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Performance of dairy cows fed diets with similar proportions of undigested neutral detergent fiber with wheat straw substituted for alfalfa hay, corn silage, or both

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ABSTRACT

This study evaluated the effects of feeding diets that were formulated to contain similar proportions of undigested neutral detergent fiber (uNDF) from forage, with wheat straw (WS) substituted for corn silage (CS), alfalfa hay (AH), or both. The diets were fed to lactating dairy cows and intake, digestibility, blood metabolites, and milk production were examined. Thirty-two multiparous Holstein cows (body weight = 642 ± 50 kg; days in milk = 78 ± 11 d; milk production = 56 ± 6 kg/d; mean ± standard deviation) were used in a randomized block design with 6-wk periods after a 10-d covariate period. Each period consisted of 14 d of adaptation followed by 28 d of data collection. The control diet contained CS and AH as forage sources (CSAH) with 17% of dietary dry matter as uNDF after 30 h of incubation ($uNDF_{30}$). Wheat straw was substituted for AH (WSCS), CS (WSAH), or both (WSCSAH) on an $uNDF_{30}$ basis, and beet pulp was used to obtain similar concentrations of NDF digestibility after 30 h of incubation ($NDFD_{30}$ = 44.5% of NDF) across all diets. The 4 diets also contained similar concentrations of net energy for lactation and metabolizable protein. Dry matter intake was greatest for WSCS (27.8 kg/d), followed by CSAH (25.7 kg/d), WSCSAH (25.2 kg/d), and WSAH (24.2 kg/d). However, yields of milk, 3.5% fat-corrected milk (FCM), and energy-corrected milk did not differ, resulting in higher FCM efficiency (kg of FCM yield/kg of dry matter intake) for WSAH (1.83) and WSCSAH (1.79), followed by CSAH (1.69) and WSCS (1.64). Milk protein percentage was greater for CSAH (2.84%) and WSCS (2.83%) than for WSAH (2.78%), and WSCSAH (2.81%) was intermediate. The opposite trend was observed for milk urea nitrogen, which was lower for CSAH (15.8 mg/dL), WSCS (15.8 mg/dL), and WSCSAH (17.0 mg/dL) than for WSAH (20 mg/dL). Total-tract NDF digestibility and ruminal pH were greater for diets containing WS than the diet without WS (CSAH), but digestibility of other nutrients was not affected by dietary treatments. Cows fed WSAH had less body reserves (body weight change = −13.5 kg/period) than the cows fed the other diets, whereas energy balance was greatest for those fed WSCS. The results showed that feeding high-producing dairy cows diets containing different forage sources but formulated to supply similar concentrations of $uNDF_{30}$ while maintaining $NDFD_{30,}$ net energy for lactation, and metabolizable protein constant did not influence milk production. However, a combination of WS and CS (WSCS diet) compared with a diet with CS and AH improved feed intake, ruminal pH, total-tract NDF digestibility, and energy balance of dairy cows.

Key words: undigested neutral detergent fiber, forage source, dairy cow, straw

INTRODUCTION

Corn silage (**CS**) and alfalfa hay (**AH**) are 2 forage sources commonly used in dairy diets worldwide. Both forages can be highly digestible and therefore promote high intake and milk production (Wang et al., 2014; Ferraretto et al., 2015). However, production of these high-quality forages requires a tremendous area of land and water, which are limited in many regions of the world. Therefore, byproduct feeds and crop residues are frequently used as fiber sources in dairy cow diets.

Wheat straw (**WS**) is a relatively inexpensive and available fiber source that is produced worldwide as a byproduct of wheat grain production. However, WS is poorly digested in the total-tract of dairy cows; its in vitro NDF digestibility (**NDFD**) at 30- and 48-h incubations has been estimated as 24 and 37% of NDF,

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respectively (Spanghero et al., 2010), and it has an estimated TDN content of 47.5% (NRC, 2001). The low digestibility of WS may compromise milk production, although WS is often used in dairy cow diets as a source of physically effective fiber to promote rumination and elevate ruminal pH (Eastridge et al., 2009). Beet pulp (**BP**) is another widely available byproduct feed that is highly digestible in the rumen (in vitro NDFD of 76–90% of NDF for 30- and 48-h incubations; Hoffman and Combs, 2003; Dal Maso et al., 2009) and high in TDN content (69.1%; NRC, 2001), but it lacks physically effective NDF (Zhang et al., 2010; Naderi et al., 2016).

Digestibility and indigestibility of NDF affect feeding and rumination behavior, ruminal fill, DMI, and milk production (Mertens, 2016). Oba and Allen (1999) indicated that NDFD was positively related to intake and milk production; on average, a 1-percentage-unit increase in in vitro NDFD (incubation times from 24 to 48 h) was associated with a 0.17 kg/d increase in DMI and a 0.25 kg/d increase in 4% FCM. Recent studies have shown that total-tract NDFD and performance of dairy cows (Fustini et al., 2017) can be accurately predicted from in vitro or in situ estimates of NDFD (Lopes et al., 2015a). The undigested NDF pool after 30-h incubation (**uNDF$_{30}$**) has been related to total mean retention time and gut fill (West et al., 1997), fiber digestibility (Oba and Allen, 1999), and intake potential (Nair et al., 2016).

Previous research has shown that WS, CS, AH, and BP differ widely in content of uNDF (at 30, 240, and 288 h of incubation), NDFD, and slowly and rapidly digestible NDF fractions (Fustini et al., 2017; Raffrenato et al., 2019). Regardless of NDF content, the NDF fraction of CS typically contains a higher proportion of potentially digestible NDF (**pdNDF**; calculated as NDF − uNDF$_{240}$ or uNDF$_{280}$) than does alfalfa NDF, but pdNDF of AH typically digests faster than that of CS (Van Soest, 1994). In contrast, WS contains a low amount of pdNDF with a slow rate of digestion (Raffrenato et al., 2019), and BP contains a high level of pdNDF with a rapid rate of digestion (Hoffman and Combs, 2003; Krizsan and Huhtanen, 2013). Therefore, formulating dairy diets on the basis of NDF concentration alone will result in variable concentrations of digestible and undigestible NDF fractions and rates of availability in the rumen. It is not clear what effect these fractions may have on milk production of high-producing dairy cows.

We hypothesized that replacing conventional forage sources (CS and AH) with WS in diets fed to high-producing dairy cows would result in similar milk production if diets were formulated to contain similar contents of uNDF$_{30}$ and NDFD after 30-h incubation (**NDFD$_{30}$**) while maintaining constant NE$_L$ and CP contents. Therefore, the study evaluated the effect of feeding diets formulated to supply similar concentrations of uNDF$_{30}$ to lactating dairy cows, with WS substituted for CS, AH, or both. Beet pulp was incorporated into diets to obtain a similar concentration of NDFD$_{30}$ across all diets. Effects on feed intake, ruminal fermentation, digestibility, blood metabolites, and milk production were measured.

