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Fibrous coproducts of corn and citrus as forage and concentrate sources for dairy cows

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ABSTRACT

This study evaluated the effect on dairy cows of the partial replacement of whole plant corn silage (WPCS) with corn ear fibrous coproduct (CEFC) in diets with concentrate coproducts from citrus and corn on dry matter intake (DMI), lactation performance, digestibility, and chewing behavior. Holstein dairy cows (n = 20) in 5, 4 × 4 Latin squares (21-d periods) were fed a combination of strategies for feeding fibrous coproducts in a 2 × 2 factorial arrangement of the following treatments: (1) forage feeds: the partial replacement of WPCS (CS) with CEFC (CO), and (2) concentrate feeds: the partial replacement of wet corn gluten feed (GF) with a blend of pelleted citrus and corn distillers dried grains (CD) to have isonitrogenous diets. The concentrations of physically effective neutral detergent fiber (NDF; ${}_{pe}NDF_{>8}$) were (% of dry matter): 21.8% for CS, 19.2% for CO, 20.7% for GF, and 20.2% for CD. Cows fed diet CS-CD had the highest yield of energy-corrected milk (30.0 kg/d) relative to the other diets (28.4 kg/d). Milk fat concentration was reduced on CO relative to CS. Cows fed the CO diets had higher DMI (21.2 vs. 20.2 kg/d) and digestible organic matter intake and tended to have a lower ratio of energy-corrected milk to DMI than cows fed CS. Diets CO reduced the daily intake of ${}_{pe}NDF_{>8}$ and the intake as percent of body weight of ${}_{pe}NDF_{>8}$, forage NDF, and total NDF relative to CS. Cows fed CO had greater meal frequency and lower daily meal time, meal duration, meal size, and duration of the largest meal than cows fed CS. The CO diet reduced rumination and total chewing in minutes per day and minutes per kilogram of DMI. When expressed per unit of ${}_{pe}NDF_{>8}$ intake, rumination and total chewing were not affected by forage source. The total-tract starch digestibility coefficient was lower for cows fed CO than CS, but the intake of digestible starch was higher on CO than CS. Cows fed GF had reduced milk yield (29.6 vs. 30.8 kg/d), tended to have reduced DMI (20.4 vs. 21.0 kg/d), and had reduced digestible organic matter intake than cows fed CD. Feed efficiency was not affected by source of concentrate. The type of concentrate did not affect the intake of forage NDF and ${}_{pe}NDF_{>8}$, but cows fed GF had higher intake of total NDF as percent of body weight than cows fed CD. The GF increased meal frequency and reduced meal size and largest meal duration and size. Cows fed GF had higher rumination and total chewing than cows fed CD (min/d, min/kg of DMI, and min/kg ${}_{pe}NDF_{>8}$). Starch digestibility was higher and the intake of digestible starch tended to be higher on cows fed GF than CD. Plasma urea-N was higher, milk urea-N tended to be higher, and N utilization efficiency tended to be lower on cows fed GF than CD. Ruminal microbial yield was not affected by any treatment. All strategies evaluated were nutritionally viable and CEFC was a feasible partial replacement for WPCS.

Key words: digestibility, eating behavior, effective fiber, intake, rumination

INTRODUCTION

The corn and citrus industries generate large amounts of coproducts in their production of human food and ethanol. The feeding of dairy cows with fibrous coproducts from corn and citrus are effective ways of providing fiber to ruminants. Fibrous coproducts may be viable options for supplying of forages or concentrates in the diet of lactating dairy cows (Armentano and Pereira, 1997). However, such feedstuffs vary greatly in the concentration and nature of protein and carbohydrates (Van Soest, 1994). The potential replacement of common forages and concentrates with fibrous coproducts, given their relative nutritive and economic values, can offer a way to maximize profit per cow, but the feeding

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strategy adopted may negatively affect feed DMI, diet digestibility, and lactation performance.

The effect of high-fiber concentrate coproducts on dairy cow intake, diet digestibility, and performance is dependent on the coproduct fed and diet composition. Relative to alfafa silage, a blend of high-fiber cereal coproducts from corn, wheat, and barley increased milk fat concentration and DMI when replacing starchy concentrates in a low forage diet, although they had no stimulatory effect on rumination (Pereira et al., 1999). Most nonforage fiber sources do not stimulate chewing as effectively as long forage (Grant, 1997). The NDF in the pericarp of cereals, such as corn, wheat, and barley, had total-tract digestibility similar to the NDF in diets formulated with silages of whole plant corn and alfalfa, but did not increase the ruminal acetate-to-propionate ratio (Pereira and Armentano, 2000). Citrus pulp is rich in highly digestible NDF, pectin, and sucrose (Miron et al., 2002) and may reduce ruminal microbial yield (Dusková and Marounek, 2001; Hall and Herejk, 2001) and DMI (Leiva et al., 2000; Broderick et al., 2002; Salvador et al., 2008) relative to starchy grain. The replacement of forages, corn grain, and protein concentrates with corn gluten feed (**CGF**) increased lactation performance and intake, as demonstrated in a recent meta-analysis (Darabighane et al., 2020). However, the response lacks consistency, likely as a result of variation in the concentration of the coproduct in the diet and type of forage in the basal diet (Gunderson et al., 1988; Allen and Grant, 2000; Sullivan et al., 2012). The type of concentrate coproduct may affect how the replacement of whole plant corn silage (**WPCS**) with long fiber coproduct sources affects dairy cows.

Coproducts from the vegetative fraction of mature corn may be viable sources of physically effective NDF (Zebeli et al., 2012) in replacement of traditional forages, potentially increasing milk yield per unit of forage produced on the farm or the efficiency of corn production for grain or ethanol. The complete replacement of alfalfa haylage with alkali-treated corn stover reduced DMI but did not affect the yields of milk and components (Casperson et al., 2018). Jami et al. (2014) observed an improvement in the concentration of fat and protein and in the yield of ECM of cows fed corn stover in replacement of wheat hay. This occurred despite reduced DMI, suggesting a favorable effect of corn stover on nutrient usage and feed efficiency. However, the low digestibility of the NDF in the vegetative fraction of cereal coproducts is a frequent concern when feeding high-producing dairy cows (Paterson et al., 1981; Zhang et al., 2021). Petzel et al. (2019) observed that the total-tract digestibility of corn leaves and husks were higher than the digestibility of stalks. In other studies, corn husks had higher in vitro digestibility than leaves and stalks (Stalker et al., 2015; Watson et al., 2015). There is possibility of increasing the nutritive value of corn stover coproducts by reducing the proportion of stalks by mechanical separation during and after harvesting. A novel corn ear fibrous coproduct (**CEFC**; WF Comidão; Cargill Agricola) has been developed by anaerobic storage of husks, cobs, wet CGF, and residual kernels from corn cultivated for seed production combined with high-protein *Aspergillus niger* biomass and steep liquor. There is no literature evaluating the replacement of forage with this coproduct in the diet of dairy cows.

The objective of this experiment was to evaluate the effect of 4 strategies of feeding fibrous coproducts to lactating dairy cows on lactation performance, intake, diet digestibility, and chewing behavior. Diets were formulated by the combination of 2 feeding strategies in a 2 × 2 factorial arrangement of treatments. Strategies included the partial replacement of WPCS by CEFC in forage feeds, and the partial replacement of wet CGF concentrate feed by a blend of pelleted citrus pulp and corn distillers dried grains (**DDG**). The goal was to provide diets in which CGF and CEFC each provided around 20 and 5% of DM and to have a 50% replacement of WPCS by CEFC, at similar concentrations in the diet of ensiled corn grain, whole cottonseeds, and soybean meal. Our hypothesis was that the partial replacement of DM from WPCS with CEFC is a feasible nutritional strategy for improving performance and chewing behavior of dairy cows, due to the increase in DMI and diet digestibility with lower concentration of mature forage NDF in the diet, independently of concentrate coproduct profile.

MATERIALS AND METHODS

Experimental procedures were approved by the University of Lavras Bioethic Committee in Utilization of Animals (Protocol number 070/19).

Cows and Treatments

The experiment was conducted from December 2019 to March 2020, during the hot-rainy season of southeast Brazil. Twenty Holstein cows (143 ± 51 DIM, 34.0 ± 3.7 kg of milk/d, and 596 ± 79 kg of BW at the start of the experiment, 8 primiparous cows, 6 cows in second lactation, and 6 cows with ≥3 lactations) were individually fed in an open-walled, sand-bedded tiestall barn with fans and high-pressure sprinklers and milked 3 times per day starting at 0500, 1300, and 2000 h in an adjacent herringbone parlor. Cows were blocked into 5 squares of 4 animals based primarily on parity (1 vs. >1) and then milk yield and DIM.

