg/d), and NDF (8.58 kg/d) intake did not differ among the treatments (Table 6). However, OM ($P < 0.01$) and CP ($P = 0.03$) intake decreased and ADF ($P = 0.03$) intake increased linearly as SB inclusion in the diets increased. The $uNDF_{288}$ intakes increased linearly ($P < 0.01$) as WS was replaced with SB. The total-tract digestibility of OM, CP, starch, and NDF decreased linearly ($P < 0.01$) as SB replaced WS.

Milk Yield and Components and Feed Efficiency

Average milk (37.0 kg/d), 3.5% FCM (39.5 kg/d), and ECM (38.2 kg/d) yield did not differ among the treatments (Table 7). Moreover, the treatments had no effect on milk composition including fat (3.89%), true protein (2.90%), and lactose (4.39%) concentrations. Feed efficiency was constant among treatments, and cows produced an average of 1.40 and 1.44 kg of raw milk or ECM per kg of DMI, respectively. The BW, BCS, and backfat thickness were not affected by treatments. Milk energy (Mcal/kg), milk energy excretion (Mcal/d), and milk energy excretion per kilogram of DMI were not different among treatments.

Milk fatty acid profiles were not different among treatments (Supplemental Table S1; https://doi.org/10.3168/jds.2020-18499). Dietary treatment had no effects on milk concentrations of nonesterified fatty acids, BHB, and MUN, which averaged 477 mEq/dL, 0.11 mmol/L, and 14.3 mg/dL, respectively.

Table 5. Effects of substitution of sugarcane bagasse for wheat straw on sorting activity and intake of particles (DM basis) of mid-lactation Holstein dairy cows (n = 9)

	Treatment[1]				*P*-value[2]	
Item	0SB	9SB	18SB	SEM	L	Q
Intake, kg/d						
19 mm	0.35	1.24	1.38	0.061	<0.01	<0.01
8 mm	6.86	6.42	5.83	0.121	<0.01	0.54
1.18 mm	13.8	13.1	13.5	0.22	0.32	0.04
Pan	5.76	5.79	5.49	0.091	0.06	0.18
peNDF$_8$,[3] % of DM	2.16	2.35	2.26	0.039	0.22	0.06
Sorting index, %						
19 mm	100.0	77.1	72.2	4.05	<0.01	0.05
8 mm	98.8	99.8	99.9	0.64	0.33	0.53
1.18 mm	101.0	102.0	104.0	0.31	<0.01	0.90
Pan	100.0	102.1	101.0	0.94	0.55	0.27

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] L = linear effect; Q = quadratic effect.

[3] peNDF$_8$ = physically effective NDF determined as NDF concentration (% DM) of TMR multiplied by physical effectiveness factor, calculated as the total DM retained on 8- and 19-mm sieves.

Chewing Behavior

Increasing SB in the diets linearly increased rumination ($P = 0.01$) and total chewing ($P = 0.02$) time, whereas eating time ($P = 0.64$) was not affected (Table 8). Eating time as minutes per kilogram of uNDF$_{288}$ ($P < 0.01$) decreased linearly as SB inclusion in the diets increased. The rumination time as minutes per kilogram of DM, NDF, and peNDF$_8$ intake increased linearly as SB inclusion in the diets increased. Total chewing time increased linearly when expressed per day or as minutes per kilogram of DM, NDF, uNDF$_{288}$, and peNDF$_8$ intake as SB inclusion in the diets increased.

Meal patterns were not affected by dietary treatments (Table 9), except for meal size of uNDF$_{288}$, which linearly increased ($P < 0.01$) with increasing SB inclusion in the diets. Rumination bout length (min; $P = 0.01$) and rate (g of DM/min, $P < 0.01$) increased and decreased linearly, respectively, with increasing the SB inclusion in the diets. The time between rumination

Table 6. Effects of substitution of sugarcane bagasse for wheat straw on nutrient intake and digestibility of mid-lactation Holstein dairy cows (n = 9)

