Effects of Heat Treatment and Physical Processing of Cottonseed on Nutrient Digestibility and Production Performance by Lactating Cows[1,2]

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ABSTRACT

Four primiparous Holstein cows were used in an experiment with a 5 × 4 Youden square design. The effects of heat processing and particle size of cottonseed used in the diets of dairy cows were investigated. Dietary treatments were control (3.6% tallow, 4.5% casein), whole cottonseed, ground cottonseed, roasted whole cottonseed, and roasted ground cottonseed. Diets consisted of 55% corn silage, 1.54% urea, and cottonseed at 18.1% of dry matter. Cottonseeds were roasted at 149°C and steeped for 30 min. Roasting increased the amount of ruminally undegradable protein measured in vivo, the ratio of ruminal acetate to propionate, pH, and milk protein percentage. Ruminal digestibilities of organic matter (OM) and neutral detergent fiber and biohydrogenation of fatty acids were reduced by roasting. The grinding of cottonseed increased the total tract digestibility of OM and N and tended to increase ruminally undegradable protein of cottonseed in vivo. Interactions between heat treatment and particle size of cottonseed revealed that roasted ground cottonseed resulted in the highest total tract digestibility of OM, N, and neutral detergent fiber. Utilization of cottonseed may be improved by heat or mechanical processing as was indicated by this study.
(**Key words**: cottonseed, roasting, digestibility)

Abbreviation key: **A:P** = ratio of acetate to propionate, **CS** = cottonseed, **FA** = fatty acid, **GCS** = ground CS, **ROCS** = roasted CS, **RWCS** = raw CS, **SB** = soybeans, **WCS** = whole CS.

INTRODUCTION

High producing dairy cows require large amounts of protein and energy, and fiber is important for maintaining optimal ruminal fermentation. Energy requirements are important not only during the first trimester of lactation but must be sufficient also to maintain persistency of production and support BW gain toward the end of lactation. Because of these requirements, whole cottonseeds (**WCS**) have been used extensively by dairy producers. Typically, WCS contain 2.22 Mcal/kg of NE_L, 23% CP, 44% NDF, and 34% ADF (21). The fiber is contributed in part by lint [about 10% of the weight of the cottonseed (**CS**)], which is nearly pure cellulose and has high potential digestibility. The energy concentration reflects the oil content (20% of DM). Often WCS are fed at a maximum of 15% of the total diet to minimize the effect of unsaturated fat on ruminal fiber digestibility.

Compared with cereal grains, CS are relatively high in N and can supply an important portion of the dietary N required by dairy cows. Several research studies (9, 24) with various protein sources have shown a correlation between increased milk production and decreased ruminal degradation of protein. The process of heating CS to at least 141°C and steeping for 30 min significantly increased in situ RUP (14). Higher temperatures further increased the percentage of RUP, but the greatest benefit was achieved by heating at 141 to 146°C. Roasting of CS increased the flow of total AA to the intestine (23). Similar responses to heat treatment of other feedstuffs have been observed (5, 31).

Sullivan et al. (30) found that cracked Pima CS was better utilized than whole Pima CS; however, information on the effects of grinding linted CS on milk production and performance by dairy cows was not available. Also, little information was available on the effect of roasted CS (**ROCS**) on nutrient digestibilities, milk production, and performance by dairy cows. The objective of this study was to determine the effects of processing CS (roasting and grinding) on ruminal and intestinal digestibilities of OM,

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NDF, fatty acids (**FA**), and N as well as on milk production and composition.

MATERIALS AND METHODS

Cows and Treatments

Four primiparous Holstein cows were used in a 5 × 4 Youden square design. At initiation of the study, all cows were in late lactation (mean DIM = 210) and had a ruminal cannula in the proximal duodenum and a simple T cannula in the distal ileum. At the beginning of the trial, urea was increased from 0.39 to 1.54% of dietary DM during 4 d to facilitate adaptation by the cows.