Within a square, cows were randomly allocated to a sequence of 4 treatments using a 4 × 4 Latin square design, with 21-d periods, including 14 d of adaptation to treatments, and balanced for carryover effects by assigning a treatment in sequence to the other 3 treatments the same number of times within a square (Williams, 1949). Treatments were a 2 × 2 factorial arrangement of dietary forage source and concentrate source (Table 1). Forage sources were substituted on an iso-DM basis: WPCS on treatment whole plant corn silage (**CS**) versus CEFC on treatment corn ear fibrous coproduct (**CO**). Concentrate sources were substituted on an iso-N basis: wet CGF (GoldenMill; Cargill Agrícola) on treatment wet corn gluten feed (**GF**) versus DDG with yeast fermentation coproduct (FlexyPro; SJC Bioenergia) plus pelleted citrus pulp on treatment citrus pulp plus corn DDG (**CD**). Limestone was used on the GF diets to adjust for the Ca concentration in citrus pulp. The concentrations of ensiled corn grain and whole cottonseeds were kept constant in all diets. The TMR for each treatment group was mixed once per day in a 1.2 m^3 stationary vertical mixer (Unimix 1200; Casale) after weighing each feed with a precision scale (MOD B-520; Líder Balanças) and cows were fed at 0700 h. Feed was pushed-up manually with a broom at least 10 times per day. The daily feed refusal per cow, on an as-fed basis, was 18.4 ± 7.1% of offered (mean ± SD) and was excessive with the purpose of evaluating sorting behavior. Samples of WPCS, CEFC, CGF, and ensiled corn grain were collected weekly for DM determination with a microwave oven (by drying for 5 min and then in 3 min steps until a stable weight was obtained) and the TMR was adjusted accordingly.

Feeds

Silages of wet feeds were prepared 32 d before the beginning of the 84-d experimental period for CGF and 21 d before the experiment for CEFC by Cargill Agricola. The CGF and CEFC were stored outdoors in

Table 1. Ingredient composition of the offered diets and nutrient composition of the consumed diets (offered − orts)[1]

Item	CS		CO	
	GF	CD	GF	CD
Ingredient (% of DM)				
Whole plant corn silage	34.9	34.2	21.6	21.1
Corn ear fibrous coproduct	4.7	4.6	19.0	18.5
Wet corn gluten feed	19.5	4.6	19.6	4.6
Corn distillers dried grains with yeast		6.3		3.6
Citrus pulp pellets		10.7		12.4
Soybean meal	9.6	9.4	9.3	9.5
Ensiled corn grain	15.2	14.9	15.3	14.9
Whole cottonseeds	10.9	10.7	11.0	10.7
Limestone	0.5		0.5	
Premix[2]	4.7	4.6	4.7	4.7
Nutrient (% of DM)				
CP	17.5	17.2	17.4	17.2
Corn gluten feed CP	5.0	1.2	5.0	1.2
Citrus pulp + DDG CP		3.8		3.7
NDF	35.4	32.8	32.7	29.8
Forage NDF (corn silage + ear coproduct)	19.9	19.5	17.1	16.7
Corn silage NDF	17.6	17.4	10.9	10.7
Corn gluten feed NDF	7.3	1.7	7.4	1.7
Ether extract	4.5	5.0	4.5	4.8
Ash	7.1	6.5	7.2	6.7
NFC[3]	35.5	38.5	38.2	41.5
Starch	22.3	21.0	23.5	22.0
Corn silage starch	7.0	6.9	4.4	4.2
Nonstarch NFC[4]	13.2	17.5	14.7	19.5
DM (% of as-fed)	42.5	46.2	46.3	50.6

[1]CS = whole plant corn silage, CO = corn ear fibrous coproduct, GF = wet corn gluten feed, CD = citrus pulp plus corn distillers dried grains.

[2]Premix: 19% limestone, 23% sodium bicarbonate, 5% magnesium oxide, 5% NaCl, 1% Azomite, 2% autolyzed yeast, 30% hydrogenated fat (100% stearic acid, Cargill Agrícola SA), and 15% minerals and vitamins (23.6% Ca, 16.9% P, 1.9% Mg, 2.2% S, 92 mg/kg Co, 1,231 mg/kg Cu, 3,077 mg/kg Mn, 7,323 mg/kg Zn, 50 mg/kg Se, 123 mg/kg I, 615,385 IU/kg vitamin A, 135,385 IU/kg vitamin D; 3,815 IU/kg vitamin E).

[3]NFC = 100 − (CP + NDF + ether extract + ash).

[4]Nonstarch NFC = NFC − starch.

bales of approximately 1,000 and 850 kg, respectively. The bales were packed and wrapped with layers of stretch plastic film with an Orkel MP2000-X compactor. The wrapping of bales was done internally with transparent film of 1,320 mm × 23 μm and 21.1 g/m^2 and externally with UV protected white film of 750 mm × 30 μm and 27.5 g/m^2 (Lusitano Ind e Com de Embalagens Plásticas). The utilization of each bale in the farm lasted 7 d for CGF and 4 d for CEFC. The density of the bales were approximately 949 kg/m^3 for CGF and 807 kg/m^3 for CEFC.

During wk 3 of period 4, 4 samples of wet CGF were obtained from feed unloaded on d 1, 4, and 7 of bale utilization (d 1 = 110 d of storage) and CEFC was sampled on d 1 and 4 of utilization (d 1 = 99 d of storage) to evaluate silage microbiota and pH (Table 2). Samples were immediately refrigerated and transported to the laboratory within 3 h of sampling. Sequential 10-fold dilutions (10^{-1} − 10^{-6}) with peptonized water and aqueous extracts were prepared. Filamentous fungi and yeast growth were evaluated in Dichloran Rose Bengal agar Chloramphenicol (Kasvi) incubated at 28°C for 168 and 72 h, respectively. For enumeration of spore forming bacteria the aqueous extract was maintained at 90°C for 10 min, and further decimal dilutions were evaluated in plate count agar medium (HiMedia Laboratories). Plates were incubated at 30°C for 24 h. Counts of colony-forming unit were performed by visual observation of each plate and data were $\log_{10}$ transformed for reporting.

Daily samples of feed ingredients and orts per cow were collected from d 15 to 21 of each experimental period and composite samples were formed per period. Samples were dried in a forced-air oven at 55°C for 72 h and ground to pass a 1-mm screen (Wiley mill, Thomas Scientific). The DM concentration was determined at 105°C for 24 h and ash was evaluated at 550°C for 8 h. Samples of feed ingredients were sent to a commercial laboratory (3rLab/Rock River Laboratories) for determination of CP with a micro Kjeldhal steam distillator (method 990.03; AOAC International, 2006), NDF by filter bag (nonwoven textile; 100 g/m^2) technique with heat-stable α-amylase and without sodium sulfite (ANKOM Technology; Schlau et al., 2021), ether extract (method 2003.05; AOAC International, 2006), and starch plus free glucose with α-amylase and amyloglucosidase and colorimetry for glucose as described in Fernandes et al. (2022), adapted from Hall et al. (2015). Data from feed analyses were used to calculate the concentrations of NFC (100 − CP − NDF − ether extract − ash) and nonstarch NFC (**NSNFC**) in feeds and diets. The nutrient composition of feeds used during the experiment is reported in Table 3.

The particle size distributions of WPCS and CEFC were evaluated with the Penn State Particle Separator (**PSPS**) with the 19- and 8-mm diameter screens and pan (Lammers et al., 1996; Table 4). Composite samples from each screen of the PSPS were produced each period and their DM and NDF concentrations were determined. The concentration in the diet of physically effective NDF ($_{\mathbf{pe}}\mathbf{NDF}_{\mathbf{>8}}$) was calculated from individual feed analysis and diet ingredient composition, assuming that only WPCS, CEFC, and whole cottonseeds contribute to NDF greater than 8 mm (Table 5). Visual evaluation of the retained material on each PSPS fraction detected that citrus pulp pellets and whole cottonseeds were totally retained on the middle screen (8 mm) of PSPS.

Performance and Intake

The mean milk yield and DMI of d 15 to 21 of each experimental period were used to compare treatments. On d 17 to 21 of each period, milk samples were obtained in proportion to the yield on each milking and duplicate daily composites were formed and analyzed per cow. Samples were stored in flasks containing 2-bromo-2-nitropropane-1–3 diol under refrigeration until shipment to a commercial laboratory (Laboratory of the Paraná State Holstein Breeders Association, Curitiba, Brazil). Milk CP, fat, lactose, TS, SCC, and MUN were analyzed by mid-infrared analysis (Nexgen FTS/

Table 2. Yeast, spore forming aerobic bacteria, filamentous fungi, and pH of 4 samples of corn ear fibrous coproduct and wet corn gluten feed during the feed-out period

	Corn ear fibrous coproduct		Wet corn gluten feed		
Item	d 1[1]	d 4	d 1[2]	d 4	d 7
Yeast ($\log_{10}$ cfu/g)	2.26 ± 1.70	<2.00	5.00 ± 1.83	6.05 ± 0.67	6.46 ± 0.35
Spore forming aerobic bacteria ($\log_{10}$ cfu/g)	4.58 ± 1.03	4.51 ± 0.43	4.48 ± 0.43	3.78 ± 0.59	4.03 ± 0.12
Filamentous fungi ($\log_{10}$ cfu/g)	2.26 ± 0.41	2.25 ± 0.41	ND[3]	ND	ND
pH	4.15 ± 0.04	4.18 ± 0.06	3.94 ± 0.18	3.97 ± 0.18	3.99 ± 0.16

[1]99 d of duration of storage.