MATERIALS AND METHODS

The experiment consisted of an in vivo study in which treatments were based on results from an in situ study that measured NDFD. Both studies were conducted at the Lavark Research Station (Isfahan University of Technology, Isfahan, Iran). Animals were cared for according to the guidelines of the Iranian Council of Animal Care (1995), and the experiment was approved by the Institutional Animal Care Committee for Animals Used in Research.

Forage Preparation

Alfalfa was harvested from a single field at an advanced stage of maturity (~50% bloom), field cured, baled, and chopped (Golchin Trasher Hay Co., Isfahan, Iran) to a 15-mm theoretical length of cut. Corn silage was harvested from a single field using a pull-type chopper (model 965, Claas, Omaha, NE) set to produce particles with an average theoretical chop length of 25 to 30 mm. Whole wheat plants were threshed to separate cereal grains from straw, and the straw was then chopped finely using a theoretical chop length setting of 10 mm (Golchin Trasher Hay Co.). The WS was reconstituted 24 h before feeding and before in situ measurements by placing the required amount of dry WS into a large container and slowly adding water during mixing to achieve a theoretical DM content of 25%. The reconstituted WS was transferred to airtight containers.

In Vivo Study: Animals and Experimental Design

Thirty-two multiparous high-producing Holstein cows (BW = 642 ± 50; DIM = 78 ± 11 d; 56 ± 6 kg of milk/d at the start of the study; mean ± SD) were used in a randomized complete block design with 4 treatments (control and 3 diets that contained WS). The cows were assigned to 2 groups (blocks) that were run consecutively due to stall availability. The experiment consisted of a 10-d covariate period, 2 wk of adaptation to the treatment diets, and 4 wk of data collection. Cows were housed in individual pens (4 × 4 m) within a

Table 1. Mean (SD in parentheses) nutrient composition (% of DM unless otherwise stated) and particle size of forages and beet pulp

Item	Beet pulp	Wheat straw	Corn silage	Alfalfa hay
Nutrient composition				
DM, % as fed	90.2 (0.52)	93.0 (0.48)	26.2 (1.05)	95.0 (0.82)
OM	92.5 (0.18)	90.9 (0.93)	93.6 (0.08)	88.5 (0.09)
CP	10.3 (0.17)	2.6 (0.21)	7.7 (0.12)	13.3 (0.15)
Ether extract	0.63 (0.07)	1.37 (0.10)	2.47 (0.27)	1.38 (0.07)
NDF	35.1 (0.06)	82.0 (0.05)	53.8 (0.04)	52.0 (0.02)
NFC[1]	46.5 (0.35)	4.9 (0.25)	29.6 (0.74)	21.8 (0.43)
Starch	1.37 (0.40)	0.405 (0.06)	23.57 (1.92)	1.12 (0.16)
Water-soluble carbohydrate	18.56 (1.40)	1.03 (0.12)	1.07 (0.19)	3.62 (0.62)
Lignin	2.06 (0.50)	8.40 (0.20)	3.90 (0.30)	9.50 (0.73)
$uNDF_{30}$[2]	7.7 (3.56)	62.4 (3.65)	37.3 (3.70)	32.0 (0.99)
$NDFD_{30}$,[3] % of NDF	78.2 (3.55)	25.9 (2.45)	30.9 (4.33)	38.6 (1.92)
$uNDF_{240}$[2]	2.82 (0.41)	27.4 (0.89)	12.9 (0.67)	27.4 (0.62)
$uNDF_{288}$[2]	2.81 (0.39)	26.6 (0.87)	12.8 (0.68)	27.2 (0.57)
$pdNDF_{288}$,[4] % of NDF	92.0 (1.12)	67.6 (1.06)	76.2 (1.27)	47.8 (1.10)
$pdNDF_{288}$ kd,[5] %/h	7.24 (0.04)	1.69 (0.07)	2.08 (0.06)	4.59 (0.06)
TTNDFD,[6] % of total NDF	74.7 (0.19)	29.1 (0.31)	37.1 (0.31)	33.6 (0.45)
Particle size, mm				
>19	0.75 (0.06)	1.00 (0.00)	18.3 (3.30)	2.00 (0.00)
8–19	65.93 (3.00)	56.0 (2.24)	56.8 (2.06)	33.0 (1.41)
1.18–8	33.32 (3.6)	37.2 (1.64)	24.0 (1.41)	43.3 (0.50)
<1.18	0.00 (0)	6.20 (1.10)	0.97 (0.06)	21.8 (1.26)
GMPL[7]	8.38 (0.35)	6.70 (0.28)	10.6 (0.67)	4.12 (0.16)

[1]Calculated as 100 − (% NDF + % CP + % fat + % ash).
[2]$uNDF_{30}$, $uNDF_{240}$, and $uNDF_{288}$ are NDF residues after 30-, 240-, and 288-h in situ incubation, respectively.
[3]In situ NDF digestibility after 30-h in situ incubation.
[4]Potentially digestible NDF after 288-h in situ incubation.
[5]Potentially digestible NDF fraction digestion rate calculated from TTNDFD model.
[6]Predicted total-tract NDF digestibility using in situ TTNDFD model (Lopes et al., 2015b).
[7]Geometric mean of particle size.

roofed facility with open sides, and clean wood shavings and sand were used for bedding and refreshed daily. Treatment arrangement was based on the amount of $uNDF_{30}$ in forages (Table 1) as measured using an in situ method, as follows.

In Situ Study

An in situ study was conducted to measure uNDF and NDFD in forages, BP, and final TMR according to the method described by Bender et al. (2016) and Donnelly et al. (2018; Table 1). Two ruminally cannulated, nonlactating Holstein dairy cows were fed a high-forage TMR diet (25% AH, 25% CS, 25% WS, 4.2% BP, 20.8% concentrate mix; DM basis) as recommended by Krizsan and Huhtanen (2013). Dried samples were ground to pass the 1-mm screen of a Wiley mill (Arthur H. Thomas, Philadelphia, PA), and 0.5 g of each sample was weighed into an Ankom F57 bag (Ankom Technology, Macedon, NY) with a pore size of 25 μm (Bender et al., 2016). This particular type of bag was selected so that digestibility estimates would be comparable with previous reports (Bender et al., 2016; Su et al., 2017; Donnelly et al., 2018). Samples were incubated in the rumen for 30, 240, and 288 h in triplicate along with 3 blank bags for each time point. Blanks were sealed Ankom bags containing 0 g of sample to correct for infiltration of NDF into the sample bags. After removal, samples were soaked in cold water and then washed twice in a commercial washing machine (1,350 rpm; model XQB 22-21GP, Pakshoma, Karaj, Iran) with cold water for 12 min to ensure that no residue adhered to the bag. This procedure was then duplicated in a second run. The equation for correcting for blanks in the calculation of NDF residue at each time point was as follows (Bender et al., 2016):