Diets consisted of 55.3% corn silage and 44.7% concentrates (Table 1). Treatments were control, whole raw CS (**RWCS**) (intact seed), ground RWCS, whole ROCS, and ground ROCS. The CS were ground through a hammer mill (Schutte Hammer Mill Co., Buffalo, NY), and the geometric mean particle size (38) of ground CS (**GCS**) was 4.97 mm (58.7, 62.0, 71.2, 83.9, 95.9, and 99.9% were retained on screens with apertures of 4.75, 2.36, 1.18, 0.6, 0.3, and 0.15 mm, respectively) after dry-sieving. The CS were added at 18.05% of dietary DM, which contributed approximately one-third of the CP and two-thirds of the FA to the diets. All CS were from the same lot. Urea was added (1.54% of DM) to all diets to provide a rapidly available source of N to ruminal microbes. Also, casein was added to the control diet to facilitate in vivo measurement of RUP for CS. The CS were roasted at 149°C using a hot air roaster (Jet-Pro, Inc., Springfield, OH), steeped for 30 min in barrels, and spread on the ground for cooling. Tallow was added to the control diet to provide similar amounts of FA across the diets.

The diets were prepared once daily as a total mixed diet, and the cows were fed twice daily at 0600 and 1800 h for ad libitum intake to allow 5% orts. Orts were weighed once daily at 1630 h.

TABLE 1. Ingredient composition of diets.

Ingredient	Control	Cottonseed[1]
	(% of DM)	
Corn silage	55.3	55.3
Cottonseed	...	18.05
Dried shelled corn	17.25	17.26
Corn starch	14.71	5.00
Casein	4.46	...
Urea	1.54	1.54
Limestone	0.93	1.12
Tallow	3.55	...
Dynafos®2	0.56	0.35
Dyna K®3	0.44	0.33
Dynamate®4	0.49	0.35
Magnesium oxide	0.07	...
Trace-mineralized salt	0.56	0.56
Vitamins A, D, and E[5]	0.14	0.14

[1]Cottonseed diets: whole raw cottonseeds, ground raw cottonseeds, whole roasted cottonseeds, and ground roasted cottonseeds.

[2]Dicalcium-monocalcium phosphate (Pitman-Moore, Inc., Mundelein, IL). Contained: 185 g/kg of P, 0.7 g/kg of K, 220 g/kg of Ca, 6 g/kg of Mg, and 11 g/kg of S.

[3]Feed-grade potassium chloride (Pitman-Moore, Inc.). Contained: 500 g/kg of K, 0.5 g/kg of Ca, 3.4 g/kg of Mg, 4.5 g/kg of S, and 10 g/kg of Na.

[4]Feed-grade double sulfate of magnesium and potassium (Pitman-Moore, Inc.). Contained: 180 g/kg of K, 0.6 g/kg of Ca, 110 g/kg of Mg, 220 g/kg of S, and 7.6 g/kg of Na.

[5]Contained 4993 IU/g of vitamin A, 1001 IU/g of vitamin D_3, and 22 IU/g of vitamin E.

Sampling and Laboratory Procedures

Each period consisted of 14 d, and the last 7 d were used for collection of milk production and DMI data. The data from the last 4 d of each period were used to determine milk composition and digestibilities of the diets. Feed and ort samples were taken once daily during d 11 through 14. Samples of feed offered and orts from d 1 through 10 were composited for the determination of DM to facilitate calculation of DMI. Samples that were taken during the collection period (d 11 through 14) were composited to determine DM, OM, N, NDF, ADF, acid detergent lignin, FA, and ash.

Digestibilities of feed components were determined by the use of Cr_2O_3, which was put in gelatin capsules and dosed via the ruminal cannulas twice daily (5.0 g per dose) from d 5 to 14 of each period. Gelatin capsules were administered to cows at 0600 and 1800 h. Concentrations of Cr in duodenal, ileal, and fecal samples were determined as described by Williams et al. (40).

To determine DMI, samples of feed offered and orts were dried in a forced-air oven for 72 h at 55 to 60°C. Representative samples of feed offered, orts, duodenal and ileal contents, and feces that were taken during the collection periods were lyophilized and ground through a Wiley mill (2-mm screen; Arthur H. Thomas, Philadelphia, PA) prior to lab analyses. Ash and OM (2) were determined for duodenal and ileal contents, feces, and ruminal bacteria. Nitrogen was determined (2) in feed, digesta, feces, and ruminal bacteria. Analyses of NDF, ADF, and ADIN were performed according to the methods of Van Soest et al. (36). To minimize the interference of fat in the fiber analyses, all samples were filtered with 100 ml

of boiling ethanol prior to treatment in 30 ml of 8 *M* urea and 0.2 ml of α-amylase (Sigma A-5426; Sigma Chemical Co., St. Louis, MO). Minerals were assayed at the Research Extension Analytical Laboratory (Wooster, OH) by plasma emission spectrometry (2).