[2]110 d of duration of storage.

[3]ND = not detected.

Table 3. Composition of feed ingredients; mean ± SD of 4 composite samples from each experimental period

Item	DM, % of as fed	CP, % of DM	EE,[1] % of DM	NDF, % of DM	Ash, % of DM	NFC,[2] % of DM	Starch, % of DM	Nonstarch NFC, % of DM
Whole plant corn silage	27.2 ± 1.8	8.6 ± 0.2	2.9 ± 0.1	53.0 ± 1.9	5.0 ± 0.9	30.5 ± 2.8	21.1 ± 2.4	9.5 ± 1.8
Corn ear fibrous coproduct	46.3 ± 2.0	15.8 ± 0.7	2.7 ± 0.3	29.8 ± 1.7	5.6 ± 0.3	46.3 ± 1.7	27.2 ± 2.3	19.1 ± 0.6
Wet corn gluten feed	51.1 ± 0.9	25.5 ± 0.9	1.3 ± 0.2	37.9 ± 4.2	5.5 ± 0.8	29.9 ± 3.0	13.5 ± 0.6	16.4 ± 3.6
Corn distillers dried grains	89.4 ± 0.5	47.0 ± 0.7	7.9 ± 0.1	22.9 ± 0.3	3.4 ± 0.1	18.9 ± 0.6	6.1 ± 0.5	12.8 ± 1.1
Citrus pulp pellets	88.2 ± 0.4	8.0 ± 0.5	1.9 ± 0.1	20.0 ± 0.4	5.6 ± 0.2	64.6 ± 0.9	7.3 ± 0.6	57.3 ± 1.0
Soybean meal	88.1 ± 0.6	51.0 ± 0.4	1.9 ± 0.1	11.7 ± 1.0	6.5 ± 0.2	29.0 ± 1.2	0.8 ± 0.2	28.2 ± 1.1
Ensiled corn grain	59.5 ± 0.9	9.0 ± 0.6	4.2 ± 0.1	6.3 ± 0.7	1.5 ± 0.2	79.0 ± 1.2	71.5 ± 1.4	7.5 ± 0.6
Whole cottonseeds	92.0 ± 0.3	19.8 ± 0.8	14.8 ± 0.5	56.3 ± 1.4	4.0 ± 0.2	5.1 ± 0.7	0.3 ± 0.3	4.8 ± 0.8

[1]EE = ether extract.

[2]NFC = 100 − (CP + NDF + EE + ash).

FCM; Bentley Instruments Inc.). Milk energy secretion (Mcal/d) was calculated (NRC, 2001): [(0.0929 × % fat) + (0.0547 × % protein) + (0.0395 × % lactose)] × kg of milk. The secretion of ECM (kg/d) was calculated as milk energy secretion/0.70 (assumes 0.70 Mcal/kg of milk with 3.7% fat, 3.2% protein, and 4.6% lactose). The 4% FCM (kg/d) was calculated (Overman and Gaines, 1933): 0.4 × kg of milk + 15 × kg of fat. The feed efficiencies were calculated as milk yield/DMI, 4% FCM/DMI, and ECM/DMI. The efficiency of N utilization (**NUE**) was calculated as milk N secretion (milk CP/6.38) as a proportion of N intake. Cow BW was measured on d 20 and 21 of each experimental period, immediately after the morning milking and BCS (1–5; Wildman et al., 1982) was the mean of 3 independent evaluators on d 21.

Total-Tract Digestibility, Ruminal Microbial Yield, and Plasma Urea-N

On d 19 to 21 of each experimental period, fecal and urinary excretions were manually collected in three 8-h collection periods, with 8-h intervals, and starting 8 h later on each consecutive day, to represent a 24-h collection. Feces and urine were collected in buckets; for every 2 cows, 1 researcher stood behind them for 8 h and collected any fecal and urine excretion into the bucket. Fecal samples were immediately weighed and subsamples (1% of defecation) were frozen throughout the collection period to provide a composite per cow per period. The sample was dried at 55°C for 72 h. The concentrations of DM, NDF, ash, and starch were measured, as previously described for feed analysis. The total-tract apparent digestibilities of DM, OM, NDF, starch, and the non-NDF OM were calculated. Digestible OM intake (**DOMI**) was estimated (OM intake × OM digestibility) and the ECM/DOMI ratio was calculated as a measure of digestible energy efficiency. Urine composite samples were formed by collecting 3% of urination volume kept under refrigeration throughout the collection period. Period composites from each cow were mixed with 4% sulfuric acid solution (5 mL of urine and 20 mL of acid) and frozen for allantoin determination. The daily excretion of allantoin was determined in urine and used as a relative measure of ruminal microbial yield (Valadares et al., 1999; Pereira et al., 2021). Allantoin was analyzed according to Chen and Gomes (1992). The relative efficiency of ruminal microbial growth was estimated as allantoin/DOMI (mmol/kg).

Blood samples (4/cow) were collected from the coccygeal vessels at 0 and 2 h relative to the first eating

Table 4. Whole plant corn silage (WPCS) and corn ear fibrous coproduct (CEFC) particle size and NDF distributions and concentrations of DM and NDF on fractions of the Penn State Particle Separator

Item	WPCS	CEFC
Particle size distribution[1] (% of as-fed)		
>19 mm	24.9 ± 7.36	33.1 ± 7.95
8–19 mm	59.8 ± 13.74	42.2 ± 9.18
<8 mm	15.3 ± 3.94	24.7 ± 6.63
Particle size distribution[1] (% of DM)		
>19 mm	24.0 ± 5.93	29.9 ± 3.96
8–19 mm	58.7 ± 8.69	42.2 ± 4.20
<8 mm	17.3 ± 3.77	25.9 ± 4.29
NDF distribution[2] (% of DM)		
>19 mm	15.5 ± 3.23	11.0 ± 0.88
8–19 mm	26.7 ± 3.65	9.9 ± 1.21
<8 mm	7.5 ± 1.85	5.5 ± 2.58
DM of fraction retained[1] (% of as-fed)		
>19 mm	26.1 ± 2.18	42.6 ± 2.79
8–19 mm	26.8 ± 2.69	49.4 ± 2.22
<8 mm	30.5 ± 1.73	49.4 ± 2.05
NDF of fraction retained[2] (% of DM)		
>19 mm	64.9 ± 1.32	37.0 ± 3.58
8–19 mm	46.0 ± 6.63	22.4 ± 0.95
<8 mm	40.3 ± 4.64	16.2 ± 1.27

[1]Mean ± SD of 12 samples of each ingredient obtained throughout the experiment.

[2]Mean ± SD of 4 composite samples from periods.

after the morning and afternoon milkings on d 18 of each experimental period. Samples were collected in tubes with EDTA and were centrifuged at 2,000 × *g* for 10 min at room temperature. Plasma was obtained and frozen at −20°C for urea-N determination (**PUN**) with a commercial kit (Urea Enzimática; Bioclin).

Chewing Behavior

During d 15 to 17 of each treatment period, rumination and eating behaviors were monitored by visual observation at 5-min intervals continuously for 24 h each day as in Pereira et al. (1999). Buccal activities were rumination, eating, drinking, and idleness. Individual feeding observations were combined and separated into meals using a meal criterion (i.e., the minimum duration of time between meals) calculated for each cow. Meal criteria were calculated for each cow using methods described by DeVries et al. (2003); in summary, a software package (MIX 3.1.3; MacDonald and Green, 1988) was used to fit normal distributions to the frequency of $\log_{10}$-transformed intervals of time between recorded eating observations. If the interval of time between 2 recorded observations of eating exceeded the determined meal criterion, this was classified as a different meal. The number of different meals in a day was termed meal frequency (meals/d). Total meal time (min/d) was the total eating time (eating observations/d × 5 min), plus all the nonfeeding intervals shorter than the length of the meal criterion of each cow. Meal duration (min/meal) was calculated as the total daily meal time divided by the meal frequency. Finally, meal size was the ratio between daily DMI (kg/d) and meals per day. The duration and time postfeeding of the longest daily meal was calculated. The duration of the first daily meal was measured with a stopwatch. Five evaluators observed the behavior of all cows, individually, after offering feed at 0700 h until the last cow finished its first meal.

