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Nutrient digestion and performance by lambs and steers fed thermochemically treated crop residues

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ABSTRACT: Five studies were conducted to determine nutrient digestibility and performance of lambs and steers fed thermochemically treated crop residues and distillers dried grains with solubles (DDGS) as a corn replacement pellet (CRP; 75% residue:25% DDGS, DM basis). Fifteen Hampshire, Suffolk, or Dorset wethers (BW 33.3 ± 5.0 kg) were utilized to evaluate nutrient digestibility of the unprocessed native (NAT) and CRP [Exp. 1: wheat straw (WS); Exp. 2: corn stover (CS); Exp. 3: switchgrass (SWG) and corn fiber:wheat chaff (CFWC)] when limit fed (Exp. 1 and 2: 1.8% of BW daily; Exp. 3: 2.5% of BW daily) compared with a 60% corn diet. In Exp. 4, 56 individually fed Dorset-cross wether lambs (BW 32.0 ± 1.4 kg) were utilized to compare performance and digestibility of WS, wheat chaff (WC), corn fiber (CF), a 3:1 blend of corn fiber:wheat straw (CFWS), a 3:1 blend of CFWC, and SWG-CRP fed for ad libitum intake compared with a 45% corn diet. In Exp. 5, 32 individually fed Holstein steers (BW 185.2 ± 0.9 kg) were used to evaluate performance and digestibility of diets containing corn, WS-CRP, CFWC-CRP, or NAT-WS fed for ad libitum intake. Crop residues were processed with 5% calcium oxide (DM basis) and 35% water in a double-shaft enclosed mixer (Readco Kurimoto Continuous Processor, York, PA) and subsequently pelleted with DDGS to form CRP. Feeding lambs WS-CRP (Exp. 1) or CS-CRP (Exp. 2) increased digestion of DM, NDF, and ADF compared with NAT ($P < 0.05$). In Exp. 3, feeding CFWC-CRP increased total tract NDF digestibility and ADF digestibility ($P < 0.05$). Experiment 4 final BW were greatest for control lambs and least for lambs fed CFWS-CRP or SWG-CRP. Body weight gains for lambs fed CRP averaged 15.9% less than control ($P < 0.05$). Lambs fed CRP diets had greater ($P < 0.05$) NDF and ADF intake and output. In Exp. 5, steers fed the corn or 2 CRP diets gained similarly and faster ($P < 0.05$) than those fed the NAT-WS diet. Steers fed the control corn diet were more efficient ($P < 0.05$) than steers fed other treatments. Steers fed the corn diet, CFWC-CRP, and WS-CRP had greater ($P < 0.01$) DM digestibility than NAT. The results confirm benefits for nutrient digestion and subsequent animal performance when crop residues are thermochemically processed. Processed crop residues may be fed in combination with DDGS to partially replace corn in ruminant diets.

Key words: corn replacement, digestibility, distillers dried grains with solubles, growing ruminant

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INTRODUCTION

In 2006, the ethanol industry fermented 55.9 million metric tons of corn to produce over 14.0 billion liters of ethanol (Eidman, 2007). Future forecasts predict that 45.4 billion liters of ethanol will be produced by the last quarter of 2010 (Eidman, 2007). This will require almost 114.3 million metric tons of corn to be fermented. Because ruminants consume 35.6% of the 154.9 million metric tons of corn fed to livestock in the United States each year, it is logical that a portion of the corn fed to ruminants will be replaced with alternative feeds because they have less efficient feed conversion compared with swine and poultry. Crop residues are abundant but require processing if they are to be used in diets that support performance above maintenance (Berger et al., 1994). Thus, the goal of this research was to develop replacements for corn in ruminant diets by combining thermochemically treated crop residues with distillers grains to create a corn replacement pellet (**CRP**).

The primary objectives of the experiments were to 1) evaluate total tract digestibility of thermochemically processed crop residues, 2) compare various levels of CRP with the goal of obtaining apparent nutrient digestibilities similar to corn-based diets, and 3) evaluate the intake and performance of growing ruminants fed CRP as a corn replacement.

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MATERIALS AND METHODS

All procedures used in this study were approved by the University of Illinois, Laboratory Animal Care Committee. Animals used in this trial were managed according to the guidelines recommended by FASS (1999).

Feed Processing

Crop residues utilized for these experiments were transported from a local source and stored at the University of Illinois, Beef Cattle and Sheep Field Laboratory (Urbana, IL). Wheat straw (**WS**), corn stover (**CS**), and switchgrass (**SWG**) were ground through a tub grinder fitted with a 3.81-cm screen and then stored under a roof. Corn fiber (**CF**) and wheat chaff (**WC**) were not ground because of their inherent small particle size. Crop residues were processed with 5% calcium oxide (DM basis) and 35% water in a double-shaft enclosed mixer (Figure 1; Readco Kurimoto Continuous Processor, York, PA). The addition of water to CaO forms calcium hydroxide, which is an exothermic reaction. Control of the CRP manufacturing process was regulated by monitoring the exiting temperature (141°C) and moisture (25%) content of the Readco-processed substrates. The experimental processor throughput was set at 45.4 kg/h from a 12.7-cm barrel to facilitate the desired retention time (5 to 15 s). The processor was set to optimize surface area contact for chemical processing. Near the end of the mixer shafts, distillers dried grains with solubles (**DDGS**) were metered in and pelleted (75% residue:25% DDGS; DM basis) to form CRP. Pellets were augured to a Belt-O-Matic rotary belt dryer (model 123B, B.N.W. Industries, Tippecanoe, IN) and dried at 100 to 110°C for 10 min to achieve 90% DM. All CRP were manufactured on-farm 4 mo before these studies were initiated and stored in 1,134-kg tote bags.