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

The bag correction factor represents the average fractional weight change of 3 Ankom blank bags following the NDF washing procedure. The $uNDF_{30,}$ $uNDF_{240}$, and $uNDF_{288}$ were the NDF residues after 30-, 240-, and 288-h incubations, respectively. The value for NDFD at each time point was calculated as

$$\text{NDFD (\% of NDF)} = 100 \times (\text{initial NDF} - \text{NDF residue})/\text{initial NDF}.$$

The pdNDF fraction (**pdNDF$_{288}$**) was calculated as NDF − uNDF$_{288}$, and total-tract NDFD was predicted using the model of Lopes et al. (2015b). The model inputs were pdNDF$_{288}$, its rate of degradation, and its rate of passage. The rate of passage was predicted from a regression model (Krizsan et al., 2010) that accounts for the selective retention of pdNDF$_{288}$ (Lund et al., 2007), determined using the flux–compartment pool method of Ellis et al. (1994). In the total-tract NDFD model, the predicted value is indexed to a 630-kg dairy cow consuming 23.4 kg of DM/d of a diet containing 30% NDF. This index sets the rate of passage of pdNDF$_{288}$ at 2.67%/h (Lund et al., 2007; Krizsan et al., 2010). Hindgut digestion of NDF was assumed to be 10% of total NDF digestion, which was similar to the estimate of hindgut NDF digestion in the Cornell Net Carbohydrate and Protein System Model (Fox et al., 2004). The rate of pdNDF$_{288}$ degradation was determined using 9 time points (6, 12, 24, 30, 36, 48, 72, 96, and 120 h). Natural logs of the pdNDF$_{288}$ residue percentages were calculated, and log-residue values less than −3 were considered invalid results and hence were discarded (Bender et al., 2016). The discarded time points were 48, 72, 96, and 120 h for BP and 72, 96, and 120 h for AH. A linear regression model was then fit to the natural log residual values versus time, and the inverse natural log of the rate of degradation was determined as the slope of the regression (Donnelly et al., 2018).

In Vivo Study Treatments

A control diet was formulated to contain CS and AH as forage sources (**CSAH**; Table 2) and supplied 13.9% of DM as forage uNDF$_{30}$ (Table 3). Three treatment diets were formulated to contain 13.9% of DM as forage uNDF$_{30}$ using WS substituted for AH (**WSCS**), CS (**WSAH**), or both (**WSCSAH**; Table 1). Pelleted BP was incorporated into the diets so that all 4 contained similar NDFD$_{30}$ content (~44.5% of NDF; Table 3). The diets were formulated using the Cornell Net Carbohydrate and Protein System Model (version 5.0; Fox et al., 2000; Table 1). The protein and energy supplements were adjusted to ensure that diets were similar in CP and NE$_L$ contents, but the amounts of NDF, forage NDF, and uNDF$_{288}$ were allowed to change (Table 2). Feed was supplied twice daily at 1000 and 1800 h in amounts that allowed 10% refusals. Diets were manually mixed and weighed into each cow's feed trough, and refusals were manually removed daily and weighed.

Table 2. Ingredient composition of the dietary treatments (values in parentheses are % of forage undigested NDF after 30 h of incubation)

		Diet[1]			
Item, % of DM	Covariate	CSAH	WSCS	WSAH	WSCSAH
Wheat straw	0.0	0.0 (0)	9.04 (40)	9.04 (40)	9.04 (40)
Corn silage	21	22.0 (59)	22.0 (59)	6.80 (19)	14.4 (39)
Alfalfa hay	13	18.0 (41)	0.40 (1)	18.0 (41)	9.20 (21)
Beet pulp	8	2.00	8.40	4.64	6.56
Barley grain, ground	15	16.0	16.0	16.0	16.0
Corn grain, ground	20	20.0	20.0	20.0	20.0
Meat meal	0	3.80	3.80	3.80	3.80
Soybean meal	8	11.1	12.4	14.1	13.4
Soybean, extruded	3	2.00	2.00	2.00	2.00
Canola meal	3	0.44	1.16	0.12	0.32
Cottonseed	3	0	0	0	0
Fish meal	1.6	0	0	0	0
Energy booster	1.5	1.84	1.56	2.72	2.24
Sodium bicarbonate	1.1	1.00	1.00	1.00	1.00
Calcium carbonate	0.5	0.52	0.68	0.48	0.64
Dicalcium phosphate	0.1	0.08	0.16	0.08	0.16
Magnesium oxide	0.2	0.16	0.24	0.16	0.20
Vitamin-mineral mix[2]	0.7	0.80	0.80	0.80	0.80
Salt	0.3	0.20	0.24	0.20	0.20

[1]Experimental diets were combinations of different forage sources to achieve similar dietary concentrations of undigested NDF after 30 h of incubation. CSAH = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH.

[2]Contained 2.5 g/kg Fe, 1.6 g/kg Cu, 3 g/kg Mn, 0.1 g/kg Co, 20 g/kg Mg, 5 g/kg Zn, 0.04 g/kg Se, 0.10 g/kg I, 3 g/kg monensin, 50 g/kg Mycosorb (Vetaque, Sirjan, Iran), 10,000,000 IU/kg vitamin A, 250,000 IU/kg vitamin D, and 5,000 IU/kg vitamin E.

Intake, Digestibility, and Analyses

The TMR amounts offered and refused were measured and sampled daily for each cow for 5 d each week of the data collection period, and daily DMI for each cow was calculated. Representative samples of forages (for each forage, weekly samples were pooled for the study), treatment TMR (pooled by diet within week), and individual refusals (pooled by cow within week) were taken immediately before the morning feeding during the 4-wk collection period. All samples were immediately frozen at −20°C until they were analyzed.