Particle size sorting behavior during the day was evaluated on d 15 to 17 of each experimental period with the PSPS with the 19- and 8-mm diameter screens and pan. The particle distribution and weight of the offered TMR and available orts of each cow was measured at 0700 (at feeding immediately after morning milking), 1200, 1900, and 0500 h (during morning milking). The predicted intake (as-fed basis) of particles on each screen was: % TMR retained on screen × kg of TMR consumed. The observed intake of particles was: % TMR retained on screen × kg of TMR offered − % orts retained on screen × kg of orts. The selection index (Leonardi and Armentano, 2003) was: 100 × (observed intake/predicted intake). Sorting values below 100% represent selective refusal, above 100% represent prefer-

Table 5. Particle size, NDF, and physically effective NDF ($_{pe}NDF_{>8}$) of the offered diets[1]

Item	CS		CO	
	GF	CD	GF	CD
Particle distribution[2] (% of as-fed)				
>19 mm	13.7 ± 3.77	16.8 ± 4.93	15.4 ± 3.60	18.3 ± 4.20
8–19 mm	49.8 ± 4.71	45.3 ± 4.85	47.7 ± 2.96	42.2 ± 3.53
<8 mm	36.5 ± 3.03	37.9 ± 2.96	36.9 ± 2.52	39.5 ± 2.56
Particle distribution[3] (% of DM)				
>19 mm	9.8 ± 1.60	9.6 ± 1.56	10.9 ± 1.29	10.7 ± 1.26
8–19 mm	33.7 ± 3.40	33.0 ± 3.33	32.3 ± 2.17	31.6 ± 2.13
<8 mm	56.5 ± 1.97	57.4 ± 1.89	56.8 ± 0.96	57.7 ± 0.92
NDF distribution[3] (% of DM)				
>19 mm	5.9 ± 0.88	5.8 ± 0.86	5.5 ± 0.53	5.3 ± 0.51
8–19 mm	16.0 ± 1.11	15.7 ± 1.09	13.9 ± 0.73	13.6 ± 3.60
<8 mm	13.5 ± 1.33	11.3 ± 0.81	13.3 ± 1.12	10.9 ± 2.22
$_{pe}NDF_{>8\ mm}$[4] (% of DM)	22.0 ± 1.27	21.5 ± 1.22	19.4 ± 0.69	19.0 ± 0.67
DM of fraction retained[3] (% of as-fed)				
>19 mm	27.7 ± 1.69	27.7 ± 1.69	32.9 ± 2.45	32.9 ± 2.45
8–19 mm	36.2 ± 1.88	36.2 ± 1.88	42.1 ± 1.49	42.1 ± 1.49
<8 mm	53.3 ± 0.67	63.7 ± 1.30	54.1 ± 0.43	64.9 ± 0.76
NDF of fraction retained[3] (% of DM)				
>19 mm	60.7 ± 1.27	60.7 ± 1.27	50.1 ± 1.71	50.1 ± 1.71
8–19 mm	47.8 ± 4.50	47.8 ± 4.50	43.2 ± 2.67	43.2 ± 2.67
<8 mm	21.2 ± 1.66	17.1 ± 0.51	20.5 ± 1.62	16.0 ± 0.54

[1]CS = whole plant corn silage; CO = corn ear fibrous coproduct; GF = wet corn gluten feed; CD = citrus pulp plus corn distillers dried grains.

[2]Mean ± SD of 60 samples along the experiment.

[3]Mean ± SD of 4 composite samples from periods.

[4]Calculated from feed analysis and diet composition assuming that only whole plant corn silage, corn ear fibrous coproduct, and whole cottonseeds contribute to NDF >8 mm.

ential intake, and equal to 100% represent no selection. A mean value was generated per cow per period. The proportion of daily DMI in the morning (0700 to 1200 h), afternoon (1200 to 1900 h), and night (1900 to 0700 h) were determined.

Statistical Analysis

Data were analyzed with the MIXED procedure of SAS (University Edition, SAS Institute Inc.). The Latin square model had the random effect of cow (1–20), the fixed effects of period (1–4), forage (CS, CO), and concentrate (GF, CD), and the interaction between forage and concentrate. Degrees of freedom were calculated using the Kenward-Roger option. For data obtained over time (PUN), the fixed effect of time and the 2- and 3-way interactions between time, forage, and concentrate were added to the previous model and data were analyzed with a repeated measures model. The interaction between cow, period, FG, and CT was defined as random. The covariance structure adopted was defined by the lowest value for the Akaike's information criterion among first order autoregressive [AR(1)], compound symmetry, and unstructured. The AR(1) covariance structure was used. Statistical significance was declared at $P \leq 0.05$ and tendency at $0.05 < P \leq 0.10$. Treatments were compared with Tukey multiple comparison adjustment for the difference of LSM when a $P \leq 0.05$ was detected for the interaction between forage and concentrate.

RESULTS

Feeds and Diets

Numeric differences are discussed as data on feeds and diets were not statistically analyzed. For the experimental feed samples, the CEFC had higher concentrations of DM (46.3 vs. 27.2% of as-fed), CP (15.8 vs. 8.6% of DM), and starch (27.2 vs. 21.1% of DM) and lower NDF (29.8 vs. 53.0% of DM) than WPCS (Table 3). The WPCS had longer particle size than CEFC (Table 4). The composition of the PSPS fractions of each forage had large variation. For both forages the long particles had lower DM concentration and higher NDF than the short particles. Yeast count was lower (2.13 vs. 5.84 $\log_{10}$ cfu/g) and pH was slightly higher (4.17 vs. 3.97) in CEFC than CGF, spore forming aerobic bacteria was similar (4.28 ± 0.35 $\log_{10}$ cfu/g, on average), and filamentous fungi was below detectable concentration in CGF and was detected in CEFC (2.26 $\log_{10}$ cfu/g; Table 2). Citrus pulp had higher concentrations of NFC (64.6 vs. 29.9% of DM) and NSNFC (57.3 vs. 19.1% of DM) than the wet CGF (Table 3).

The CO diets had higher DM concentration than the CS diets (48.5 vs. 44.3% of as-fed) and the GF diets had lower DM concentration than the CD diets (44.4 vs. 48.4% of as-fed; Table 1). The CO diets had less forage NDF (**FNDF**, 16.9 vs. 19.7% of DM) and total NDF (31.3 vs. 34.1% of DM) than the CS diets. The GF diets had more NDF (34.1 vs. 31.3% of DM) and less NSNFC (14.0 vs. 18.5% of DM) and NFC (36.9 vs. 40.0% of DM) than the CD diets. Diet CO-GF had the largest proportion of the NDF from CGF (22.6% of NDF). Diet CO-CD had the lowest NDF concentration (29.8% of DM) and the highest concentrations of NFC (41.5% of DM) and NSNFC (19.5% of DM).

The proportion of TMR particles retained on each screen of the PSPS was similar on all diets, both on a DM and on an as-fed basis (Table 5). Conversely, the partial replacement of WPCS by CEFC reduced the concentration of $_{pe}NDF_{>8}$ in the diet (19.2 vs. 21.8% of DM). The GF diets had similar $_{pe}NDF_{>8}$ concentration relative to CD (20.7 vs. 20.2% of DM).

Performance and Intake

Dry matter intake and lactation performance are presented in Table 6. Cows fed CO had higher DMI than cows fed CS (21.2 vs. 20.2 kg/d, $P = 0.01$) and there was a tendency for cows fed GF to have lower DMI than cows fed CD (20.4 vs. 21.0 kg/d, $P = 0.08$). Milk fat concentration was lower on cows fed CO than on cows fed CS (3.24 vs. 3.37%, $P = 0.03$). The GF diets reduced the yields of milk (29.6 vs. 30.8 kg/d, $P < 0.01$), protein (0.936 vs. 0.990 kg/d, $P < 0.01$), and lactose (1.374 vs. 1.432 kg/d, $P < 0.01$) and protein concentration (3.10 vs. 3.17%, $P = 0.02$) relative to CD. Interactions between forage and concentrate were detected ($P \leq 0.04$) for ECM, 4% FCM, and the yields of fat and TS. Cows fed CD had higher yields of ECM, 4% FCM, fat, and TS than cows fed CGF only when fed the diet with CS. Cows fed diet CS-CD had the highest ECM (30.0 vs. 28.4 kg/d) and 4% FCM (28.5 vs. 27.0 kg/d) relative to cows on the other 3 diets ($P \leq 0.05$). The increased DMI at similar milk yield of cows fed CO, induced tendencies for the ratio of milk to DMI ($P = 0.06$) and ECM to DMI ($P = 0.08$) to be lower on CO than on CS. Similarly, the 4% FCM to DMI ratio was lower ($P = 0.05$) on cows fed CO than on cows fed CS. Cow BW, BCS, and milk SCC did not differ by treatment ($P \geq 0.15$).