Exp. 1 and 2

Fifteen wether lambs of Hampshire, Suffolk, and Dorset breeds were used to measure diet digestibility. In period 1, lambs had an initial BW of 33.3 ± 5.0 kg. In period 2, a separate group of 15 wethers (same breed types; BW 33.7 ± 4.7 kg) was used. In Exp. 2, the same set of wethers was used (period 1, BW 33.4 ± 5.5 kg; period 2, BW 37.0 ± 5.5 kg). Before each period (14 d) of evaluation, all lambs were fed a common diet. Lambs were individually housed in elevated, mesh-bottom crates in a temperature-controlled (23°C) room with constant fluorescent lighting. Lambs were randomly assigned to diet and digestion crate. Upon allotment, lambs consumed their respective experimental diet for 7 d to allow for acclimation to the feed and the digestion crates. Lambs were fed once daily at 0800 h. Water was available continuously. The acclimation period was followed by a 6-d fecal collection during which feces were quantitatively collected and a 15% subsample was saved daily.

Ingredient composition and nutrient analysis of the diets fed in Exp. 1 and 2 are described in Tables 1 and 2, respectively. The complete-mixed diets were fed at 1.8% of BW daily during the trial. Before daily feeding, feed refusals were collected and recorded for each lamb. In Exp. 1, 5 treatments were evaluated as follows: 1) 60% cracked corn, 24% DDGS, 14% corn silage, 2.0% $CaCO_3$ and 0.40% urea; 2) 30% cracked corn, 30% WS-CRP, 24% DDGS, 14% corn silage, and 0.40% urea; 3) 60% WS-CRP, 24% DDGS, 14% corn silage, and 0.40% urea; 4) 22% unprocessed native (**NAT**)-WS, 32% DDGS, 30% cracked corn, 14% corn silage, 2.0% $CaCO_3$ and 0.40% urea; and 5) 44% NAT-WS, 40% DDGS, 14% corn silage, 2.0% $CaCO_3$, and 0.40% urea. In Exp. 2, CS replaced WS (treated CRP or NAT) in respective diets. Diets were formulated based on the NRC (1985). The corn silage used in this study was

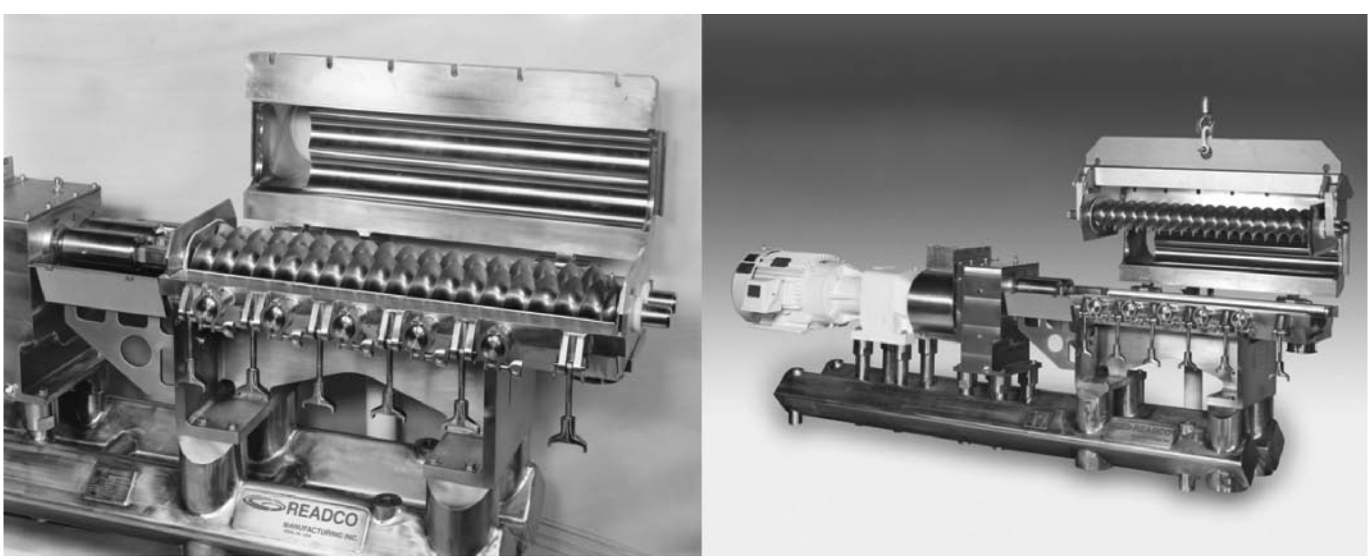

Figure 1. The Readco Kurimoto Continuous Processor (York, PA).

Table 1. Ingredient and chemical composition of diets fed to lambs (Exp. 1)

	Treatment[1]				
Item	Control	30% WS-CRP	60% WS-CRP	30% NAT-WS	60% NAT-WS
Ingredient, % of DM					
Cracked corn	60.0	30.0	—	30.0	—
DDGS	24.0	24.0	24.0	32.0	40.0
Corn silage	13.6	13.6	13.6	13.6	13.6
WS-CRP[2]	—	30.0	60.0	—	—
NAT-WS	—	—	—	22.0	44.0
Limestone	2.00	—	—	2.00	2.00
Urea	0.40	0.40	0.40	0.40	0.40
Nutrient, % of DM					
DM	77.4	82.5	71.8	80.3	81.6
CP	15.3	18.0	15.7	16.9	17.5
NDF	20.9	31.9	39.3	39.0	56.9
ADF	9.23	18.1	24.8	20.8	32.0
Crude fat	4.4	4.0	2.4	3.9	3.4

[1]WS = wheat straw, CRP = corn replacement pellet, NAT = native form of the residue, DDGS = distillers dried grains with solubles.
[2]WS-CRP consisted of 75% treated wheat straw: 25% DDGS on a DM basis.

a by-product of the seed-corn industry and contained corn husks, grain, cobs, and minimal stalk.

Feed and fecal samples were collected daily during the collection phase. Feed and fecal samples were composited, dried at 55°C, and ground in a Wiley mill (2-mm screen, Swedesboro, NJ). Feed and feces were analyzed for DM, OM (AOAC, 1975), NDF (Robertson and Van Soest, 1977), and ADF (Goering and Van Soest, 1970) for digestibility calculations. Amylase was added during NDF analysis. Neither NDF nor ADF was adjusted for ash content.