	Treatment[1]				*P*-value[2]	
Item	0SB	9SB	18SB	SEM	L	Q
Intake, kg/d						
DM	26.88	26.52	26.19	0.437	0.30	0.98
OM	24.94	24.77	24.45	0.030	<0.01	0.17
Ether extract	1.56	1.68	1.63	0.033	0.24	0.16
CP	4.52	4.37	4.24	0.035	0.03	0.88
Starch	7.19	7.19	7.26	0.069	0.57	0.71
NDF	8.44	8.59	8.72	0.131	0.28	0.96
uNDF$_{30}$[3]	5.94	6.04	6.15	0.151	0.38	0.98
uNDF$_{288}$[3]	2.15	2.45	3.01	0.041	<0.01	0.06
pdNDF$_{30}$[4]	2.51	2.55	2.60	0.152	0.68	0.99
pdNDF$_{288}$[4]	6.30	6.14	5.74	0.041	<0.01	0.07
ADF	4.26	4.38	5.13	0.110	0.03	0.14
Total-tract digestibility, %						
OM	84.6	80.1	76.4	1.11	<0.01	0.73
CP	85.1	82.3	78.3	1.17	<0.01	0.60
Starch	97.1	96.4	95.8	0.23	<0.01	0.99
NDF	70.1	63.5	54.4	2.17	<0.01	0.66

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] L = linear effect; Q = quadratic effect.

[3] uNDF = NDF residue after 30- or 288-h in situ incubation.

[4] pdNDF = potentially degradable NDF after 30- or 288-h in situ incubation.

Table 7. Effects of substitution of sugarcane bagasse for wheat straw on milk production and composition and feed efficiency of mid-lactation Holstein dairy cows (n = 9)

	Treatment[1]				*P*-value[2]	
Item	0SB	9SB	18SB	SEM	L	Q
Yield, kg/d						
Milk	36.6	37.5	37.1	1.25	0.51	0.37
FCM 3.5%	39.2	40.2	39.1	1.60	0.93	0.35
ECM	37.9	38.9	37.9	1.49	0.98	0.30
Fat	1.44	1.47	1.42	0.071	0.73	0.43
True protein	1.06	1.09	1.04	0.036	0.70	0.32
Lactose	1.61	1.65	1.63	0.058	0.62	0.35
SNF	2.95	3.03	2.98	0.104	0.62	0.28
TS	4.39	4.51	4.40	0.171	0.90	0.26
Milk $\mathrm{NE_L}$, Mcal/kg	0.70	0.70	0.69	<0.001	0.28	0.62
Milk $\mathrm{NE_L}$ excretion, Mcal/d	25.6	26.2	25.5	1.03	0.92	0.30
Milk $\mathrm{NE_L}$ excretion/DMI, Mcal/kg	0.94	0.98	0.97	0.040	0.39	0.56
Milk composition, %						
Fat	3.93	3.91	3.83	0.097	0.37	0.77
True protein	2.90	2.90	2.90	0.032	0.84	0.85
Lactose	4.39	4.39	4.38	0.051	0.52	0.82
SNF	8.05	8.07	8.03	0.073	0.64	0.58
TS	11.98	12.00	11.85	0.131	0.21	0.40
Efficiency, kg/kg						
Milk/DMI	1.36	1.41	1.43	0.049	0.24	0.75
ECM/DMI	1.41	1.46	1.45	0.059	0.48	0.66
BW, kg	660	659	652	11.5	0.06	0.41

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] L = linear effect; Q = quadratic effect.

Table 8. Effects of substitution of sugarcane bagasse for wheat straw on chewing activity of mid-lactation Holstein dairy cows (n = 9)

	Treatment[2]				*P*-value[3]	
Item[1]	0SB	9SB	18SB	SEM	L	Q
Eating						
Min/d	283	298	290	22.3	0.64	0.52
Min/kg of DM	10.5	11.2	11.1	0.84	0.31	0.47
Min/kg of NDF	33.5	34.8	33.3	2.55	0.92	0.40
Min/kg of uNDF_{288}	132	122	96.3	9.04	<0.01	0.20
Min/kg of peNDF_{8}	131	127	128	11.9	0.67	0.60
Rumination						
Min/d	376	426	477	32.4	0.01	0.97
Min/kg of DM	13.9	16.1	18.2	1.04	<0.01	0.93
Min/kg of NDF	44.5	49.8	54.7	3.17	0.01	0.89
Min/kg of uNDF_{288}	175	174	158	11.9	0.23	0.56
Min/kg of peNDF_{8}	174	181	211	12.6	<0.01	0.26
Total chewing activity						
Min/d	659	724	767	33.6	0.02	0.77
Min/kg of DM	24.5	27.3	29.3	1.04	<0.01	0.73
Min/kg of NDF	77.9	84.6	87.9	3.25	0.02	0.62
Min/kg of uNDF_{288}	306	295	255	12.5	<0.01	0.31
Min/kg of peNDF_{8}	305	308	340	17.4	0.04	0.27