Chewing Behavior

The smaller particle size and lower NDF concentration of CEFC, compared with WPCS, reduced ($P \leq 0.04$) $_{pe}NDF_{>8}$ intake (−0.3 kg/d) and also the intakes

Table 6. Effect of fibrous coproducts of corn and citrus as forage and concentrate sources[1] on DMI, lactation performance, SCC, feed efficiencies, BW, and BCS of dairy cows

	CS		CO			P-value[2]		
Item	GF	CD	GF	CD	SEM	For	Con	For × Con
DMI (kg/d)	19.9	20.5	20.8	21.5	0.75	0.01	0.08	0.92
Milk (kg/d)	29.4	30.7	29.7	30.8	0.79	0.54	<0.01	0.73
4% FCM (kg/d)	26.6[b]	28.5[a]	27.0[b]	27.4[b]	0.75	0.24	<0.01	0.02
ECM (kg/d)	27.8[b]	30.0[a]	28.4[b]	29.0[b]	0.87	0.51	<0.01	0.03
Fat (kg/d)	0.981[b]	1.062[a]	0.986[b]	0.994[b]	0.0343	0.07	0.01	0.04
Protein (kg/d)	0.925	0.991	0.948	0.988	0.0326	0.40	<0.01	0.29
Lactose (kg/d)	1.346	1.440	1.403	1.424	0.0477	0.28	<0.01	0.06
TS (kg/d)	3.517[c]	3.771[a]	3.609[bc]	3.686[ab]	0.1091	0.93	<0.01	0.03
Fat (% of milk)	3.33	3.40	3.25	3.23	0.104	0.03	0.65	0.46
Protein (% of milk)	3.11	3.15	3.09	3.18	0.058	0.85	0.02	0.27
Lactose (% of milk)	4.52	4.55	4.57	4.57	0.061	0.24	0.62	0.54
TS (% of milk)	11.85	11.98	11.81	11.87	0.168	0.28	0.21	0.68
Ln SCC[3] (0 to 9)	2.19	2.24	2.61	2.66	0.418	0.15	0.86	0.99
Milk/DMI	1.49	1.51	1.45	1.46	0.038	0.06	0.66	0.82
4% FCM/DMI	1.33	1.38	1.30	1.29	0.033	0.05	0.46	0.29
ECM/DMI	1.39	1.45	1.37	1.37	0.035	0.08	0.24	0.32
BW (kg)	607	606	605	606	18.1	0.40	0.98	0.63
BCS (1 to 5)	3.13	3.13	3.13	3.18	0.100	0.34	0.27	0.28

[a–c]Means in a row with differing superscripts differ at $P \leq 0.05$ (Tukey).

[1]CS = whole plant corn silage; CO = corn ear fibrous coproduct; GF = wet corn gluten feed; CD = citrus pulp plus corn distillers dried grains.

[2]For = forage; Con = concentrate; For × Con = interaction between For and Con.

[3]Equivalency of the Ln SCC: 2.19 = 57,000 cells/mL; 2.24 = 59,000 cells/mL; 2.61 = 76,500 cells/mL; 2.66 = 79,100 cells/mL.

as percent of BW of $_{pe}NDF_{>8}$, FNDF, and total NDF of cows fed CO relative to cows fed CS (Table 7). Cows fed the CO diets had increased meal frequency (10.2 vs. 9.4 meals/d, $P < 0.01$) and reduced meal size (2.25 vs. 2.35 kg of DM, $P = 0.04$), meal duration (34.9 vs. 42.5 min/meal, $P < 0.01$), daily meal time (336 vs. 370 min/d, $P < 0.01$), and duration of the largest meal (59.0 vs. 67.0 min/meal, $P < 0.01$) than cows fed CS. There was no interaction ($P \geq 0.32$) between source of forage and source of concentrate for variables describing meal behavior ($P \geq 0.15$), except for the duration of the first daily meal ($P < 0.01$). Cows fed CS-CD had the longest duration of the first meal relative to the other 3 diets (56.8 vs. 44.3 min/meal, $P \leq 0.05$).

Eating rate (13.5 vs. 14.7 min/kg of DMI, $P < 0.01$), rumination time (458 vs. 485 min/d, $P < 0.01$), and rumination rate (21.8 vs. 23.8 min/kg of DMI, $P < 0.01$) were also reduced for cows fed CO relative to cows fed CS. Cows fed CO also had lower total chewing per day (740 vs. 782 min/d, $P < 0.01$) and per DMI (35.3 vs. 38.5 min/kg DMI, $P < 0.01$) than cows fed CS. Interactions between forage and concentrate were detected ($P = 0.02$) for eating time per day and per unit of $_{pe}NDF_{>8}$. Cows fed CO-CD had lower eating time than cows fed CS-CD (276 vs. 303 min/d, $P \leq 0.05$) and no other difference was detected among treatments. Eating rate per unit of $_{pe}NDF_{>8}$ intake was higher for cows fed CO-GF than cows fed CS-GF (75 vs. 69 min/kg $_{pe}NDF_{>8}$, $P \leq 0.05$) and no other difference was detected among treatments. When expressed per unit of $_{pe}NDF_{>8}$ intake, rumination and total chewing were not affected ($P \geq 0.14$) by forage source. There was a tendency for cows on the CO diets to reduce sorting against long feed particles (>19 mm) at night (97 vs. 86% observed/predicted, $P = 0.10$), but no effect of forage source was detected for variables describing feed particles sorting behavior in the morning and afternoon ($P \geq 0.24$).

The replacement of wet CGF by citrus pulp and DDG did not affect ($P \geq 0.52$) the intake of $_{pe}NDF_{>8}$ (kg/d and % of BW) and the intake of FNDF as % of BW (Table 7), but cows fed the GF diets had higher intake of total NDF than cows fed CD (1.16 vs. 1.09% of BW, $P < 0.01$). Meal size was smaller (2.25 vs. 2.35 kg of DM, $P = 0.04$) and meal frequency was higher (10.0 vs. 9.6, $P = 0.02$) for cows fed GF than for cows fed CD. Cows fed GF also had lower size (4.43 vs. 4.93 kg of DM/meal, $P = 0.02$) and duration (60 vs. 66 min, $P = 0.04$) of the largest daily meal than cows fed CD. Source of concentrate had no detectable effect on meal duration and daily meal time ($P \geq 0.26$). Cows fed GF had higher rumination rates (23.8 vs. 21.7 min/kg DMI and 120 vs. 110 min/kg $_{pe}NDF_{>8}$, $P < 0.01$) and time (488 vs. 454 min/d, $P < 0.01$) than cows fed CD, and total chewing rates and daily time followed the same trends of increase on cows fed GF relative to cows fed CD ($P < 0.01$).

Table 7. Effect of fibrous coproducts of corn and citrus as forage and concentrate sources[1] on intakes of physically effective fiber ($_{pe}NDF_{>8}$), forage NDF (FNDF), and total NDF, meal and chewing behavior, proportion of intake during the day, and feed particle sorting behavior of dairy cows

Item	CS GF	CS CD	CO GF	CO CD	SEM	P-value[2] For	P-value[2] Con	P-value[2] For × Con
Intake of $_{pe}NDF_{>8}$ (kg/d)	4.4	4.4	4.0	4.1	0.15	<0.01	0.52	0.96
Intake of $_{pe}NDF_{>8}$ (% of BW)	0.72	0.73	0.68	0.68	0.026	<0.01	0.62	0.71
Intake of FNDF (% of BW)	0.66	0.66	0.59	0.60	0.023	<0.01	0.57	0.81
Intake of NDF (% of BW)	1.18	1.12	1.14	1.07	0.042	0.04	<0.01	0.56
Meal behavior								
Meal frequency (meals/d)	9.6	9.2	10.4	10.0	0.36	<0.01	0.02	0.75
Meal size (kg of DM/meal)	2.3	2.4	2.2	2.3	0.13	0.04	0.04	0.32
Meal duration (min/meal)	42.2	42.9	35.0	34.8	2.50	<0.01	0.84	0.73
Meal time (min/d)	372	368	343	329	14.7	<0.01	0.26	0.60
Largest meal size (kg of DM/meal)	4.44	5.09	4.41	4.77	0.254	0.39	0.02	0.47
Largest meal duration (min/meal)	61.9	72.0	58.0	59.9	4.13	<0.01	0.04	0.15
Largest meal moment[3] (min)	479	459	485	470	58.8	0.83	0.67	0.95
First meal duration (min/meal)	47.4[b]	56.8[a]	43.9[b]	41.7[b]	3.89	<0.01	0.08	<0.01
Chewing behavior								
Eating (min/d)	291[ab]	303[a]	288[ab]	276[b]	11.7	<0.01	0.97	0.02
Rumination (min/d)	497	472	479	437	13.2	<0.01	<0.01	0.31
Chewing[4] (min/d)	789	775	767	714	18.5	<0.01	<0.01	0.06
Eating (min/kg of DMI)	14.6	14.8	13.8	13.2	0.94	<0.01	0.44	0.15
Rumination (min/kg of DMI)	24.8	22.8	22.8	20.7	1.15	<0.01	<0.01	0.89
Chewing (min/kg of DMI)	39.3	37.6	36.7	33.9	1.95	<0.01	<0.01	0.52
Eating (min/kg of $_{pe}NDF_{>8}$)	69[b]	72[ab]	75[a]	70[ab]	4.6	0.15	0.46	0.02
Rumination (min/kg of $_{pe}NDF_{>8}$)	117	110	123	110	5.5	0.26	<0.01	0.24
Chewing (min/kg of $_{pe}NDF_{>8}$)	186	182	198	180	9.4	0.14	<0.01	0.06
Proportion of daily intake (%)								
0700–1200 h	36.2	39.6	38.0	37.9	1.43	0.96	0.16	0.10
1200–1900 h	40.2	41.0	39.5	39.2	1.12	0.24	0.78	0.59
1900–0700 h	23.6[a]	19.4[b]	22.5[ab]	22.9[ab]	1.21	0.26	0.08	0.03
Feed particle sorting[5] (% observed/predicted)								
0700–1200 h								
>19 mm[6]	80	82	79	94	6.1	0.35	0.14	0.31
8–19 mm	103	104	101	102	1.6	0.24	0.64	0.78
<8 mm	100	99	105	99	2.2	0.27	0.13	0.28
1200–1900 h								
>19 mm	88	82	85	86	4.6	0.90	0.55	0.31
8–19 mm	98	99	96	99	1.1	0.49	0.10	0.25
<8 mm	107[ab]	109[ab]	110[a]	105[b]	2.2	0.79	0.54	<0.01
1900–0700 h								
>19 mm	80	92	100	94	7.0	0.10	0.65	0.19
8–19 mm	100	100	98	99	1.4	0.22	0.69	0.48
<8 mm	109	105	102	110	3.3	0.76	0.60	0.07

[a,b]Means in a row with differing superscripts differ at $P \leq 0.05$ (Tukey).