Exp. 3

Fifteen wethers lambs of Hampshire, Suffolk, and Dorset breeds (period 1 BW 41.8 ± 5.1 kg) were used to measure diet digestibility. In period 2, a separate group of 15 wethers (same breed types; BW 42.8 ± 3.3 kg) was used. Facilities and experimental procedures were similar to Exp. 1 and 2.

Ingredient composition and nutrient analysis of the diets fed in Exp. 3 is described in Table 3. The complete-mixed diets were fed at 2.5% of BW daily during the trial. The 5 treatments were as follows: 1) 60% cracked corn, 24% DDGS, 14% corn silage, 2% $CaCO_3$, and 0.40% urea; 2) 30% corn, 30% SWG-CRP, 24% DDGS, 14% corn silage, and 0.40% urea; 3) 60% SWG-CRP, 24% DDGS, 14% corn silage, and 0.40% urea; 4) 30% corn, 30% CF:WC 3:1 blend (**CFWC**)-CRP, 24% DDGS, 14% corn silage, and 0.40% urea; 5) 60% CFWC-CRP, 24% DDGS, 14% corn silage, and 0.40% urea. The corn silage used in this study was the same as that used in Exp. 1 and 2. The corn fiber was sourced from a corn wet mill without corn steep liquor being

Table 2. Ingredient and chemical composition of diets fed to lambs (Exp. 2)

	Treatment[1]				
Item	Control	30% CS-CRP	60% CS-CRP	30% NAT-CS	60% NAT-CS
Ingredient, % of DM					
Cracked corn	60.0	30.0	—	30.0	—
DDGS	24.0	24.0	24.0	32.0	40.0
Corn silage	13.6	13.6	13.6	13.6	13.6
CS-CRP[2]	—	30.0	60.0	—	—
NAT-CS	—	—	—	22.0	44.0
Limestone	2.00	—	—	2.00	2.00
Urea	0.40	0.40	0.40	0.40	0.40
Nutrient, % of DM					
DM	77.4	84.3	75.6	80.6	82.3
CP	15.3	18.0	15.7	16.8	17.3
NDF	20.9	32.0	39.5	37.1	41.9
ADF	9.2	17.0	22.6	21.5	33.4
Crude fat	4.4	4.0	3.4	3.9	3.4

[1]CS = corn stover, CRP = corn replacement pellet, NAT = native form of the residue, DDGS = distillers dried grains with solubles.
[2]CS-CRP consisted of 75% treated corn stover: 25% DDGS on a DM basis.

Table 3. Ingredient and chemical composition of diets fed to lambs (Exp. 3)

	Treatment[1]				
Item	Control	30% SWG-CRP	60% SWG-CRP	30% CFWC-CRP	60% CFWC-CRP
Ingredient, % of DM					
Cracked corn	60.0	30.0	—	30.0	—
DDGS	24.0	24.0	24.0	24.0	24.0
Corn silage	13.6	13.6	13.6	13.6	13.6
SWG-CRP[2]	—	30.0	60.0	0.00	—
CFWC-CRP[3]	—	—	—	30.0	60.0
Limestone	2.00	—	—	—	—
Urea	0.40	0.40	0.40	0.40	0.40
Nutrient, % of DM					
DM	77.4	84.8	76.4	82.7	71.2
CP	15.3	17.3	13.2	19.2	18.1
NDF	20.9	32.0	39.5	31.2	37.8
ADF	9.23	18.6	25.7	12.8	14.2
Crude fat	4.4	4.0	3.4	4.0	3.3

[1]SWG = switchgrass, CRP = corn replacement pellet, CFWC = corn fiber:wheat chaff, DDGS = distillers dried grains with solubles.

[2]SWG-CRP consisted of 75% treated SWG: 25% DDGS on a DM basis.

[3]CFWC-CRP consisted of 56.25% treated corn fiber: 18.75% treated wheat chaff: 25% DDGS on a DM basis.

applied. The wheat chaff was sourced by harvesting the wheat plant less the grain and included a greater proportion of seed hull compared with WS. Chemical composition of dietary ingredients fed to lambs is presented in Table 4. Feed and feces were collected, processed, and analyzed as described for Exp. 1 and 2.

Exp. 4

Fifty-six Dorset-cross wether lambs (BW 32.0 ± 1.4 kg) were utilized in a randomized, complete-block design to assess the relative performance and nutrient excretion of lambs fed treated WS, WC, CF, a 3:1 blend of corn fiber:wheat straw (**CFWS**), CFWC, and SWG-CRP as replacements for corn in a grower diet. Lambs were blocked by BW (4 blocks) and fed in individual crates for 29 d at the ADM Animal Nutrition Research Center (Decatur, IN).

Seven treatments were evaluated; treated residues were fed at 22.5% (30% CRP) dietary inclusion (Table 5). Treated residue replaced corn, whereas dietary amount of DDGS remained constant. Initial and final (shrunk) BW were measured on 2 consecutive days, and an interim (full) BW was taken on d 14 (interim data not reported). Animals were fed for ad libitum intake at 0800 h once daily and were allowed ad libitum access to water. Before feeding, feed refusals were collected and recorded for each lamb. Nutrient intake was measured, and nutrient output and digestibility were calculated using chromic oxide as the indigestible marker (Williams et al., 1962). Lambs were fed chromic oxide at 1 g/d for 1 wk before fecal collection on d 26 and 27. Feed and fecal samples were composited, dried at 55°C, and ground in a Wiley mill (2-mm screen). Feed and feces were analyzed as described in Exp. 1, 2, and 3. Chemical composition of dietary ingredients is summarized in Table 6.