After thawing, the DM concentration of forages, TMR, and refusal samples was determined by drying at 60°C in a forced-air oven for 48 h. All samples were ground to pass the 1-mm screen of a Wiley mill (Arthur H. Thomas, Philadelphia, PA) and analyzed for CP using the Kjeldahl method (Kjeltec 1030 Auto Analyzer, Tecator, Höganäs, Sweden; AOAC International, 2006, method 955.04), ether extract (AOAC International, 2006, method 920.39), ash (AOAC International, 2006, method 942.05), and NDF using heat-stable α-amylase and sodium sulfite with an Ankom system (Van Soest et al., 1991). The samples of forages, BP, and TMR were also analyzed for the amount of starch (Zhu et al., 2016) and water-soluble carbohydrate (Dubois et al., 1956). Starch was hydrolyzed to glucose using a modified glucoamylase method as described by Zhu et al. (2016), and glucose concentration was analyzed using an enzymatic-colorimetric method. Concentrations of water-soluble carbohydrate were quantified using the phenol-sulfuric acid reaction, and final concentrations of water-soluble carbohydrate were determined colorimetrically using glucose as the standard curve (Dubois et al., 1956). Acid detergent lignin was determined using AOAC International (2006) method 973.18, modified to use 1.0 g/sample in Ankom F57 bags (Ankom Technology). Nonfiber carbohydrate was calculated as 100 – (CP + NDF + ether extract + ash). Forage, BP, and TMR samples were used to determine particle size distribution on an as-fed basis, in triplicate, using the Penn State Particle Separator equipped with 3 sieves

Table 3. Mean (SD in parentheses) nutrient composition (% of DM unless otherwise stated) and particle size of dietary treatments

		Diet[1]			
Item	Covariate	CSAH	WSCS	WSAH	WSCSAH
Nutrient composition					
DM, % as fed	55.5 (2.5)	42.6 (2.0)	42.6 (1.2)	41.4 (2.2)	40.0 (1.5)
OM	91.1 (0.15)	91.2 (0.1)	91.2 (0.1)	90.7 (0.1)	91.1 (0.0)
CP	15.9 (0.5)	16.3 (0.4)	15.9 (0.3)	16.9 (0.5)	16.4 (0.3)
NDF	31.8 (0.6)	30.0 (0.4)	30.9 (0.6)	31.3 (0.4)	31.1 (0.5)
Ether extract	4.80 (0.2)	4.9 (0.2)	4.7 (0.2)	5.6 (0.1)	5.1 (0.2)
NFC[2]	38.6 (1.1)	39.9 (0.8)	39.7 (0.9)	37.8 (1.2)	38.4 (1.1)
Starch	28.2 (1.35)	29.1 (1.40)	28.9 (1.12)	25.9 (1.32)	27.3 (1.20)
Water-soluble carbohydrate	4.1 (0.48)	3.14 (0.47)	3.9 (0.52)	3.65 (0.45)	3.75 (0.40)
Lignin	1.93 (0.1)	2.1 (0.1)	1.8 (0.1)	2.2 (0.4)	2.0 (0.3)
Forage NDF	19.0 (0.3)	21.2 (0.2)	19.5 (0.2)	20.4 (0.3)	19.9 (0.01)
NE_L,[3] Mcal/kg of DM	1.70	1.65	1.66	1.65	1.65
Forage $uNDF_{30}$, % of DM	12.3 (0.5)	13.9 (0.6)	13.9 (0.6)	13.9 (0.3)	13.9 (0.4)
$uNDF_{30}$[4]	17.8 (1.5)	16.9 (0.7)	16.9 (1.3)	17.5 (1.4)	17.0 (1.4)
$NDFD_{30}$,[5] % of NDF	49.9 (3.2)	43.7 (2.4)	45.1 (3.5)	43.7 (3.4)	45.3 (3.5)
$uNDF_{240}$[4]	8.0 (0.5)	9.52 (0.5)	8.31 (0.4)	10.9 (0.4)	9.02 (0.4)
$uNDF_{288}$[4]	7.76 (0.5)	9.4 (0.5)	8.1 (0.4)	10.8 (0.3)	8.9 (0.3)
$pdNDF_{288}$,[6] % of NDF	75.2 (2.5)	68 (2.3)	73 (2.1)	65 (1.6)	71 (2.4)
Particle size, mm					
>19	6.0 (0.8)	5.0 (0.8)	5.6 (0.8)	1.5 (0.3)	3.8 (0.6)
8–19	18.4 (1.2)	23.6 (0.6)	29.0 (1.9)	22.3 (1.6)	26.3 (2.0)
1.18–8	43.1 (2.5)	56.1 (2.1)	49.9 (2.2)	62.4 (2.1)	59.0 (3.2)
<1.18	30.8 (2.8)	15.0 (0.2)	15.0 (2.9)	13.6 (2.7)	10.8 (2.0)
GMPL[7]	4.18 (0.2)	4.3 (0.1)	4.6 (0.1)	4.0 (0.1)	4.6 (0.3)

[1]Experimental diets were combinations of different forage sources to achieve similar dietary concentrations of undigested NDF after 30 h of incubation. CSAH = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH.

[2]Calculated as 100 − (% NDF + % CP + % fat + % ash).

[3]Based on tabular values (Fox et al., 2000).

[4]$uNDF_{30}$, $uNDF_{240}$, and $uNDF_{288}$ are NDF residues after 30-, 240-, and 288-h in situ incubation, respectively.

[5]In situ NDF digestibility after 30-h in situ incubation.

[6]Potentially digestible NDF after 288-h in situ incubation.

[7]Geometric mean of particle size.

(19, 8, and 1.18 mm) and a bottom pan (Kononoff, 2002). The geometric mean particle length (**GMPL**) was calculated according to ANSI (1995; method S424.1).

A fecal sample was collected from the rectum of each cow at 0030, 0830, and 1630 h on the first and second days of the final week of the experiment (6 samples/cow) to represent a 24-h feeding cycle. Fecal samples were composited by period and analyzed for nutrient content as described to calculate apparent total-tract digestibilities using dietary $uNDF_{288}$ as an internal marker.

Ruminal pH

On the final day of the experiment, ruminal fluid (~3 mL) was sampled approximately 4 h after the morning feeding from the ventral sac via rumenocentesis, the technique developed by Nordlund and Garrett (1994). The pH of the ruminal fluid was immediately determined using a portable digital pH meter (HI 8318, Hanna Instruments, Cluj-Napoca, Romania).