[1]CS = whole plant corn silage; CO = corn ear fibrous coproduct; GF = wet corn gluten feed; CD = citrus pulp plus corn distillers dried grains.

[2]For = forage; Con = concentrate; For × Con = interaction between For and Con.

[3]Minutes from first daily feeding at 0700 h.

[4]Chewing: eating + rumination.

[5]>100 = preferential intake, <100 = refusal, 100 = no sorting.

[6]Screens of the Penn State Particle Separator.

There was a tendency for cows fed GF to have greater rejection of particles in the middle screen of the PSPS in the afternoon than cows fed CD (97 vs. 99% observed/predicted, $P = 0.10$) (Table 7). Within the CO diet, cows fed GF also sorted more in favor of particles <8 mm in the afternoon than cows fed CD (110 vs. 105%, observed/predicted, $P \leq 0.05$), but this sorting behavior in response to the source of concentrate was not observed for cows fed CS ($P < 0.01$ forage × concentrate). No treatment effect was detected for the proportion of daily intake in the morning and afternoon ($P \geq 0.10$), but within the CS diet, cows fed GF had a higher proportion of daily intake at night than cows fed CD (23.6 vs. 19.4%, $P \leq 0.05$) and no other difference was detected among treatments ($P = 0.03$ forage × concentrate).

Table 8. Effect of fibrous coproducts of corn and citrus as forage and concentrate sources[1] on urine volume, total-tract apparent digestibility of DM, OM, NDF, non-NDF OM, and starch, fecal starch concentration, intake of digestible starch, NDF, and OM (DOMI), ECM/DOMI, allantoin in urine, plasma urea-N (PUN), MUN, and N utilization efficiency (NUE) of dairy cows

	CS		CO			*P*-value[2]		
Item	GF	CD	GF	CD	SEM	For	Con	For × Con
Urine (L/d)	28.7	27.1	34.3	32.4	2.39	<0.01	0.33	0.94
Apparent digestibility (% of intake)								
DM	67.8[ab]	69.0[ab]	66.3[b]	71.0[a]	1.01	0.81	<0.01	0.05
OM	70.2[ab]	71.3[ab]	68.8[b]	73.1[a]	0.97	0.86	<0.01	0.05
NDF	51.0[a]	51.2[a]	46.0[b]	51.1[a]	1.59	0.07	0.06	0.05
Non-NDF OM	81.8	82.2	81.0	86.5	0.70	0.70	0.02	0.08
Starch	98.0	96.7	96.4	95.1	0.40	<0.01	<0.01	0.96
Fecal starch (% of DM)	1.4	2.3	2.5	3.7	0.25	<0.01	<0.01	0.52
Digestible starch intake (kg/d)	4.2	4.0	4.5	4.4	0.16	<0.01	0.10	0.64
Digestible NDF intake (kg/d)	3.5	3.3	3.1	3.2	0.17	0.07	0.88	0.12
DOMI (kg/d)	12.7	13.3	13.3	15.2	0.57	<0.01	<0.01	0.17
ECM/DOMI	2.17[ab]	2.28[a]	2.22[ab]	1.95[b]	0.090	0.09	0.32	0.02
Allantoin (mmol/d)	347	382	407	413	33.8	0.13	0.49	0.63
Allantoin/DOMI (mmol/kg)	28.5	28.0	32.9	28.4	3.00	0.37	0.34	0.45
PUN[3] (mg/dL)	22.5	22.1	24.2	22.1	0.77	0.12	0.03	0.12
MUN (mg/dL)	21.4	20.9	22.2	20.7	0.81	0.63	0.10	0.43
NUE[4] (%)	26.0	26.8	25.5	26.7	0.73	0.60	0.10	0.80

[a,b]Means in a row with differing superscripts differ at $P \leq 0.05$ (Tukey).

[1]CS = whole plant corn silage; CO = corn ear fibrous coproduct; GF = wet corn gluten feed; CD = citrus pulp plus corn distillers dried grains.

[2]For = forage; Con = concentrate; For × Con = interaction between For and Con.

[3]Sampling at 0 and 2 h relative to the end of morning (immediately before feeding) and afternoon milkings, 4 times daily. $P < 0.01$ for time of sampling, $P = 0.85$ for For × Time, $P = 0.09$ for Con × Time, and $P = 0.18$ for For × Con × Time.

[4]NUE = (milk CP secretion/6.38)/N intake.

Digestibility, Ruminal Microbial Yield, Energy and N Usage

Significant interactions forage × concentrate were detected for the total-tract digestibilities of DM, OM, and NDF (Table 8). Within the CO diets, cows fed GF had lower digestibility coefficients of DM (66.3 vs. 71.0% of intake) and OM (68.8 vs. 73.1% of intake) than cows fed GF, but did not differ within CS ($P \leq 0.05$). The total-tract NDF digestibility was lowest on cows fed CO-GF and was similar for the other 3 diets (46.0 vs. 51.1% of intake, $P \leq 0.05$).

The DOMI was higher ($P < 0.01$) for cows fed CO than CS and for cows fed CD than GF (14.3 vs. 13.0 kg/d, for both; Table 8). Within the CD diet, cows fed CO had lower ECM/DOMI than cows fed CS (1.95 vs. 2.25, $P \leq 0.05$), suggestive of reduced efficiency of digestible energy usage, and no other difference was detected among treatments ($P = 0.02$ forage × concentrate). Cows fed CO had reduced total-tract starch digestibility coefficient (95.8 vs. 97.4% of intake, $P < 0.01$) and higher fecal starch concentration (3.1 vs. 1.9% of DM, $P < 0.01$) than cows fed CS. Source of concentrate also affected starch digestibility. Cows fed GF had higher total-tract starch digestibility (97.2 vs. 95.9% of intake, $P < 0.01$) and lower fecal starch concentration (2.0 vs. 3.0% of DM, $P < 0.01$) than cows fed CD. Even with lower total-tract digestibility coefficient, the intake of digestible starch was higher on cows fed CO than CS (4.5 vs. 4.1 kg/d, $P < 0.01$) and there was tendency for digestible starch intake to be higher on cows fed GF than on cows fed CD (4.4 vs. 4.2 kg/d, $P = 0.10$). The intake of digestible NDF tended to be reduced on cows fed CO relative to CS (3.2 vs. 3.4 kg/d, $P = 0.07$), but source of concentrate did not affect ($P = 0.88$) the daily intake of digestible NDF.

Cows fed GF had higher PUN (23.4 vs. 22.1 mg/dL, $P = 0.03$) than cows fed CD, and there were tendencies ($P = 0.10$) for cows fed GF to have higher MUN (21.8 vs. 20.8 mg/dL) and lower NUE (25.8 vs. 26.8%) than cows fed CD (Table 8). There was a tendency ($P = 0.09$) for a sampling time by treatment interaction for PUN (Figure 1). The relative ruminal microbial yield and efficiency did not differ by treatment ($P \geq 0.13$). Cows fed CO excreted more urine than cows fed CS (33.4 vs. 27.9 L/d, $P < 0.01$).