Exp. 5

Thirty-two Holstein steers (BW 185.2 ± 0.9 kg) were utilized in a 120-d study to evaluate growth perfor-

Table 4. Chemical composition of dietary ingredients (Exp. 1, 2, and 3)[1]

Nutrient, % of DM	Cracked corn	DDGS	Corn silage	WS-CRP[2]	NAT-WS	CS-CRP[2]	NAT-CS	SWG-CRP[2]	CFWC-CRP[3]	NAT-CF	NAT-WC	NAT-SWG
DM	88.2	88.5	46.9	88.1	90.0	94.3	91.7	95.7	87.1	40.0	89.1	92.5
OM	98.6	94.7	96.6	82.6	93.1	84.5	94.6	85.4	93.1	99.5	84.6	93.9
CP	9.8	31.7	8.7	14.9	4.9	14.8	4.4	12.6	18.8	10.8	6.7	9.3
NDF	12.0	34.0	31.7	50.1	89.6	50.5	81.3	50.5	47.7	58.9	71.6	75.7
ADF	3.4	19.4	14.2	33.5	51.4	29.8	54.6	35.0	15.8	18.3	51.4	47.5
Crude fat	4.0	7.1	3.1	1.7	0.1	1.9	0.1	1.9	1.7	0.3	0.7	—

[1]CRP = corn replacement pellet, DDGS = distillers dried grains with solubles, WS = wheat straw, NAT = native form of the residue, CS = corn stover, SWG = switchgrass, CFWC = corn fiber:wheat chaff, CF = corn fiber, WC = wheat chaff.

[2]CRP consisted of 75% thermochemically processed residue: 25% DDGS on a DM basis.

[3]CFWC-CRP consisted of 56.25% treated corn fiber: 18.75% treated wheat chaff: 25% DDGS on a DM basis.

Table 5. Ingredient and chemical composition of diets fed to lambs (Exp. 4)

Item	Treatment[1]						
	Control	WS-CRP	WC-CRP	CF-CRP	CFWS-CRP	CFWC-CRP	SWG-CRP
Ingredient, % of DM							
Cracked corn	45.0	22.5	22.5	22.5	22.5	22.5	22.5
DDGS	24.0	16.5	16.5	16.5	16.5	16.5	16.5
Soybean hull pellets	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Cottonseed hull pellets	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Concentrate, 36% CP[2]	4.86	5.46	5.66	6.00	5.91	5.97	5.93
Molasses	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Urea, 287% CP	0.28	0.54	0.34	—	0.09	0.03	0.07
Calcium carbonate	0.86	—	—	—	—	—	—
WS-CRP[3]	—	30.0	—	—	—	—	—
WC-CRP[3]	—	—	30.0	—	—	—	—
CF-CRP[3]	—	—	—	30.0	—	—	—
CFWS-CRP[4]	—	—	—	—	30.0	—	—
CFWC-CRP[5]	—	—	—	—	—	30.0	—
SWG-CRP[3]	—	—	—	—	—	—	30.0
Nutrient, % of DM							
DM	88.8	89.2	90.1	89.4	89.4	89.6	89.7
CP	15.5	15.5	15.5	15.7	15.5	15.5	15.5
NDF	30.1	46.4	44.4	42.4	43.4	42.9	46.1
ADF	19.5	30.8	30.4	22.9	24.9	24.8	30.0
Crude fat	4.2	3.6	3.6	3.6	3.6	3.6	4.1

[1]CRP = corn replacement pellet, DDGS = distillers dried grains with solubles, WS = wheat straw, WC = wheat chaff, CF = corn fiber, CRWS = corn fiber:wheat straw, CFWC = corn fiber:wheat chaff, SWG = switchgrass.

[2]Commercial supplement formulated to contain (DM basis): 39.7% protein, 4.1% Ca, 1.1% P, 3.3% salt, 0.41% Mg, 1.31% K, 0.35% S, 940 mg/kg of Zn, 2.49 mg/kg of Co, 18.0 mg/kg of Cu, 1.0 mg/kg of I, 730 mg/kg of Fe, 326 mg/kg of Mn, 2.28 mg/kg of Se, 14,000 IU/kg of vitamin A, 1,500 IU/kg of vitamin D, and 41.6 IU/kg of vitamin E.

[3]CRP consisted of 75% treated residue: 25% DDGS on a DM basis.

[4]CFWS-CRP consisted of 56.25% treated CF: 18.75% treated WS: 25% DDGS on a DM basis.

[5]CFWC-CRP consisted of 56.25% treated CF: 18.75% treated WC: 25% DDGS on a DM basis.

mance when fed CFWC- or WS-CRP compared with a corn-based diet or NAT-WS. Steers were implanted with Revalor-G (40 mg of trenbolone acetate and 8 mg of estradiol; Intervet Inc., Millsboro, DE) before allotment, outfitted with an electronic identification tag, and stratified by BW into 4 pens. Individual feed intakes were monitored using the GrowSafe feed management system (GrowSafe Systems Ltd., Airdrie, Alberta, Canada) at the University of Illinois, Beef Cattle and Sheep Field Laboratory (Urbana, IL).

Steers were fed a common diet consisting of cracked corn, DDGS, corn silage, and supplement 14 d before allotment and for 7 d before termination of trial. Upon initiation and termination of the trial, the average of 2 consecutive-day BW taken before the morning feeding served as starting and final BW. Dietary treatments were 1) 50% cracked corn, 25% DDGS, 15% corn silage, and 10% supplement, 2) 50% CFWC-CRP, 25% DDGS, 15% corn silage, and 10% supplement, 3) 50% WS-CRP, 25% DDGS, 15% corn silage, and 10% supplement, and 4) 50% NAT-WS, 25% DDGS, 15% corn silage, and 10% supplement (Table 7). The corn silage used in this study was the same as that used in the lamb trials. Both CRP diets were designed to replace an equal fraction of cracked corn or NAT-WS and DDGS with treated residues and DDGS composing 75% of the total diet. Chemical composition of dietary ingredients is summarized in Table 8. Digestibilities were measured by collecting fecal grab samples from individual animals at d 7, 56, and 102 of the trial. Diet samples were

Table 6. Chemical composition of dietary ingredients (Exp. 4)[1]