Blood Sampling and Analyses

On d 3 of wk 3 of sampling, blood samples (7 mL) were collected 4 h after the morning feeding via the coccygeal vein using an evacuated tube without anticoagulant. Blood samples were placed on ice immediately after collection and centrifuged at 3,000 × *g* for 15 min at 4°C. Serum samples were separated and stored in plastic tubes frozen at −10°C until analysis. The concentrations of serum glucose (glucose oxidase-phenol 4-aminoantipyrine peroxidase method, kit no. 96004), cholesterol (cholesterol oxidase-phenol 4-aminoantipyrine peroxidase method, kit no. 96003), BUN (Berthelot method, kit no. 96003), total protein (Biuret method, kit no. 96004), albumin (bromocresol green method, kit no. 96003), aspartate aminotransferase (IFCC method, kit no. 96004), and alkaline phosphatase (DGKC method, kit no. 96004) were measured using an autoanalyzer (Abbott Alcyon 300, Abbott Laboratories, Chicago, IL) and commercial kits (Pars Azmoon Co., Tehran, Iran) according to the manufacturer's instructions. The analyzer was calibrated and controls were assayed daily according to the manufacturer's instructions to ensure acceptable assay performance. Serum BHB (kit no. 441054, Randox Laboratories Ltd., Ardmore, UK), nonesterified fatty acids (kit no. 427888, Randox Laboratories Ltd.), and total antioxidant capacity (kit no. NX2332, Randox Laboratories Ltd.) were determined by commercial colorimetric kits using the same autoanalyzer. The concentration of serum malondialdehyde was determined using the thiobarbituric acid reacting substances method, in which the absorbance of a colored complex that is formed from the reaction of malondialdehyde with 2-thiobarbituric acid in an acid environment is measured at 532 nm (Wullepit et al., 2012). Globulin concentrations were calculated by subtracting albumin concentrations from total protein.

Milk Yield and Components, BW, BCS, and Back Fat Thickness

Cows were milked 3 times daily at 0100, 0900, and 1700 h in a herringbone milking parlor. Milk yield for all cows was recorded and sampled at each milking during the final 5 d of each sampling week of the study. Milk samples were preserved with potassium dichromate, stored at 4°C, and submitted to the Isfahan University of Technology Central Milk Testing Laboratory (Isfahan, Iran) for fat, true protein, and lactose analyses using an infrared analyzer (MilkoScan 134 BN, Foss Electric, Hillerød, Denmark; AOAC International, 2006, method 972.16). The yields of 3.5% FCM and ECM were calculated according to the following NRC (2001) equations:

$$\text{FCM} = 0.432 \times \text{milk yield} + 16.23 \times \text{fat yield};$$

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

The MUN content was determined by enzymatic assay (Wilson et al., 1998). Milk was centrifuged at 1,200 × *g* for 15 min at 4°C, the fat was removed, and the defatted milk was thoroughly mixed and deproteinized by mixing 0.2 mL of defatted milk with 1.8 mL of cold 3% trichloracetic acid with a blender and allowing the mixture to stand for 5 min. The samples were then centrifuged at 1,200 × *g* for 5 min at 20°C, and 0.2 mL of the supernatant was analyzed for MUN using a colorimetric diacetyl monoxine procedure.

At the beginning (d 0) and end of the 6-wk experimental period, cows were weighed and BCS was determined using a 5-point scale where 1 = emaciated and 5 = obese (Ferguson et al., 1994). Also, at the beginning (d 5 of wk 1) and end of the 6-wk experimental period, back fat thickness was measured according to Schroder and Staufenbiel (2006) using a portable B-mode ultrasound generator (SonoVet 600V, BCF Technology Ltd., West Lothian, Scotland) with a linear transducer and frequency between 5.0 and 6.5 MHz. All the measurements at the beginning were considered as covariates for the measurement at the end of the experiment.

Statistical Analyses

Data were analyzed as a randomized complete block (group) design with covariate using the MIXED procedure of SAS (version 9.0, SAS Institute Inc., Cary, NC). The model included block, treatment, week, and interaction of treatment and week as fixed effects and cow within treatment as a random effect. The corresponding value of the dependent variable from the covariate period was considered as a covariate (when available). When week of treatment was included as a repeated measure, compound symmetry structure was used to account for autocorrelated errors. Five covariance structures were tested (compound symmetry, compound symmetry with heterogeneous variance, autoregressive order 1, autoregressive order 1 with heterogeneous variance, and antedependence 1) to select the structure with the lowest Akaike information criterion. For the variables without repeated measures during the study, week and its interaction with treatment were removed from the model. Means were determined using the least squares means statement, and treatment means were compared using the Bonferroni *t*-test option after a significant ($P \leq 0.05$) overall treatment *F*-test. Treatment differences were declared significant at $P \leq 0.05$, and tendencies were discussed at $0.05 < P < 0.10$.

RESULTS

Forages and Diets

The nutrient composition, in situ NDFD, and particle size distribution of the fiber sources are presented in Table 1. The $uNDF_{30}$ contents (% of DM) of the fiber sources were as follows : AH, 32.0; CS, 37.3; WS, 62.4; and BP, 7.7. The $NDFD_{30}$ contents (% of NDF) were 38.6, 30.9, 25.9, and 78.2, respectively. The concentration of $uNDF_{288}$ was not consistent with the ranking of the fiber sources for $uNDF_{30}$; it was greatest for AH (27.2% of DM) and WS (26.6% of DM), followed by CS (12.8% of DM) and then BP (2.8% of DM).

The finely chopped WS had a very small (1%) proportion of particles >19 mm; the greatest proportion (56%) of WS was retained on the 8-mm sieve, resulting in a GMPL of 6.70 mm. In contrast, a large portion of CS material was retained on the 19-mm (18.3%) and 8-mm (56.8%) sieves, resulting in a GMPL of 10.6 mm. Alfalfa hay had the lowest GMPL (4.12 mm), and most of the material was collected on the 1.18-mm (43.3%) and 8-mm (33.0%) sieves.

As planned, all diets had similar forage $uNDF_{30}$ (13.9% of DM) and forage NDF contents (~20% of DM; Table 3). The diet formulations also resulted in relatively similar dietary $uNDF_{30}$ (~17% of DM) and $NDFD_{30}$ (~44% of NDF) contents. The $uNDF_{288}$ was 9.4, 8.1, 10.8, and 8.9% of DM for CSAH, WSCS, WSAH, and WSCSAH, respectively, and ADL varied minimally from 1.8 to 2.2% of DM. The contents of pdNDF, starch, and NFC were marginally lower in WSAH than in other diets. The WSAH diet had the lowest proportion of particles that were >19 mm and 8 to 19 mm and the greatest proportion of particles that were 1.18 to 18 mm, whereas the other TMR were fairly similar in particle size distribution.

Intake, Milk Production, Feed Efficiency, and BW Change

Intake of DM was greater ($P < 0.01$) for WSCS (27.8 kg/d) than for CSAH (25.7 kg/d), WSCSAH (25.2 kg/d), and WSAH (24.2 kg/d; Table 4). Consequently, NDF intake was greatest for WSCS ($P = 0.02$), whereas the other diets had similar NDF intakes ($P > 0.10$). The DMI of all diets increased over the study (week effect, $P = 0.02$) as shown in Figure 1, with differences among diets detected starting at wk 4 of feeding. Milk, 3.5% FCM, ECM, and component yields did not differ among the treatments (Table 4). However, protein concentration ($P = 0.01$) was lower for WSAH than for CSAH and WSCS, with WSCSAH being similar to all diets. Milk yield decreased over the study (week effect, $P < 0.01$) without significant differences among diets (Figure 2). The MUN content was greater ($P < 0.01$) for WSAH (20.0 mg/dL) compared with the other diets (mean = 16.2 mg/dL). Efficiency of milk production (milk yield/DMI) and 3.5% FCM (3.5% FCM/DMI) were lowest for WSCS, intermediate for CSAH, and greatest for WSAH and WSCSAH ($P < 0.05$).