[1] uNDF_{288} = NDF residue after 288-h in situ incubation; peNDF_{8} = physically effective NDF determined as NDF concentration (% DM) of TMR multiplied by physical effectiveness factor, calculated as the total DM retained on 8- and 19-mm sieves.

[2] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[3] L = linear effect; Q = quadratic effect.

Table 9. Effects of substitution of sugarcane bagasse for wheat straw on meal patterns of mid-lactation Holstein dairy cows (n = 9)

Item[1]	Treatment[2]			SEM	*P*-value[3]	
	0SB	9SB	18SB		L	Q
Eating						
Meals/d	14.1	14.4	14.1	0.70	0.60	0.20
Min/meal	19.7	20.5	20.4	1.96	0.72	0.41
Time between meals, min	123	130	134	11.8	0.51	0.97
Rate, g of DM/min	95.5	90.0	90.0	0.01	0.20	0.78
Meal size						
kg of DM	1.85	1.85	1.82	0.179	0.58	0.73
kg of NDF	0.58	0.60	0.61	0.061	0.14	0.80
kg of $uNDF_{288}$	0.15	0.17	0.21	0.021	<0.01	0.39
kg of $peNDF_8$	0.15	0.16	0.16	0.021	0.15	0.20
Rumination						
Bouts/d	12.7	12.8	12.7	0.53	0.51	0.47
Min/bout	29.6	33.2	37.7	2.81	0.01	0.87
Time between bouts, min	122.4	93.5	82.4	17.22	0.08	0.64
Rate, g of DM/min	72.0	62.0	55.0	0.01	<0.01	0.69

[1] $uNDF_{288}$ = NDF residue after 288-h in situ incubation; $peNDF_8$ = physically effective NDF determined as NDF concentration (% DM) of TMR multiplied by physical effectiveness factor, calculated as the total DM retained on 8- and 19-mm sieves.

[2] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[3] L = linear effect; Q = quadratic effect.

bouts tended to decrease linearly with inclusion of SB ($P = 0.08$).

Ruminal pH, Fermentation, and N Metabolism

The average ruminal pH value for cows fed 0SB, 9SB, and 18SB diets was 6.68, 6.50, and 6.10, respectively, and it decreased linearly as WS was replaced by SB ($P < 0.01$; Table 10). No differences in ruminal NH_3 concentration occurred among treatments. Total VFA concentration ($P = 0.02$) and propionate proportion ($P < 0.01$) increased linearly as SB inclusion in the diets increased, whereas acetate proportion and acetate:propionate ratio decreased linearly ($P < 0.01$).

The N intake (g/d) tended to decrease linearly with inclusion of SB ($P = 0.07$), whereas milk N and predicted urinary N were not affected by diet (Supplemental Table S2; https://doi.org/10.3168/jds.2020-18499). Also, predicted fecal N ($P = 0.02$) decreased linearly and apparent N efficiency ($P = 0.03$) increased linearly as WS was replaced by SB.

DISCUSSION

The study examined the effects of replacing WS with SB in the diet of mid-lactation dairy cows on performance, digestibility, chewing activity, and ruminal fermentation. The basal diet fed to the cows was ex-

Table 10. Effects of substitution of sugarcane bagasse for wheat straw on ruminal fermentation of mid-lactation Holstein dairy cows (n = 9)