Ruminal samples were taken via a core sampler (10) on d 11 and 13 of each period at 3, 6, 9, and 12 h postfeeding for determination of pH, NH_3 N, and VFA. For analyses of NH_3 N and VFA, 3 ml of 6 *N* HCl were added to 50 ml of filtrate, and samples from d 11 and 13 were composited and frozen. Ruminal fluid samples were thawed, mixed, and centrifuged at 27,000 $\times$ *g* at 4°C for 15 min. The supernatant was filtered through Whatman number 1 paper (Whatman, Clifton, NJ) and analyzed for NH_3 N (8) and VFA (11). A Hewlett Packard GLC (model 5890, Series II; Hewlett Packard Co., Avondale, PA) equipped with a HP 3396A integrator was used for all FA analyses.

To determine bacterial N, ruminal samples were taken at 3, 6, 9, and 12 h postfeeding on d 11, 12, 13, and 14, respectively, of each period (7). Samples were handled and processed according to the procedures described by Tice et al. (32). After lyophilization, bacterial samples were analyzed for N, OM, and purines (35, 42).

Duodenal (n = 16) and ileal (n = 16) samples were taken every 6 h during the 4-d collection period; the starting time was advanced 1.5 h/d. Samples were composited by cow and period, frozen, and later lyophilized and ground for analysis of N, NH_3 N, purines, FA, NDF, OM, and Cr. Calculation of the RUP in CS from in vivo measures was as reported by Tice et al. (32). Some data used to calculate the RUP in the CS were deleted for a cow during the time the control diet was fed because of low nonammonia, nonbacterial, noncasein N flow to the duodenum.

Fecal samples were taken every 12 h during the collection period; the starting time was advanced 3 h/d. Samples of feces were lyophilized, composited, and ground before analysis for N, FA, NDF, OM, and Cr.

Milk production was recorded daily at 0500 and 1600 h. Separate a.m. and p.m. milk samples were taken on the last 2 d of each period to determine fat and protein concentrations by infrared analysis (DHI Cooperative, Inc., Powell, OH). To determine FA composition in milk, samples were composited by period. Cows were weighed during the last 2 d of each collection period at 0800 h.

Analysis of FA in feed offered, orts, duodenal and ileal contents, feces, and bacterial samples has been described by Sukhija and Palmquist (29). Milk FA were analyzed according to a modification of the procedure of Sukhija and Palmquist as described by Tice et al. (33). The GLC was equipped with a fused silica capillary column (30-m, 0.25-mm i.d.; 10% SP™-2380; Supelco, Inc., Bellefonte, PA). For feed, digesta, and bacterial FA, the injector port temperature was 230°C, and the detector port temperature was 250°C. The column was held at 165°C for 10 min and then increased at 2°C/min to 190°C. For milk FA, the injector port temperature was 235°C, and the detector port temperature was 250°C. The column was held at 60°C for 3 min, was increased at 8°C/min to 156°C, and then was increased at 2.5°C/min up to 200°C.

Protein Digestibility In Situ

Two ruminally cannulated cows were used to determine in situ protein degradability of RWCS and ROCS. Raw CS and ROCS were ground through a Wiley mill (2-mm screen). Approximately 5 g of GCS (triplicate) and 2.5 g of cotton balls (duplicate) were placed in dacron bags (10 $\times$ 20 cm, approximately 50-μm pore size; Ankom, Fairport, NY). Before placement in the rumen, the bags (n = 38) were soaked briefly in water. Dacron bags were then submerged about 30 cm into the ruminal contents just prior to the 0700-h feeding and removed at 3, 6, 12, 24, 48, and 72 h. After removal, bags were thoroughly rinsed in cold tap water. Samples were dried at 56°C for 72 h and analyzed for N content by the micro-Kjeldahl method (2). Nitrogen on cotton balls was used to correct for microbial contamination of CS.