DISCUSSION

Forage source determined the $_{pe}NDF_{>8}$ concentration of the diet, as would be expected, because the NDF in CGF and citrus pulp pellets do not contribute to $_{pe}NDF_{>8}$, as does the long NDF in WPCS and CEFC. The NDF in CGF and citrus pulp were assumed to be retrieved on the bottom pan of PSPS (100% <8 mm; no $_{pe}NDF_{>8}$ value). The pellets of citrus pulp fed dur-

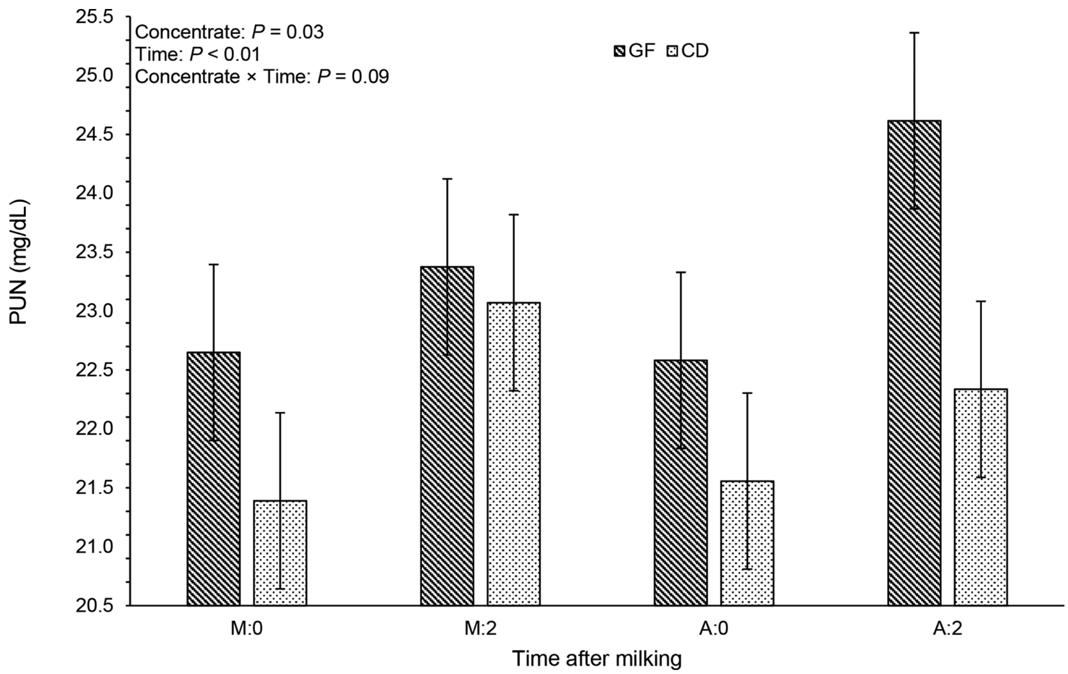

Figure 1. Plasma urea nitrogen (PUN) at 0 and 2 h relative to the start of the first meal following the morning (M:0 and M:2) and afternoon (A:0 and A:2) milkings on treatments with wet corn gluten feed (GF) or citrus pulp plus corn distillers dried grains (CD). Error bars = SEM.

ing the experiment had sufficient size to be completely retrieved on the 8 mm screen of PSPS, as is usual for all citrus pulp pellets commercialized for cattle in Brazil. The NDF in citrus pulp would be accounted as $_{pe}NDF_{>8}$ if the particle fractions of the TMR were weighed and analyzed for DM and NDF to generate the $_{pe}NDF_{>8}$ concentration of the diet.

Treatments induced changes in particle size and carbohydrate and protein profiles of the diets. The CD diets had more pectin, highly digestible fiber, and sugars from citrus pulp (Miron et al., 2002) and diets GF had more hemicelulose from CGF NDF (NASEM, 2021). The protein profile of the diets was slightly changed by the replacement of CP from CGF with CP from DDG to make CD diets iso-nitrogenous relative to the GF diets. The CP in CGF is considered to be more rumen degradable (75 vs. 53% of CP) and with similar postruminal digestibility (79 vs. 75% of RUP) relative to CP in high-protein DDG (NASEM, 2021). Crude protein from DDG represented around 15% of the CP in the CD diets (2.5 of 17.2% of diet DM). The protein in the same source of DDG coproduct used in this experiment was less degradable in the rumen than the CP in conventional soybean meal (**SBM**), due to higher proportion of CP as indigestible fraction C, lower proportion of CP as fraction B, and lower fractional degradation rate of the B fraction (Vasconcelos et al., 2021). The RUP in this DDG also had lower intestinal digestibility than SBM RUP (Vasconcelos et al., 2021) and MUN and PUN of dairy cows were reduced when this DDG partially replaced SBM in the diet (11.6% SBM and 6.3% DDG in DM vs. 17.8% SBM in DM; Dias et al., 2021). The change in diet protein profile induced by the partial replacement of the more rumen degradable CP from CGF with CP from DDG, in conjunction with the change in diet carbohydrate profile, may have be involved with the highest ECM yield observed for cows fed CS-CD. The diet CS-CD induced the highest ECM due to the increase in milk fat secretion, suggesting that the diet more adequate in $_{pe}NDF_{>8}$, with NSNFC from citrus pulp, and protein from DDG was the most stimulatory of solids-corrected milk yield.

Forage source affected diet digestibility, intake, and lactation performance. Relative to the CS diets, cows fed CO had higher DMI and DOMI, lower intake of NDF and $_{pe}NDF_{>8}$, higher digestible starch intake, ruminated less per day and per DMI, and had lower milk fat concentration. Cows fed CO had lower feed efficiency than cows fed CS, due to the higher DMI at similar milk yield. Our measure of digested energy efficiency (ECM/DOMI) showed that cows fed CO-CD had lower energy efficiency than cows fed CS-CD, suggesting a loss in energy efficiency with more CEFC in the diet, but only within the CD diet. Pectin degradation in the rumen generates acetic and formic acids and relatively little propionic acid (Dehority, 1969). Ruminal fermentation profile may have been affected by forage source. However, the loss of energetic efficiency with more CEFC in the diet did not happen within the GF diet, showing that the source of forage and concentrate coproduct can interact and can affect the efficiency of energy usage of dairy cows.

The nutritional strategies evaluated were performed with diets that apparently did not induce excessive filling of the rumen by NDF. It is supported by the low values of the various forms of expressing NDF intake as a proportion of BW (Mertens, 1997). The intake of FNDF was 0.66% of BW on CS diets and 0.60% of BW on CO diets. The theoretical high acidogenicity of the diets is supported by the low milk fat concentration (3.30%) at 30.2 kg/d of milk yield and milk fat-to-protein ratios ranging from 1.01 (CO-CD) to 1.08 (CS-CD; mean 1.05). The increase in diet $_{pe}NDF_{>8}$ induced by WPCS may explain the lower intake of DOMI on CS than CO. The filling of the rumen by long NDF is a plausible mechanism for the reduced intake (Mertens, 1997; Allen, 2000). Long NDF (FNDF, $_{pe}NDF_{>8}$) has longer ruminal retention time than NDF from other sources and is more related to chewing, ruminal pH, filling, and distension than total NDF (Allen, 1997).

The reduction in diet $_{pe}NDF_{>8}$ concentration induced by the partial replacement of WPCS with CEFC, on an iso-DM basis, may have affected gut filling, buffering (salivation), ruminal VFA clearance (ruminal motility), mat formation, and the rates of passage and degradation of feedstuffs (Allen, 1997; Grant, 1997; Allen and Grant, 2000). However, the similarity in ruminal microbial yield suggests that diets with reduced $_{pe}NDF_{>8}$ did not seriously penalize rumen function. Curiously, rumination and total chewing per unit of $_{pe}NDF_{>8}$ were not affected by forage source. The similarity in rumination and total chewing per unit of $_{pe}NDF_{>8}$ across forage source suggests that this measure of diet particle size was adequate to describe the physically effective NDF content of diets using vegetative corn fiber differing in plant maturity (WPCS vs. CEFC) and with similar particle size distribution on an as-fed and DM basis. The substitution of WPCS with CEFC on an iso-$_{pe}NDF_{>8}$ basis might have been adequate to avoid the reduction in milk fat concentration and feed efficiency when CEFC replaced WPCS, and may deserve further experimental evaluation.

The diets with more citrus pulp and DDG (CD) reduced PUN and tended to reduce MUN and to increase NUE. The CD diets had more DDG than GF, and consequently a greater proportion of diet CP more resistant to ruminal degradation. Relative to the GF diets, the CD diets also had more NSNFC and NFC, lower NDF from CGF, and greater proportion of the NDF as highly digestible citrus pulp NDF, which should favor ruminal microbial growth and N incorporation. The CD diets had more rumen-resistant protein and more rapidly degradable carbohydrates, at similar dietary starch concentration of GF. The type of concentrate coproduct affected the efficiency of N usage. Apparently, the protein and carbohydrate profile of diet CD associated with a more adequate supply of $_{pe}NDF_{>8}$, as in diet CS, was most stimulatory of ECM (+ 1.6 kg/d of ECM) than the other 3 nutritional strategies. However, all strategies evaluated seemed to be feasible nutritionally, and the choice should be based on economics and farm feed management.