During the 6-wk experimental period, cows fed WSAH lost BW, whereas cows fed CSAH, WSCS, or WSCSAH gained BW ($P = 0.04$; Table 5). The BCS and back fat thickness were not affected by the dietary treatments ($P > 0.10$). Calculated energy balance was greater for WSCS (4.62 Mcal/d; $P < 0.01$) compared with the other treatments (CSAH = 2.11; WSAH = 0.24; WSCSAH = 1.07 Mcal/d).

Ruminal pH, Total-Tract Apparent Digestibility, and Blood Metabolites

Ruminal pH was greater ($P = 0.04$) for WSCS than for CSAH, and WSAH and WSCSAH were similar to the other treatments (Table 6). Total-tract apparent digestibly of DM, OM, ether extract, and NFC did not differ among treatments, but total-tract NDFD was greater ($P = 0.03$) for WSCS and WSAH compared with CSAH, with WSCSAH being similar to all diets.

Table 4. Lactation performance and feed efficiency of dairy cows fed diets with similar concentrations of undigested NDF after 30 h of incubation from different forage sources

	Diet[1]					*P*-value		
Item	CSAH	WSCS	WSAH	WSCSAH	SEM	Treatment	Week	Treatment × week
Intake, kg/d								
DM	25.7[b]	27.8[a]	24.2[b]	25.2[b]	0.76	0.01	0.02	0.88
NDF	7.61[b]	8.49[a]	7.56[b]	7.82[b]	0.24	0.02	0.04	0.92
Yield, kg/d								
Milk	49.3	50.0	48.8	49.9	1.24	0.91	<0.01	0.98
3.5% FCM[2]	44.5	45.8	43.9	44.8	1.34	0.78	<0.01	0.85
ECM[2]	44.5	45.6	44.0	44.7	1.26	0.75	<0.01	0.88
Fat	1.46	1.55	1.46	1.47	0.06	0.66	0.07	0.73
Protein	1.42	1.45	1.39	1.42	0.04	0.73	<0.01	0.98
Lactose	2.12	2.17	2.06	2.14	0.09	0.72	<0.01	0.53
Milk composition, %								
Fat	2.92	3.12	2.97	2.96	0.09	0.37	0.24	0.81
Protein	2.84[a]	2.83[a]	2.78[b]	2.81[ab]	0.01	0.01	<0.01	0.39
Lactose	4.51	4.53	4.44	4.52	0.07	0.74	0.54	0.37
Fat/protein	1.02	1.10	1.06	1.05	0.03	0.20	0.30	0.84
MUN, mg/dL	15.8[b]	15.8[b]	20.0[a]	17.0[b]	1.13	<0.01	—	—
Efficiency, kg/kg								
Milk yield/DMI	1.93[ab]	1.80[b]	2.03[a]	1.99[a]	0.05	0.02	<0.01	0.87
3.5% FCM/DMI	1.69[ab]	1.64[b]	1.83[a]	1.79[a]	0.05	0.04	<0.01	0.72

[a,b]Least squares means within a row with different superscripts differ significantly ($P \leq 0.05$).

[1]Experimental diets were combinations of different forage sources to achieve similar dietary concentrations of undigested NDF after 30 h of incubation. CSAH = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH.

[2]3.5% FCM (kg/d) = 0.432 × milk yield + 16.23 × fat yield; ECM (kg/d) = 12.82 × fat yield + 7.13 × protein yield + 0.323 × milk yield (NRC, 2001).

Concentrations of BUN, glucose, cholesterol, high-density lipoprotein, nonesterified fatty acids, BHB, total protein, albumin, aspartate aminotransferase, alkaline phosphatase, total antioxidant capacity, malondialdehyde, Na, K, and Cl in blood were unaffected by dietary treatment (Supplemental Table S1, https://doi.org/10.3168/jds.2019-16869).

DISCUSSION

Incorporation of WS into the diet of high-producing dairy cows has been the subject of various studies (Poore et al., 1991; Eastridge et al., 2009; Ghasemi, 2013; Wang et al., 2014). However, most of those studies did not consider forage NDFD and uNDF, and thus the diets compared varied in rumen availability of fiber and NE_L content. Substitution studies are difficult to design because adjustments made (in this case, incorporation of WS) can result in unintended changes in other important dietary characteristics. The present study addressed this issue by substituting WS for AH or CS in the diet of high-producing dairy cows on the basis of $uNDF_{30}$ and NDFD contents and balancing the diets to supply similar concentrations of CP and NE_L. When WS was incorporated in the diet as described, milk production was not affected. Interestingly, the combination of WS and CS (WS substituted for AH) increased feed intake, ruminal pH, NDFD, and energy balance of dairy cows compared with a diet with CS and AH. The results are important because in previous experiments the inclusion of WS in diets of high-producing dairy cows on the basis of dietary DM, NDF, or forage NDF generally decreased intake, digestibility, or milk production (Poore et al., 1991; Eastridge et al., 2009; Wang et al., 2014).

Although all diets supplied similar concentrations of forage $uNDF_{30}$ and $NDFD_{30,}$ DMI was influenced by the dietary treatments. A possible reason for greater DMI of WSCS compared with the other treatments is its lower concentration of dietary $uNDF_{288}$ (8.1 vs. 9.7% of DM; WSCS vs. the average of other treatments), which is negatively associated with feed intake (Harper and McNeill, 2015). Cotanch (2015) indicated that the amount of $uNDF_{240}$ (presumed to be similar to $uNDF_{288}$) consumed is a good indicator of ruminal fill and is inversely related to DMI. The difference in $uNDF_{288}$ content of diets containing CS and AH was attributed to the difference in the original $uNDF_{288}$ contents of the forages (12.8 vs. 27.1% of DM, respectively) even though they had similar NDF contents (54 vs. 52% of DM, respectively). The greater intake of diets containing CS versus AH is in agreement with Akbari-Afjani et al. (2014) and Lopes et al. (2015a), who reported greater DMI for cows consuming CS-based diets than