Nutrient, % of DM	Cracked corn	DDGS	Soybean hulls	Cottonseed hulls	Concentrate	Molasses	WS-CRP[2]	WC-CRP[2]	CF-CRP[2]	CFWS-CRP[3]	CFWC-CRP[4]	SWG-CRP[2]
DM	85.8	87.8	88.8	91.8	91.1	72.5	87.8	91.0	86.2	82.1	86.0	90.9
CP	8.5	33.2	11.9	7.7	40.8	6.1	12.7	14.3	17.3	16.0	16.4	14.2
NDF	9.8	38.3	59.8	80.4	16.3	0.2	44.2	44.6	44.2	37.2	40.3	48.8
ADF	5.2	19.6	46.1	72.8	10.0	0.1	32.2	32.5	16.4	20.7	21.1	33.1

[1]CRP = corn replacement pellet, DDGS = distillers dried grains with solubles, WS = wheat straw, WC = wheat chaff, CF = corn fiber, CRWS = corn fiber:wheat straw, CFWC = corn fiber:wheat chaff, SWG = switchgrass.

[2]CRP consisted of 75% treated residue: 25% DDGS on a DM basis.

[3]CFWS-CRP consisted of 56.25% treated CF: 18.75% treated wheat straw: 25% DDGS on a DM basis.

[4]CFWC-CRP consisted of 56.25% treated CF: 18.75% treated wheat chaff: 25% DDGS on a DM basis.

Table 7. Composition and nutrient analysis of diets fed to cattle (Exp. 5)

	Treatment[1]			
Item	Control	50% CFWC-CRP	50% WS-CRP	50% NAT-WS
Ingredient, % of DM				
Cracked corn	50.0	—	—	—
DDGS	25.0	25.0	25.0	25.0
Corn silage	15.0	15.0	15.0	15.0
Supplement[2]	10.0	10.0	10.0	10.0
CFWC-CRP[3]	—	50.0	—	—
WS-CRP[4]	—	—	50.0	—
NAT-WS	—	—	—	50.0
Nutrient, % of DM				
DM	82.3	81.7	82.2	83.2
OM	95.1	88.8	84.4	90.0
CP	18.9	20.1	18.1	16.5
NDF	19.3	37.1	38.3	58.1
ADF	8.7	14.9	23.7	32.7
Crude fat	4.2	3.1	3.1	2.3

[1]CFWC = corn fiber:wheat chaff, CRP = corn replacement pellet, WS = wheat straw, NAT = native form of residue, DDGS = distillers dried grains with solubles.

[2]Supplement for control and 50% NAT-WS formulated to contain (DM basis): 46.3% protein, 4.1% Ca, 1.1% P, 3.3% salt, 0.41% Mg, 1.31% K, 0.35% S, 940 mg/kg of Zn, 2.49 mg/kg of Co, 18.0 mg/kg of Cu, 1.0 mg/kg of I, 730 mg/kg of Fe, 326 mg/kg of Mn, 2.28 mg/kg of Se, 14,000 IU/kg of vitamin A, 1,500 IU/kg of vitamin D, and 41.6 IU/kg of vitamin E. Supplement for CRP formulated to contain (DM basis): 14.4% protein, 4.1% Ca, 1.1% P, 3.3% salt, 0.41% Mg, 1.31% K, 0.35% S, 940 mg/kg of Zn, 2.49 mg/kg of Co, 18.0 mg/kg of Cu, 1.0 mg/kg of I, 730 mg/kg of Fe, 326 mg/kg of Mn, 2.28 mg/kg of Se, 14,000 IU/kg of vitamin A, 1,500 IU/kg of vitamin D, and 41.6 IU/kg of vitamin E.

[3]CFWC-CRP consisted of 56.25% treated CF: 18.75% treated wheat chaff: 25% DDGS on a DM basis.

[4]WS-CRP consisted of 75% treated WS: 25% DDGS on a DM basis.

taken for 5 d before fecal sampling for each period. Acid insoluble ash of feed and fecal samples was used to determine digestibility (Van Keulen and Young, 1977).

Statistical Analysis

In Exp. 1, 2, and 3, data were analyzed by the MIXED procedure (SAS Inst. Inc., Cary, NC). Variables measured were DM digestibility (**DMD**), NDF digestibility (**NDFd**), and ADF digestibility (**ADFd**). Independent variables included lamb, period, and treatment. Treatment means were separated using the LSD procedure.

In Exp. 4, data were analyzed by the MIXED procedure of SAS. Independent variables included block and treatment. Dependent variables included nutrient digestibility, DMI, ADG, G:F, and initial and final BW. Treatment means were separated using the LSD procedure.

In Exp. 5, differences among means for performance parameters were evaluated using the MIXED procedure of SAS with individual animal as the experimental unit. Dependent variables DMI, ADG, G:F, and diet digestibility were tested against the fixed effect of diet. The LSD procedure of SAS was utilized to separate means.

RESULTS

Exp. 1

Processing of WS increased ($P < 0.05$) apparent total tract digestion of DM, NDF, and ADF when compared with NAT (Table 9). Lambs fed the corn diet had greater total tract DMD than lambs fed CRP or

Table 8. Chemical composition of ingredients and CRP[1] fed to cattle (Exp. 5)

Nutrient, % of DM	Cracked corn	DDGS	Corn silage	Control supplement	CRP supplement	CFWC-CRP[2]	WS-CRP[3]	NAT-WS
DM	88.2	88.5	46.9	92.9	89.4	87.1	88.1	90.0
OM	98.6	94.7	96.6	62.8	75.9	93.1	82.6	93.1
CP	9.8	31.7	8.7	46.3	16.4	18.8	14.9	4.9
NDF	12.2	34.0	31.7	7.0	9.0	47.7	25.6	89.6
ADF	3.4	19.4	14.2	3.8	2.5	15.8	33.5	51.4
Crude fat	4.0	7.1	3.1	3.2	4.4	1.2	3.3	0.7

[1]CRP = corn replacement pellet, DDGS = distillers dried grains with solubles, CFWC = corn fiber:wheat chaff, WS = wheat straw, NAT = native form of residue.