Item	Treatment[1]			SEM	*P*-value[2]	
	0SB	9SB	18SB		L	Q
pH	6.68	6.50	6.10	0.077	<0.01	0.31
NH_3, mg/dL	10.5	10.5	9.7	1.66	0.51	0.71
Total VFA, mmol/L	111	115	127	3.9	0.02	0.34
Acetate, mol/100 mol	66.0	64.1	63.4	0.60	<0.01	0.16
Propionate, mol/100 mol	18.4	19.9	21.1	0.49	<0.01	0.68
Butyrate, mol/100 mol	11.4	11.6	11.0	0.44	0.55	0.43
Isobutyrate, mol/100 mol	0.82	0.83	0.86	0.059	0.48	0.89
Valerate, mol/100 mol	1.15	1.12	1.29	0.088	0.08	0.92
Isovalerate, mol/100 mol	2.32	2.23	2.39	0.160	0.54	0.23
Acetate:propionate	3.61	3.26	3.02	0.111	<0.01	0.60

[1] 0SB = 0% sugarcane bagasse + 27.4% wheat straw; 9SB = 9.0% sugarcane bagasse + 18.4% wheat straw; 18SB = 18.1% sugarcane bagasse + 9.32% wheat straw.

[2] L = linear effect; Q = quadratic effect.

ceptionally high in concentrate (73% of DM) to provide the NE_L required, given the relative low quality of the roughage sources used in the study. As a result, average ECM yield of the cows (38.2 kg/d) during the study was relatively high. The Latin square design accounted for cow and period effects while individually housing the cows allowed for measurements of individual animal responses to changes in dietary roughage source and proportion. However, the results should be interpreted in context of the conditions employed, as the relatively short (21 d) length of the periods in the Latin square design and limited number of cows per treatment ($n = 9$) are limitations of the study. In particular, the milk production results need to be confirmed over a longer feeding period using a greater number of cows.

The chemical compostion of WS was typical of wheat grown in Iran (Kahyani et al., 2019a,b), but its nutritive value was poor compared with other research (Eastridge et al., 2009). The chemical composition of SB was similar to that reported by others (Ramli et al., 2005; de Almeida et al., 2018; Freitas et al., 2018). The greater NDF, ADF, and ADL concentrations of SB compared with WS resulted in more fibrous diets when WS was replaced by SB. Diets containing SB also had greater proportion of long particles (retained on the 19-mm sieve), $peNDF_8$, and GMPS, indicating that SB was a superior source of physical fiber compared with WS. However, SB was also less degradable than WS; it had greater uNDF concentrations when measured at 30 and 288 h compared with WS. Hence, the pdNDF concentration of SB was less than that of WS. Therefore, the dietary concentration of $uNDF_{288}$ linearly increased as the level of SB increased in the diets. The $uNDF_{288}$ in SB represented nearly 41% of NDF compared with 28% for WS, consistent with a previous study by de Almeida et al. (2018). The SB also had substantially greater ADL concentration than WS (19.9 vs. 10.3% of DM). The greater uNDF and ADL concentrations of SB resulted in a decrease in total-tract digestibility of nutrients when SB replaced WS in the diets. Compared with other forages, total-tract NDF digestibility of SB is low (<35%; Oliveira et al., 2011) due to its high proportion of uNDF (~50% of NDF) and lesser pdNDF concentration (Daniel et al., 2014).

The concentrations of fiber, lignin, ash, and fat in feeds have a direct effect on NE_L concentration; fiber (ADF and NDF) and lignin concentrations are negatively related to NE_L because fiber, on average, is less digestible than nonfiber and lignin is not digestible (Weiss, 1998). Furthermore, ash contributes no energy and therefore dilutes digestible OM (Weiss, 1998). In the current experiment, the ash concentration of WS was 3 times that of SB, but the fiber (ADF and NDF) and lignin concentrations of SB were greater than those in WS. Consequently, the digestible energy concentrations of WS and SB were similar.

Although substituting WS with SB increased the particle size and peNDF concentration of the TMR, it also increased the sorting against >19-mm particles. It was previously observed that cows sort against longer particles to a greater degree when low-digestibility forage is offered (Suarez-Mena et al., 2013; Miller-Cushon and DeVries, 2017). Hence, decreasing the particle size of low-quality forage can help minimize sorting against longer particles (Suarez-Mena et al., 2013; Coon et al., 2018). Because the cows in the current experiment sorted against long particles, $peNDF_8$ intake was only marginally increased with incorporation of SB in diets, even though it was a better source of physical fiber than WS. Increased sorting was surprisingly not accompanied by an increase in eating time or a change in meal characteristics. Consequently, more kilograms of $uNDF_{288}$ were consumed per meal with an increase in SB in diets.