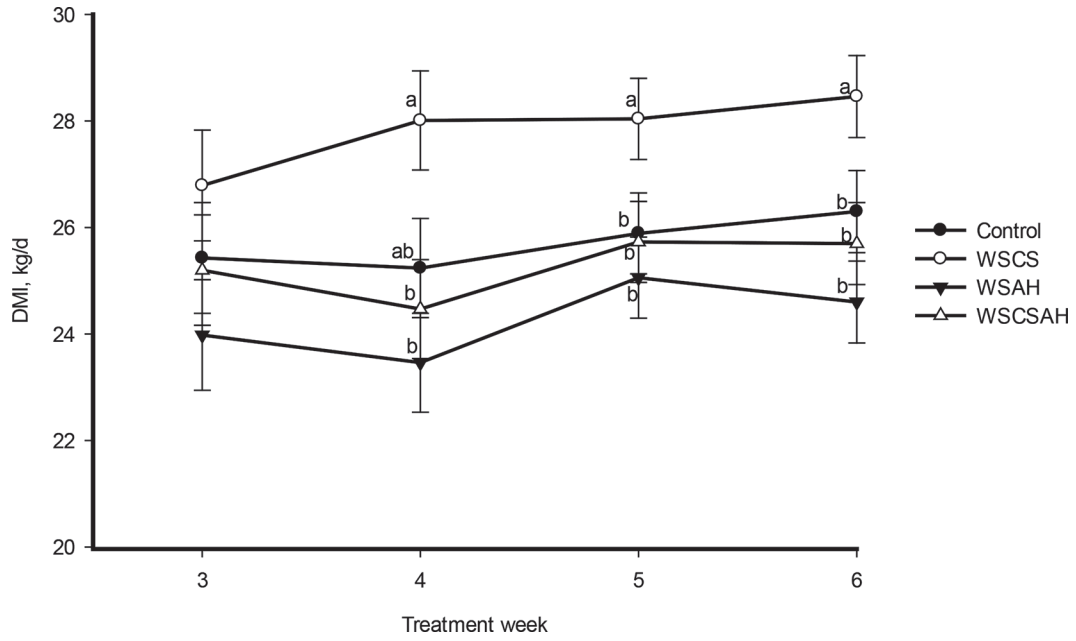

Figure 1. Least squares means of DMI by week for cows fed diets with similar concentrations of undigested NDF after 30 h of incubation ($uNDF_{30}$) from forage sources. Experimental diets were combinations of different forage sources to achieve similar dietary $uNDF_{30}$ concentrations (DM basis). Control = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH. For each treatment week, least squares means with different letters (a, b) differ significantly ($P \leq 0.05$). Error bars indicate SEM.

for cows consuming AH-based diets, but the results contrast with Onetti et al. (2002) and Brito et al. (2006), who observed greater intake of AH-based diets compared with CS-based diets. The discrepancy among studies might be due to the concentration of NDF and $uNDF_{288}$ in the original forages (Lopes et al., 2015a), which is mainly due to forage maturity (Akbari-Afjani et al., 2014). Therefore, formulating diets to account for $uNDF_{30}$ content of forage sources may have varying effects on DMI because $uNDF_{288}$ content may also vary. In addition, greater BP in the WSCS diet compared with the other diets could have contributed to greater DMI because BP has a high amount of pdNDF and greater rate of degradation of pdNDF as well as a high cation exchange capacity (McBurney et al., 1983). In the present study, treatment effects on DMI did not occur until wk 4, in agreement with Lopes et al. (2015a), indicating that the filling effect of NDF sources is delayed, which would not be perceived in short-term studies (i.e., 21-d Latin square designs).

Including WS in the diet increased ruminal pH regardless of all diets having similar forage NDF, forage $uNDF_{30}$, $uNDF_{30}$ and $NDFD_{30}$ concentrations, and particle size. It should be noted that a single measure of pH via rumenocentesis does not represent the diurnal fluctuations due to diet that may have occurred. However, Nasrollahi et al. (2017) reported that rumenocentesis and indwelling rumenoreticular probes produced consistent ranking of cows based on pH. Fustini et al. (2016) showed that inclusion of WS could promote rumination and elevate ruminal pH even in diets with low peNDF content. They suggested that straw, even with short particle size, promotes more chewing per kilogram of NDF compared with other forages. Furthermore, reconstituting chopped WS before feeding, as was done in the present study, might have decreased sorting activity (Teimouri Yansari et al., 2004) by enhancing adherence of straw particles to other feed particles, making it more difficult for cows to sort the TMR.

The improvement in ruminal pH due to WS may account for the greater total-tract NDFD of cows receiving diets containing WS. Cellulolytic bacteria in the rumen are sensitive to low rumen pH, and therefore decreasing rumen pH can affect fiber digestibility by diminishing the activity of these bacteria (Russell and Wilson, 1996). However, greater DMI and total-tract NDFD of WSCS compared with CSAH did not improve milk, FCM, or ECM production. In addition, milk production efficiency was decreased in cows fed WSCS as milk production was similar but feed consumption was greater in cows fed WSCS than in cows fed other dietary treatments. Lower milk production efficiency of cows fed WSCS might partly be explained by greater weight gain and energy balance of these cows indicating

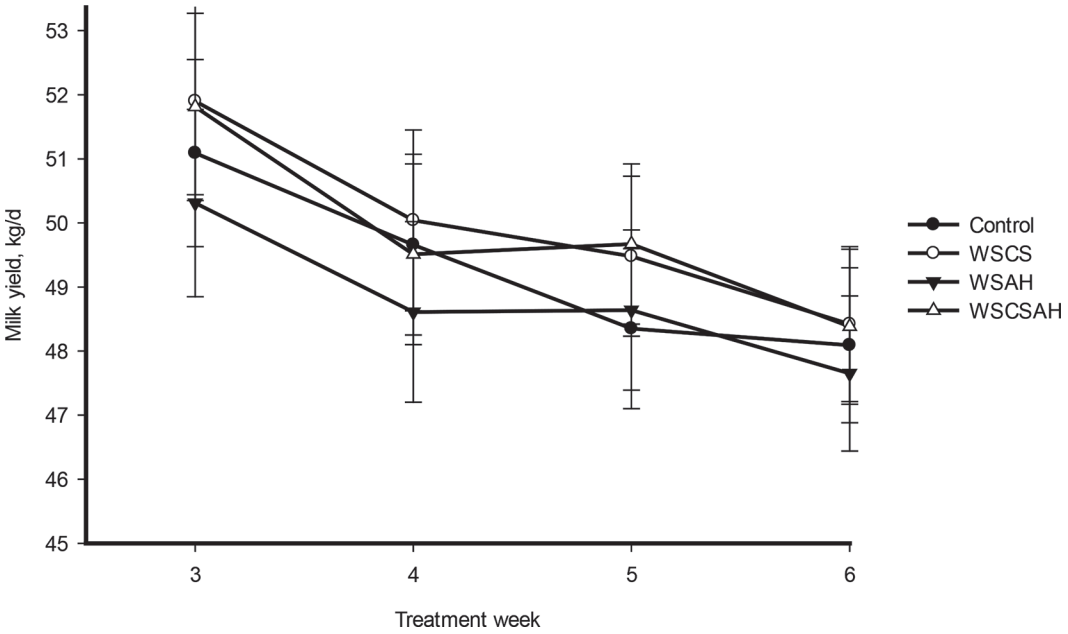

Figure 2. Least squares means of milk yield by week for cows fed diets with similar concentrations of undigested NDF after 30 h of incubation ($uNDF_{30}$) from forage sources. Experimental diets were combinations of different forage sources to achieve similar dietary $uNDF_{30}$ concentrations. Control = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH. Error bars indicate SEM.