Nitrogen washout was determined by placing 2.5 g of GCS in dacron bags and allowing the bags to sit in borate-phosphate buffer solution for 1 h (16). Samples were dried at 56°C for 72 h and were analyzed for N. Protein degradability was determined using the NRC (20) formula and assuming a rate of passage of 0.05/h.

Nitrogen solubility was determined by placing 2.5 g of GCS in an Erlenmeyer flask with 50 ml of borate-phosphate buffer solution for 1 h (16). Samples were filtered (number 541 filter; Whatman Corp.), and the residue was analyzed for N.

Statistical Methods

The study was originally designed as a 5 $\times$ 5 Latin square with 5 cows; however, because of several health problems, data from all periods were deleted for one cow. Therefore, a 5 $\times$ 4 Youden square design was used for analysis of data using the general linear models procedure of SAS (25). Also, another cow had abnormal duodenal flow values during period 2;

TABLE 2. Chemical composition of diets.[1]

Nutrient[2]	Control	Whole RWCS	Ground RWCS	Whole ROCS	Ground ROCS
DM, %	42.7	44.0	43.3	43.6	43.2
	(DM basis)				
OM, %	94.7	94.4	94.3	94.4	94.3
CP, %	15.9	14.8	14.8	14.8	15.2
NDF, %	22.2	30.1	28.7	31.9	30.2
ADF, %	11.9	17.8	16.5	18.9	17.7
ADL, %	1.63	3.23	2.91	3.40	3.09
FA, %	5.12	5.24	5.09	5.31	5.40
NE_L,[3] Mcal/kg	1.86	1.73	1.74	1.70	1.73
Ca, %	0.66	0.74	0.81	0.80	0.80
P, %	0.34	0.35	0.36	0.35	0.35
Mg, %	0.25	0.22	0.22	0.22	0.22
K, %	0.89	1.05	1.04	1.12	1.12
Na, %	0.24	0.25	0.25	0.27	0.27
Mn, ppm	47.6	47.1	47.8	50.8	50.8
Cu, ppm	15.7	11.9	13.3	13.0	13.0
Zn, ppm	65.1	63.0	60.2	64.6	64.6

[1]Control = no cottonseed, RWCS = raw cottonseed, and ROCS = roasted cottonseed.

[2]ADL = Acid detergent lignin; FA = fatty acids.

[3]Calculated according to the method of Weiss et al. (39).

therefore, all data related to duodenal flow for this period were removed from data analyses. Ruminal data were analyzed as a split plot to detect interactions between treatment and time. However, no interactions were found; therefore, all references were made to main plot effects. Treatment comparisons among means were made with single degree of freedom comparisons using the contrast statement of the general linear models procedure of SAS (25). Contrasts were control versus CS, RWCS versus ROCS, WCS versus GCS, and the interaction between heat processing and particle size of CS. Significance was identified at $P \leq 0.05$, and tendencies were noted at $0.05 < P < 0.10$.

RESULTS AND DISCUSSION

Chemical composition of the experimental diets is given in Table 2. The concentrations of NDF, ADF, and acid detergent lignin of the control diet were low because of the low fiber content of the corn silage. Also, the control diet had ingredients with no NDF, such as casein, and three times more corn starch than the CS diets. Calculated NE_L was higher for the control diet than for the CS diets because of the low fiber concentration in the control diet. The other dietary components were similar and generally in accordance with NRC (21) recommendations.

The percentage of soluble N in RWCS and ROCS was 20.3 and 16% of total N, respectively. Using the dacron bags, washout N was 39.2 and 29.2% of total N for RWCS and ROCS, respectively (Table 3). The RUP from in situ measurements was 30.4 and 34.2% of CP for RWCS and ROCS, respectively. Hsu et al. (14) reported RUP from in situ measurements of 23.7% for RWCS and 33% of CP for CS roasted at 150°C and steeped for 30 min. The RUP values from in situ measurements in our study were slightly lower than, but somewhat similar to, the RUP values determined by calculations from duodenal N flows (Table 4). The ADIN percentages for RWCS and ROCS were 9.9 and 10.7% of total N, respectively. These ADIN percentages were similar to those reported by Arieli et al. (1) for RWCS and CS roasted at 140°C for 1 or 2 h in a forced-air oven.