[2]CFWC-CRP consisted of 56.25% treated corn fiber: 18.75% treated wheat chaff: 25% DDGS on a DM basis.

[3]WS-CRP consisted of 75% treated WS: 25% DDGS on a DM basis.

Table 9. Least squares means for apparent digestibility of nutrients by growing lambs fed corn replacement pellet (CRP) in Exp. 1, 2, and 3

Item	Treatment[1]									SEM
	Control	30% CRP	60% CRP	30% NAT	60% NAT	30% SWG-CRP	60% SWG-CRP	30% CFWC-CRP	60% CFWC-CRP	
Exp. 1 WS-containing diets, % digestibility										
DM	87.7[a]	81.3[b]	69.6[c]	74.1[c]	61.0[d]					1.4
NDF	83.6[a]	79.8[a]	70.2[b]	53.8[c]	34.6[d]					3.7
ADF	66.8[a]	64.5[a]	60.3[a]	34.7[b]	38.7[b]					9.6
Exp. 2 CS-containing diets, % digestibility										
DM	92.2[a]	83.3[b]	70.7[c]	76.4[d]	66.9[c]					2.0
NDF	87.6[a]	79.2[ab]	70.4[b]	54.1[c]	48.8[c]					3.8
ADF	78.8[a]	66.5[b]	57.3[c]	34.6[d]	42.4[d]					3.7
Exp. 3 SWG/CFWC-containing diets, % digestibility										
DM	82.2[a]					74.9[b]	54.4[d]	76.9[b]	68.9[c]	1.8
NDF	71.3[bc]					69.2[bc]	55.8[d]	72.9[bc]	75.2[a]	2.6
ADF	52.8[a]					53.8[a]	38.4[b]	56.4[a]	57.3[a]	3.7

[a–d]Means within a row without a common superscript differ ($P < 0.05$).

[1]NAT = native form of residue, SWG = switch grass, CFWC = corn fiber:wheat chaff blended 3:1 on a DM basis before processing, WS = wheat straw, CS = corn stover, DDGS = distillers dried grains with solubles.

NAT-WS diets ($P = 0.01$). Lambs fed WS-CRP at the 60% level had DMD similar to lambs fed 30% NAT-WS ($P = 0.07$). The 30% WS-CRP had a 7.2 percentage unit increase in DMD when compared with the 30% NAT. Lambs fed 60% WS-CRP had an 8.6 percentage unit increase in DMD when compared with lambs fed 60% NAT. Trach et al. (2001) reported increased OM digestibilities when rice straw was treated with quick lime, urea, or the combination, with 3% quick lime with 4% urea being most efficacious. In that work, treatments were mixed and sprayed onto the straw, which then was wrapped, sealed, and stored for 3 wk before feeding. The authors reported an 8% increase in OM digestibility ($P < 0.05$), increases of 229 g/d gain, and a 23.9% increase in feed efficiency vs. the control rice straw. In this study, Readco processing of WS improved ($P < 0.05$) NDFd compared with NAT. Lambs fed the corn diet had NDFd similar to lambs fed 30% WS-CRP ($P = 0.47$). Lambs fed 30 and 60% NAT-WS had reduced NDFd compared with lambs fed corn or CRP diets ($P < 0.05$). Likewise, 30 and 60% NAT wheat straw diets had decreased ADFd when compared with corn and CRP diets ($P < 0.05$).

Exp. 2

Processing of CS increased ($P < 0.05$) apparent total tract digestion of DM, NDF, and ADF when compared with NAT. Lambs fed the corn diet had greater DMD than lambs fed all CRP or NAT-CS diets ($P < 0.01$). Lambs fed 30% NAT-CS had greater DMD when compared with lambs fed 60% CRP diet ($P = 0.05$). Total tract DMD improved by 5.7% for lambs fed 60% CS-CRP compared with lambs fed 60% NAT, and by 9.0% for lambs fed 30% CS-CRP compared with lambs fed 30% NAT. Oji et al. (2007) reported slightly greater improvements in digestibility for treated CS. The authors utilized maize stalks, husks, cobs and treated this residue with 3% aqueous NH_3 and urea equivalent to 3% NH_3 in 2 separate trials. Treatment of residues with 3% NH_3 and urea improved DMD ($P < 0.05$) by 13.9 and 15.3% vs. untreated residue. In contrast, Rounds et al. (1976) demonstrated the effect of various levels of $Ca(OH)_2$ in combination with KOH or NaOH on corn cob IVDMD. The authors allowed a reaction time of 24 h and observed that $Ca(OH)_2$ without KOH or NaOH appeared to be ineffective as a chemical treatment for corn cobs. The authors concluded that the dissociation constant for $Ca(OH)_2$ is less than NaOH or KOH and that a longer reaction time may be required to yield the same benefits. Data from this study suggest that the heat and pressure created by applying CaO in a semi-moist and enclosed reaction was beneficial for increasing ligno-cellulosic hydrolysis. Extensive cellulosic ethanol research also indicates that pretreatment of CS with steam will allow enzymatic access to cellulose by partial hydrolysis of lignocellulosic bonds, thus liberating cellulose, which can be converted to glucose for fermentation. Öhgren et al. (2005) pretreated CS at 190°C for 5 min using SO_2 as an acid catalyst. This resulted in a 90% overall glucose yield and approximately 80% xylose yield after a 72-h enzymatic hydrolysis. This demonstrates that, in the presence of steam and a catalyst, lignocellulosic bonds as well as hemicellulosic bonds can be disrupted to release bound cellulose, which was observed by using the Readco processor.

Processing of CS improved ($P < 0.05$) NDFd when compared with NAT. Lambs fed the corn diet and 30% CS-CRP had similar NDFd ($P = 0.10$). Lambs fed 60% NAT-CS had decreased NDFd when compared with lambs fed 60% CRP diet ($P < 0.05$). Diets with CS-CRP had greater ($P < 0.05$) ADFd when compared with diets containing similar levels of CS-NAT. Lambs fed the corn diet had greater ADFd when compared with lambs fed all other diets ($P < 0.05$). Lambs fed 30 and 60% NAT-CS had similar ADFd ($P = 0.13$).