a potential change in nutrient partitioning among the diets. The difference in BW gain might be related to gut filling due to greater DMI in WSCS. However, the considerably greater BW change gain and numerically greater back fat thickness of WSCS cows would suggest an improvement in energy status. Nasrollahi et al. (2012, 2014) reported a similar effect of feeding corn grain with a coarse particle size on increasing feed intake and BW gain without improving milk production. They proposed that a change in partitioning of nutrients to visceral metabolism and body fat accumulation accounted for the lack of response in milk production. The review by Reynolds (2006) indicates that digestion of starch in the small intestine and its absorption in the form of glucose trigger insulin secretion, causing nutrient partitioning to body reserve accumulation. The CS used in the present study contained unprocessed kernels, which may have led to greater postruminal digestion of starch and body gain compared with diets containing AH. The forage sources may have affected site of starch

Table 5. Body weight change, BCS, and back fat thickness of dairy cows fed diets with similar concentrations of undigested NDF after 30 h of incubation from different forage sources

	Diet[1]					
Item	CSAH	WSCS	WSAH	WSCSAH	SEM	*P*-value
BW change,[2] kg/period	8.76[a]	11.8[a]	−13.5[b]	2.88[ab]	6.74	0.04
BCS[3]	2.71	2.80	2.68	2.88	0.11	0.38
Back fat thickness[4]	26.6	30.3	28.11	29.8	1.39	0.10
NE balance,[5] Mcal/d	2.11[b]	4.62[a]	0.24[b]	1.07[b]	1.09	<0.01

[a,b]Least squares means within a row with different superscripts differ significantly ($P \leq 0.05$).

[1]Experimental diets were combinations of different forage sources to achieve similar dietary concentrations of undigested NDF after 30 h of incubation. CSAH = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH.

[2]Over a 6-wk period from wk 1 of adaptation to wk 4 of sampling.

[3]Determined using a 5-point scale where 1 = emaciated and 5 = obese (Ferguson et al., 1994).

[4]Measured using ultrasonographic method (Schröder and Staufenbiel, 2006).

[5]NE balance = (energy intake, Mcal of NE_L) − [(maintenance energy, Mcal of NE_L) + (milk energy, Mcal of NE_L)] (NRC, 2001).

Table 6. Rumen pH and total-tract apparent digestibility in dairy cows fed diets with similar concentration of undigested NDF after 30 h of incubation from different forage sources

	Diet[1]					
Item	CSAH	WSCS	WSAH	WSCSAH	SEM	*P*-value
pH	5.74[b]	6.29[a]	6.08[ab]	6.03[ab]	0.12	0.04
Digestibility, %						
DM	65.5	69.4	67.9	67.7	1.66	0.25
OM	68.8	72.4	70.9	70.7	1.56	0.28
NDF	38.9[b]	49.4[a]	46.6[a]	43.8[ab]	3.05	0.03
CP	66.6	68.6	71.0	70.1	1.36	0.13
Ether extract	82.3	85.7	84.3	86.3	1.28	0.13
NFC	89.8	89.9	89.7	89.9	0.81	0.99

[a,b]Least squares means within a row with different superscripts differ significantly ($P \leq 0.05$).

[1]Experimental diets were combinations of different forage sources to achieve similar dietary concentrations of undigested NDF after 30 h of incubation. CSAH = 0% wheat straw (WS), 59% corn silage (CS), and 41% alfalfa hay (AH); WSCS = 40% WS, 59% CS, and 1% AH; WSAH = 40% WS, 41% AH, and 19% CS; WSCSAH = 40% WS, 39% CS, and 21% AH.

digestion and thereby lactation efficiency, which is a factor that should be considered when balancing diets for uNDF and NDFD concentrations.

The lower milk protein concentration of cows fed WSAH corresponded to increased MUN concentration. Milk protein secretion in dairy cows is closely associated with the supply of MP (NRC, 2001), especially microbial protein synthesis (Zhu et al., 2013). Incorporation of WS in dairy cow diets has previously been shown to increase MUN concentration (Farmer et al., 2014; Wang et al., 2014) and decrease milk protein production (Ghasemi, 2013; Wang et al., 2014), although this relationship has not been observed in all studies (Poore et al., 1991; Eastridge et al., 2009). Wang et al. (2014) proposed that feeding WS instead of conventional forages might decrease fermentable carbohydrate concentration of diets and therefore diminish available carbohydrates for ruminal microbial synthesis. Other studies showed that elevating NFC or starch content of diets containing WS prevented a decrease in MUN and milk protein production (Eastridge et al., 2009) or actually increased milk protein content (Poore et al., 1991). The numerically lower NFC and starch contents and presumably lower pectin content (due to less BP) in the WSAH diet compared with the other WS-containing diets could have reduced the carbohydrate available for fermentation to capture N in the rumen. The relatively mature AH used in the current study may also have contributed to the decrease in protein content of milk. Therefore, fermentable carbohydrate fractions that are important energy sources for microbial protein synthesis and milk protein production need to be considered when adjusting diets for uNDF and NDFD contents.

Finally, it should be said that some marginal modification of the ingredient composition other than forages was required to make the treatment diets in the present study isocaloric and isonitrogenous while balancing for forage $uNDF_{30}$. Although these modifications were relatively small, the potential for unintended consequences needs to be considered when reviewing the results of the present study.

CONCLUSIONS

Inclusion of WS in isocaloric and isonitrogenous dairy cow diets when substituted for either AH or CS based on NDFD characteristics ($uNDF_{30}$) resulted in similar milk production. However, a combination of WS and CS (WSCS diet) improved feed intake, ruminal pH, total-tract NDFD, and energy balance of dairy cows but reduced the efficiency of milk production. Thus, adding straw to diets containing CS can help improve ruminal function of high-producing dairy cows but may decrease feed efficiency. We conclude that a $uNDF_{30}$-based inclusion of WS in dairy cow diets can sustain lactation performance, and combination with CS rather than AH is recommended.

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