It was expected that SB would limit feed intake compared with WS because of its greater NDF concentration and potential filling effect. It is well documented that DMI of ruminants is limited by physical distension of the gastrointestinal tract (de Almeida et al., 2018); however, that was not the case in the present study as DMI was not affected by substituting WS with SB. Similar $pdNDF_{30}$ concentrations, despite lesser $pdNDF_{288}$ concentrations, of SB compared with WS likely accounted for the lack of differences in DMI among diets. Grant and Cotanch (2012) reported that the filling effect of the diet could be related to the amount and rate of degradation of pdNDF. Wells (2016) reported that DMI was inversely related to hay $uNDF_{30}$ concentration.

A high level of $uNDF_{288}$ reduces the amount of OM available for degradation in the rumen, and therefore is associated with lesser total-tract digestibility of DM and NDF (Freitas et al., 2018). Other studies have similarly observed a decrease in total-tract digestibility with incorporation of SB in diets (Corrêa et al., 2003; de Almeida et al., 2018; Freitas et al., 2018). The $uNDF_{288}$ was greater in SB than WS, and Ahvenjärvi et al. (2006) and Lopes et al. (2015b) indicated that $uNDF_{288}$ decreases total-tract digestibility. In the current experiment, inclusion of SB in diets increased $uNDF_{288}$ and decreased $pdNDF_{288}$ concentrations in a linear manner. Moreover, SB had greater concentration of ADL, which would also contribute to lowering digestibility of DM and NDF in the gastrointestinal tract (Grabber, 2005; de Almeida et al., 2018).

Despite a decrease in diet total-tract apparent digestibility with increasing levels of SB added to diets, milk yield was not affected. All diets had similar amount of

$uNDF_{30}$ (22.7% of DM) and $pdNDF_{30}$ (9.6% of DM), even though concentration of $uNDF_{288}$ was increased with added SB. Consistent with our results, Sá Neto et al. (2014) compared a corn silage–based diet with a SB silage–based diet and reported similar DMI, milk yield, and milk composition in late-lactation dairy cattle. However, others reported that the DMI and milk production decreased linearly with incorporation of SB in diets (Corrêa et al., 2003; Freitas et al., 2018; de Almeida et al., 2018). In those experiments, SB replaced a higher quality forage (corn silage: Corrêa et al., 2003; spineless cactus: de Almeida et al., 2018; Freitas et al., 2018) unlike in our study where SB replaced WS. In addition, those studies used a greater proportion of SB in the diets (45% of DM: Corrêa et al., 2003; 30–54% of DM: Freitas et al., 2018; 45–60% of DM: de Almeida et al., 2018) in comparison with the present experiment (9–18% of DM). Cotanch et al. (2012) suggested that the negative response of milk production to uNDF concentration of the diet depends on forage proportion, because milk production was not affected by the source of corn silage when cows were fed diets with low forage content but milk production increased with the use of brown midrib corn silage when cows were fed high-forage diets. In our experiment, roughage content of the diets was low (28%) and WS was only partially replaced. Thus, the effects of incorporating SB in dairy cow diets on cow productivity may depend on stage of lactation and hence requirements for energy, inclusion rate of SB in the diets, as well as the digestibility of the ingredient replaced by SB. In the present study, the lack of negative effect of SB on milk production was attributed to the mid-lactation stage of the cows, the replacement of WS, another low-quality crop byproduct, with SB such that $pdNDF_{30}$ was not affected, and the relatively low inclusion rate in the diet.

The linear increase in total chewing and rumination time with increasing proportion of SB is consistent with the greater $peNDF_8$ and $uNDF_{288}$ concentrations of the SB diets. Chewing and rumination per kg of NDF and $peNDF_8$ intake linearly increased with inclusion SB, as a result of greater physical effectiveness of SB fiber. Mertens (1997) and Pereira et al. (1999) indicated that total chewing time greater than 650 min/d and 30 min/kg of DM are characteristic of high-forage-based diets. Total chewing time in the current experiment averaged 716 min/d and 26 min/kg of DM, even though the diets contained only 28% roughage DM. This finding suggests that uNDF and $peNDF_8$ levels are probably more important than forage level in maintaining rumen health and milk fat production of dairy cows.