The CD diets increased milk protein concentration and the daily yields of milk, protein, and lactose, reduced PUN, tended to reduce MUN, and tended to increase NUE, but had no effect on feed efficiency, due to the tendency for increased DMI. Although pectin may limit ruminal microbial yield when replacing dietary starch (Hall and Herejk, 2001), ruminal microbial yield did not differ by treatment in our experiment. As suggested by the high MUN in all diets (21.3 mg/dL, on average), it seems that ruminal protein balance was positive and excessive for all diets. Under excessive RDP supply, there was no evidence that the difference among diets on the synergy between the supplies of RDP and carbohydrates were capable of affecting ruminal microbial yield. The excessive MUN and PUN concentration also suggests that at high CP supply (17.3% of DM, on average) possible differences in the total-tract true digestibility of CP induced by the replacement of CP from CGF with CP from DDG did not affect animal performance. The increased efficiency of N usage on cows fed CD may also be related to increased supply of metabolizable protein from DDG. The CD diets may have improved blood AA profile and milk protein and lactose secretions relative to GF (Yoder et al., 2020). The DDG may have been a better source of absorbable AA than CGF, especially leucine, isoleucine, and methionine (NASEM, 2021), at similar ruminal microbial protein supply.

The intake of $_{pe}NDF_{>8}$ was similar and intake of total NDF as % of BW was higher on GF than CD. Intake regulation in response to the change in diet concentrate source was not mediated by $_{pe}NDF_{>8}$ intake. High-fiber coproducts of cereals with short particle size do not limit NDF intake, such as FNDF, when added to low-forage diets (Pereira and Armentano, 2000; Darabighane et al., 2020). The NDF in high-fiber coproducts is less filling than FNDF because of the small particle size, density between 1.2 and 1.5 g/mL to bypass rumen fermentation (Grant, 1997), and sometimes because of the high degradation of the NDF, such as in citrus pulp, beet pulp, and soyhulls (Bhatti and Firkins, 1995). Corn gluten feed has higher functional specific gravity than typical forage (Bhatti and Firkins, 1995) and may have fast ruminal passage rate. Low-forage diets with high inclusion of short-particle cereal coproducts did not induce more rumen digesta volume and mass of fresh digesta and fiber than a low-forage, high starch diet; as was induced by the inclusion of alfalfa haylage to the low-forage diet (Pereira et al., 1999). The ruminal fractional passage rate of NDF may be faster when CGF replaces other feedstuffs (Allen and Grant, 2000; Mullins et al., 2010; Sullivan et al., 2012). Changes induced by treatments on ruminal passage rate are plausible to have happened in our experiment.

The numeric similarity in the total-tract digestibility coefficient of NDF suggests that the NDF in CEFC and CGF were as digestible as the NDF in WPCS, although diet CO-GF had the lowest NDF digestibility coefficient. Increased ruminal passage rate of CGF NDF in diet CO, induced by the deficiency of long fiber (Allen and Grant, 2000), and negative associative effects of the low ruminal pH and starch on ruminal NDF degradation (Grant and Mertens, 1992; Russell and Wilson, 1996), may have reduced the NDF digestibility of CO-GF, because the replacement of CGF with citrus pulp and DDG in diet CO-CD resulted in NDF digestibility similar to the 2 CS diets. The lower dietary concentration of ${}_{pe}NDF_{>8}$ on the CO diets may have reduced ruminal mat consistency and induced a faster passage rate of CGF NDF in diet CO-GF (Allen and Grant, 2000). The NDF in CGF has lower degradation rate than the NDF in citrus pulp and therefore can have a greater reduction in effective ruminal degradation as result of an increase in passage rate, as compared with citrus pulp NDF. The partial replacement of CGF with citrus pulp pectin may have contributed to the increase in NDF digestibility of CO-CD. Although citrus pulp is capable of reducing ruminal pH more acutely than ground corn (Pereira et al., 2015), ruminal microbes degrading pectin may have the capacity to degrade hemicelulose (Osborne and Dehority, 1989), suggesting the possibility of synergism between pectin and fiber digestibility when citrus pulp substituted CGF in the low forage diet. Diet CO-GF had lower total-tract digestibility of DM and OM than diet CO-CD, suggesting that the faster passage rate or negative associative effects of ruminal fermentation on fiber digestion may have been more detrimental to cereal NDF digestion than to the fermentation of sugars, pectin, and NDF in citrus pulp.

The effect of forage and concentrate source on digestible starch intake, total-tract starch digestibility, and fecal starch concentration had divergent trends. Cows fed CO had higher digestible starch intake, lower total-tract starch digestibility, and higher fecal starch concentration than cows fed CS, and also had higher DMI and DOMI. Although a reduction in ruminal starch degradation is known to be highly compensated by intestinal digestion in dairy cows (Oba and Allen, 2003a), an increased passage rate of starchy sources induced by the higher DMI of the less gut filling, CO diets may have reduced total-tract starch digestibility, but increased digestible starch intake. Cows fed CS also had greater proportion of dietary starch from WPCS than cows fed CO. Starch in CEFC came from mature corn and in WPCS came from silage harvested at immature stage of growth (27.2% DM). Maturity has marked negative effect on flint corn kernel ruminal degradation (Pereira et al., 2004). The association between more rumen-resistant starch and high passage rate may explain the reduced starch digestibility coefficient in CO relative to CS. However, digestible starch intake was higher on cows fed GF than CD, but unlike the forage source effect, the total-tract starch digestibility coefficient was increased and fecal starch concentration was reduced by GF. The DMI and DOMI were lower on cows fed GF than on cows fed CD, at similar ${}_{pe}NDF_{>8}$ intake. This is suggestive that intake regulation induced by the change in concentrate source was not modulated by the gut filling effect of the diets. Intake regulation in response to the change in concentrate source may have been the result of differences in the chemical nature of the carbohydrates and ruminal fermentation profile. Propionate from ruminal starch degradation is a known depressor of DMI (Allen et al., 2009). The intake of digestible starch tended to be higher on GF than CD and was associated with reduced DOMI, probably as a result of reduced passage rate of rumen digestible starch with CGF in the diet.

Diets had major effect on chewing behavior. Cows fed CO took a shorter time to eat the same amount of DM, had shorter eating time and meal time per day, had shorter duration of the largest daily meal, and had shorter, more frequent, and smaller meals than cows fed CS, which was associated with lower DMI on CS than CO. Cows on CO tended to be less selective against feed particles on the 19-mm screen at night than cows on CS, suggesting a change in sorting behavior to attenuate a reduction in ruminal pH on CO. The supplementation of dairy cows with exogenous amylase capable of increasing ruminal starch degradation increased sorting in favor of long feed particles and the rejection of short particles (Andreazzi et al., 2018) and experimental induction of acidosis have induced preferential consumption of long feed particles (DeVries et al., 2008; Maulfair et al., 2013). A reduction in meal size has also been associated with more propiogenic diets (Oba and Allen, 2003b). Diets with CS increased chewing behavior and reduced digestible starch intake, suggestive of being less acidogenic than CO diets. Diet CS-CD, the diet that resulted in highest ECM, reduced the proportion of daily intake at night and increased the duration of the first daily meal. The lower intake of digestible starch on the CS diets may be related to the observed changes in eating behavior.

The partial replacement of CGF with citrus pulp and DDG reduced meals per day and increased meal size, with no effect on meal duration and daily meal time. The size of the largest meal and largest meal duration were also increased by CD. The CD diets reduced ruminations per day and per unit of DMI and $_{pe}NDF_{>8}$. The increase in rumination behavior per unit of $_{pe}NDF_{>8}$ intake on GF, at similar intake of $_{pe}NDF_{>8}$ and FNDF, suggests that wet CGF had a beneficial effect on rumination, and, as already discussed, may have reduced the passage rate of starch. Allen and Grant (2000) observed that CGF NDF was 0.13 as effective as 1 unit of alfalfa NDF in increasing ruminal pH and 0.11 as effective as alfalfa NDF in stimulating rumination time. More rumination per unit of FNDF has been observed when nonforage high-fiber coproducts were incorporated into low forage diets (Beauchemin et al., 1991). It is not clear if the increased chewing with more CGF in the diet was the result of CGF per se or the result of some adaptive mechanism affecting rumination efficiency in response to diet composition.

CONCLUSIONS

Cows fed a combination of high inclusion of WPCS with citrus pulp and DDG had the highest yield of ECM compared with diets with high inclusion of CEFC and CGF. The CO diets reduced the intake of $_{pe}NDF_{>8}$ and increased DOMI, probably because of lower filling of the digestive tract by long NDF compared with CS, but had no effect on milk yield. The CO diets increased the intake of digestible starch and reduced rumination per d and per DMI and milk fat concentration. Forage source did not affect rumination per unit of $_{pe}NDF_{>8}$ intake. Cows fed the GF diets had lower DOMI and yields of milk, protein, and lactose, tended to have higher intake of digestible starch, and had more rumination per unit of $_{pe}NDF_{>8}$, at similar $_{pe}NDF_{>8}$ intake than cows fed CD. All strategies evaluated were nutritionally viable and the partial replacement of WPCS with CEFC was a feasible feeding strategy for dairy cows. The replacement of WPCS with CEFC in diets for dairy cows should be evaluated on an iso-$_{pe}NDF_{>8}$ basis.

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