Table 10. Performance of lambs (Exp. 4)

	Treatment[1]							
Item	Control	WS-CRP	WC-CRP	CF-CRP	CFWS-CRP	CFWC-CRP	SWG-CRP	SEM
No. of lambs	8	8	8	8	8	8	8	
Initial BW, kg	33.0	32.7	32.4	32.2	31.6	31.3	31.0	1.42
Final BW, kg	39.6[a]	37.9[ab]	37.6[ab]	38.1[ab]	36.4[b]	37.6[ab]	36.5[b]	0.86
ADG, g/d	220[a]	180[ab]	180[ab]	200[ab]	150[b]	210[a]	190[ab]	20.0
DMI, kg/d	1.10[ab]	1.19[ab]	1.15[ab]	1.16[ab]	1.06[b]	1.16[ab]	1.24[a]	0.063
G:F, g/kg	203.5[a]	146.0[b]	154.9[b]	174.8[ab]	147.7[b]	187.2[ab]	152.5[b]	1.48

[a,b]Means within a row without a common superscript letter differ ($P < 0.05$).

[1]CRP = corn replacement pellet, WS = wheat straw, WC = wheat chaff, CF = corn fiber, CFWS = corn fiber:wheat straw, CFWC = corn fiber:wheat chaff, SWG = switchgrass.

Exp. 3

Lambs fed the corn diet had greater ($P < 0.05$) apparent total tract DMD than lambs fed the CFWC and SWG-CRP (Table 9). Lambs fed 30% SWG and CFWC diets had similar DMD ($P = 0.46$). Lambs fed CFWC and SWG-CRP at the 30% inclusion level had greater ($P < 0.05$) DMD when compared with 60% inclusion level. Lambs fed 60% SWG-CRP diet had the least DMD among all diets ($P < 0.01$). Lambs fed 60% SWG-CRP had less NDFd when compared with lambs fed other diets ($P < 0.01$). Lambs fed 60% CFWC-CRP had the greatest NDFd. Diets had similar ($P > 0.10$) ADFd with the exception of the 60% SWG-CRP, which was less ($P < 0.05$).

Exp. 4

All lambs consumed feed at greater than 3.0% of BW daily (DM basis). Final BW were greater for control lambs than for lambs fed CFWS-CRP or SWG-CRP (Table 10). Cumulative ADG of lambs fed control or CFWC-CRP diets were greater ($P < 0.05$) than those of lambs fed CFWS-CRP. The DMI was numerically greater (5.45%) for CRP-fed lambs than for control lambs. Efficiency was not different among control, CFWC-CRP, and CF-CRP. Blends performed similarly to the weighted means of the individual substrates. Fecal DM output increased for WS-, WC-, and SWG-CRP treatments vs. control. In general, CRP lambs had 5.5% greater DMI and 31.5% more fecal output (DM basis; 26.7% more wet weight basis).

Apparent total tract digestibility of nutrients is summarized in Table 11. The DMD were not different among control, CF, and CFWC treatments, but were less ($P < 0.05$) for other substrates. Averaged across the CRP diets, lambs had 21.9% less DMD compared with control lambs. Lambs fed CRP diets had greater ($P < 0.05$) NDF and ADF intakes and outputs, but digestibilities similar to lambs fed the control diet.

Exp. 5

Steers fed the CFWC-CRP gained equally to the corn positive control diet at 1.4 kg/d (Table 12) and tended to gain faster than those fed the WS-CRP ($P = 0.09$). Steers fed the negative control NAT-WS diet performed the poorest of all treatments, gaining just 0.82 kg/d ($P < 0.01$). Steers fed the WS-CRP performed better (1.38 kg/d) than NAT ($P < 0.01$). Average daily DMI of steers fed CFWC-CRP, WS-CRP, and NAT-WS were not different ($P > 0.12$). However, DMI were greater ($P < 0.05$) for steers fed CRP and NAT diets when compared with the corn diet.

Steers fed the corn diet were more efficient than those fed other treatments (Table 12, $P < 0.05$). Steers fed the CFWC-CRP were more efficient than the NAT-WS negative control and WS-CRP treatments (G:F = 0.18 vs. 0.10 and 0.15, respectively; $P < 0.05$). Steers fed the WS-CRP were about 50% more efficient than those fed the NAT-WS control ($P < 0.05$).

Steers fed either CFWC or WS-CRP diets had similar ($P > 0.05$) apparent total tract DMD when compared with steers fed the corn diet (60.0 and 62.0 vs. 65.9%, respectively). Steers fed the corn diet or CRP diets had greater total tract DMD than steers fed the NAT-WS diet.

DISCUSSION

The greater DMD for 30% NAT-WS than for 60% NAT-WS reflects the inclusion of corn in the diet; the DMD of the 30% NAT-WS diet was similar to the 60% WS-CRP diet. The thermochemical processing is the predominant reason for increased DMD over NAT diets. In a preliminary study, 48 h in situ DM disappearance was used to determine the proportion of improvement due to Readco processing by itself, Readco processing plus steam due to water addition, and Readco processing plus steam plus CaO treatment. Wheat straw in situ DM disappearance was improved by 0.0, 4.0, and 16.0 percentage units for Readco processing, Readco processing plus water, and Readco processing plus water plus CaO, respectively (unpublished data).