Increased chewing time with inclusion of SB in diets was entirely due to longer rumination time, which manifested by longer rumination bouts and shorter intervals between bouts. The linear increase in rumination time per kilogram of DM and NDF indicated the greater need for particle size reduction of diets that included SB (Beauchemin et al., 2001), despite sorting against long particles. These results indicate that intake of $peNDF_8$ (particle size) and $uNDF_{288}$ (resistance to chewing) are the main contributing factors to rumination time. As DMI was similar among treatments, yet rumination time increased linearly with SB inclusion, rumination rate (g of DM/min) decreased with the increase of SB content. Rumination activity has a more significant influence on the reduction of feed particle size and salivary secretion than eating activity (Grant et al., 1990). In agreement with our results, Freitas et al. (2018) and de Almeida et al. (2018) reported a linear increase in rumination time with SB level in the diet, but a linear decrease in rumination rate. In general, the cows in the present experiment were able to maintain their feed intake and ultimately milk production by sorting more against the particles retained on the 19-mm sieve and ruminating more to process the greater intake of less degradable fiber. In contrast to our results, Corrêa et al. (2003) noted no difference in chewing behavior when SB silage replaced corn silage in dairy cow diets.

It was expected that cows fed SB would have greater ruminal pH than cows fed 0SB, because of increased rumination time due to greater intake of long particles and $uNDF_{288}$. However, the opposite effect was observed with ruminal pH decreasing with increased incorporation of SB into diets. The decrease in pH was associated with an increase in molar proportion of propionate and decrease in molar proportion of acetate, indicative in a shift in ruminal fermentation toward nonstructural carbohydrates. This shift in fermentation is consistent with the greater NFC concentration of SB. Contrary to our results, ruminal pH was not different between cows fed corn or SB silages (Corrêa et al., 2003). Beauchemin and Yang (2005) demonstrated that increasing the peNDF concentration of diets increased chewing time, but increased chewing time did not necessarily increase ruminal pH. They stated that in addition to peNDF, fermentable OM intake also affects ruminal pH. Beauchemin (2000) reported poor relationship ($R^2 < 0.13$) between ruminal pH and dietary fiber measured as NDF, forage NDF or peNDF. It can be concluded that greater dietary $uNDF_{288}$ intake increased rumination time, but did not improve ruminal pH.

The lesser CP concentration of SB diets, combined with similar DMI, tended to linearly decrease N intake as SB content of the diet increased. Lack of effect of lesser N intake on milk N concentration indicated increased efficiency of transfer of dietary N to milk N with SB inclusion in diets. Thus, the cows fed SB used N more efficiently with more N directed toward milk rather than feces. Sá Neto et al. (2014) reported that N efficiency was similar between cows fed corn or SB silages. In contrast to our results, Freitas et al. (2018) reported that N efficiency decreased linearly with the increase of SB inclusion from 30 to 54% of DM. According to the NRC (2001), a 591-kg cow producing 41 kg of milk containing 3.5% milk fat requires 0.405 kg of CP for maintainance and 3.44 kg of CP for milk production, with a total CP requirement of 3.84 kg/d. In the current experiment, cows on 0SB, 9SB, and 18SB treatments consumed 4.5, 4.3, and 4.2 kg/d of CP, respectively, with these CP intakes greater than the requirement (NRC, 2001). The decrease in CP intake combined with a decrease in CP digestibility with increased SB inclusion in the diets likely promoted N efficiency.

CONCLUSIONS

There was no difference in the uNDF_{30} concentration of diets containing increasing proportions of SB and decreasing proportions WS, but dietary uNDF_{288} and peNDF_{8} concentrations increased linearly with SB inclusion. Partial substitution of WS with SB reduced total-tract apparent digestibility but did not negatively affect DMI or lactational performance of mid-lactation Holstein dairy cows producing 37 kg/d of milk. We conclude that SB is a good source of peNDF for cows fed high-concentrate diets. However, SB is less digestible than WS in the total tract; therefore, performance of dairy cows may decrease when fed diets containing SB that limit DMI.

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