The increased NDFd observed in this trial is attributed to thermochemical processing increasing exposure of residues to rumen microbes, while partially hydrolyzing hemicellulosic bonds. The net benefit is that more digestible plant cell walls are contained in the thermochemically processed crop residues. Similarly, Saha

Table 11. Apparent total tract nutrient digestion by lambs (Exp. 4)

	Treatment[1]							
Item	Control	WS-CRP	WC-CRP	CF-CRP	CFWS-CRP	CFWC-CRP	SWG-CRP	SEM
DM								
Intake,[2] g/d	1,062[a]	1,030[a]	1,044[a]	989[ab]	821[b]	988[ab]	1,092[a]	80.4
Fecal output, g/d	395[c]	564[ab]	548[ab]	445[bc]	396[bc]	530[abc]	596[a]	60.1
Digestibility, %	62.4[a]	45.2[b]	47.5[b]	54.8[ab]	53.0[ab]	46.4[b]	45.6[b]	5.0
Fecal DM, %	38.6	43.4	38.7	38.3	40.5	38.7	40.5	2.7
OM								
Intake, g/d	864[a]	791[ab]	803[ab]	780[ab]	654[b]	770[ab]	841[a]	60.6
Fecal output, g/d	363[b]	448[ab]	431[ab]	382[ab]	326[b]	437[ab]	477[a]	50.4
Digestibility, %	57.8[a]	43.4[b]	46.1[ab]	51.1[ab]	51.1[ab]	43.4[b]	43.6[b]	5.3
NDF								
Intake, g/d	330[b]	406[a]	411[a]	389[ab]	326[b]	390[ab]	447[a]	29.4
Fecal output, g/d	230[ab]	269[ab]	266[ab]	222[ab]	199[b]	260[ab]	295[a]	33.5
Digestibility, %	29.3	34.2	35.8	42.4	41.0	33.7	34.8	6.7
ADF								
Intake, g/d	218[c]	284[ab]	288[a]	226[c]	199[c]	238[bc]	305[a]	19.2
Fecal output, g/d	132[c]	210[a]	199[ab]	134[c]	140[bc]	178[abc]	209[a]	25.3
Digestibility, %	38.0	30.6	31.6	40.6	31.7	34.3	32.6	7.1

[a–c]Means within a row without a common superscript letter differ ($P < 0.05$).

[1]CRP = corn replacement pellet, WS = wheat straw, WC = wheat chaff, CF = corn fiber, CFWS = corn fiber:wheat straw, CFWC = corn fiber:wheat chaff, SWG = switchgrass.

[2]Intake observed during week of fecal collection.

and Cotta (2007) reported that treating wheat straw with 10% $Ca(OH)_2$ at 121°C for 1 h resulted in 82% of the sugars being available for fermentation to ethanol.

Processing WS also increased ADFd vs. NAT-WS. Readco processing decreased the NDF concentration by 25.3% and ADF concentration by 10% for WS-CRP compared with the respective NAT combination. This indicates that the thermochemical processing of WS resulted in solubilization of some of the hemicellulose and cellulose, creating more digestible plant cell walls and thus increasing ADFd.

In the preliminary study, when corn stover was processed by itself, in situ DM disappearance was improved by 10.5, 18.4, and 24.7 percentage units for processing through the Readco machine dry, processing plus water, and processing plus water plus CaO, respectively. The amount of corn in the 30% NAT-CS diet increased its digestibility over the 60% CS-CRP inclusion rate.

Processing of CS increased the NDFd vs. the NAT-CS. The NDF content of Readco-processed CS was 19% less after processing vs. native CS. Readco processing appeared effective for partially solubilizing NDF and rendering insoluble fiber more susceptible to digestive enzymes. Kim and Holtzapple (2005) reported that when CS was treated with an excess of $Ca(OH)_2$ (0.5 g/g of CS) at 55°C in oxidative conditions for 4 wk, 91.2% of the glucans and 51.8% of the xylans were converted to glucose and xylose, respectively, when exposed to enzymatic treatment.

Processing of CS increased the ADFd vs. the NAT-CS. When the ADF content of Readco processed CS was compared with NAT-CS, a 16.1% reduction in ADF concentration was measured. Therefore, we can attribute the increase in NDFd and ADFd to thermochemical processing, which increased hydrolysis of ligno-cellulosic bonds and increased the surface area of residues, thus potentiating rumen microbial attachment and fermentation.

For Exp. 3, no native residues were tested, but rather treated residues were fed at 30 and 60% of diet DM and

Table 12. Performance and apparent total tract DM digestibility of Holstein steers (Exp. 5)

	Treatment[1]				
Item	Control	CFWC-CRP	WS-CRP	NAT-WS	SEM
Initial BW, kg	195	193	195	193	
Final BW, kg	363[a]	360[a]	349[a]	291[b]	18.7
ADG, kg/d	1.35[a]	1.44[a]	1.38[a]	0.82[b]	0.13
DMI, kg/d	7.07[a]	7.86[ab]	8.65[b]	8.24[b]	0.35
G:F, g:kg	201[a]	177[c]	149[b]	101[d]	10
Fecal DM output, kg/d	2.39[a]	3.12[ab]	3.29[b]	4.78[c]	0.21
Apparent DM digestibility, %	65.9[a]	62.0[a]	60.0[a]	42.1[b]	4.2

[a–d]Means within a row without a common superscript letter differ ($P < 0.05$).

[1]CRP = corn replacement pellet, WS = wheat straw, CFWC = corn fiber:wheat chaff, NAT = native form of residue.

compared with a corn-based control diet. The decrease in DMD between the 30 and 60% SWG-CRP diets reflects the relatively poor digestibility of SWG-CRP.

Experiment 5 demonstrated the potential to replace corn in feedlot diets using DDGS and CRP. Steers fed the WS-CRP gained 0.56 kg/d faster and gained 48 g more per kg of feed DM than those fed the NAT-WS diet. When Trach et al. (2001) fed rice straw treated with 3% CaO, bulls grew 0.14 kg/d faster ($P < 0.05$) and gained 44 g more per kg of feed ($P < 0.05$) than those fed untreated rice straw diets. An 18 percentage unit increase in digestibility was observed for WS-CRP, which was similar to in vitro results of pressure-cooked wheat straw by Guggolz et al. (1971).

Overall Conclusions

These data indicate that replacing the native form with thermochemically treated crop residues can improve diet digestibilities in lambs and steers. These results indicate that these CRP products may serve as a partial corn replacement for growing lambs and steers.

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