TABLE 3. Fractions and degradation of protein in situ from cottonseed (CS).

Item[1]	Raw CS	Roasted CS
Fraction A (washout), % of N	39.2	29.2
Fraction B, % of N	58.3	67.1
Fraction C, % of N remaining at 72 h	2.5	3.7
K_d, /h	0.055	0.060
K_p, /h	0.05	0.05
RUP, % of CP	30.4	34.2
RDP, % of CP	69.6	65.8

[1]Fraction A (washout) = N leaving in situ bag after soaking in borate-phosphate buffer, fraction B = 100% minus fraction A minus fraction C, K_d = rate of digestion, and K_p = rate of passage (20).

Ruminal NH_3 N concentration was not significantly affected by dietary treatments (Table 5). However, ruminal NH_3 N tended to be higher in cows fed the control diet because of more rapid hydrolysis of N sources (lower RUP). As expected, the NH_3 N concentration was highest at 3 h postfeeding, and the concentration decreased linearly with time (3, 6, 9, and 12 h postfeeding; data not shown) because NH_3 N was utilized by microorganisms to synthesize their own AA, was absorbed by the ruminal wall, or was passed to the small intestine.

Total VFA concentrations were similar among diets (Table 5). Total ruminal VFA concentration was not altered in other studies with heat-treated soybeans (**SB**) or SB meal (3, 12, 18, 19, 28, 32) or with whole ROCS (23).

Ruminal acetate concentration was lower for cows fed the control diet, probably because of the decreased amount of fiber in the diet. An interaction between heat treatment and particle size tended to occur because grinding RWCS decreased ruminal acetate, but grinding ROCS did not affect ruminal acetate.

TABLE 4. Apparent digestibilities of OM, N, and NDF by cows fed cottonseed (CS) processed in different ways.

	Diet[1]						Contrast[2]			
Item	Control	Whole RWCS	Ground RWCS	Whole ROCS	Ground ROCS	SE	Control vs. CS	RWCS vs. ROCS	WCS vs. GCS	Interaction
							P			
OM										
Intake, kg/d	12.0	13.5	13.4	12.3	14.1	0.50	0.02	0.71	0.55	0.37
Duodenal flow, kg/d										
Total OM	7.56	8.59	9.03	10.16	10.28	0.33	0.01	0.01	0.42	0.64
Bacterial OM	2.52	2.93	2.47	3.53	2.74	0.35	0.34	0.30	0.12	0.66
Digestibility, % of intake										
Stomach, apparent	36.3	36.5	32.8	23.5	26.2	3.1	0.09	0.02	0.87	0.34
Stomach, true[3]	42.9	41.9	48.8	50.1	54.3	4.8	0.29	0.22	0.28	0.78
SI[4]	30.5	24.0	28.6	31.2	33.7	3.1	0.75	0.10	0.29	0.74
Total tract	67.1	62.2	64.3	56.4	67.1	1.7	0.04	0.43	0.01	0.04
SI, % of Duodenal flow	46.8	35.6	42.5	40.6	44.8	3.8	0.19	0.40	0.19	0.74
N										
Intake, g/d	329	346	340	339	367	12	0.21	0.46	0.41	0.21
Duodenal flow, g/d										
Total	307	367	347	383	373	16	0.01	0.26	0.38	0.78
NAN	297	352	334	370	361	15	0.01	0.24	0.43	0.80
Bacterial N	204	242	211	233	227	21	0.36	0.90	0.42	0.58
NANBN[5]	92	109	123	137	134	13	0.06	0.22	0.70	0.55
RUP,[6] % of N Intake	29.2	31.6	36.6	40.1	36.3	4.7	0.22	0.43	0.88	0.39
RUP of CS, % of N	. . .	10.8	35.8	39.8	42.8	7.5	. . .	0.04	0.07	0.14
Digestibility										
Total tract, % of intake	72.8	67.0	68.2	62.1	71.9	1.6	0.01	0.74	0.01	0.03
SI, % of Duodenal flow	70.3	70.5	68.1	68.0	69.0	1.8	0.53	0.72	0.72	0.39
Bacterial protein synthesis, g of bacterial N/kg of OM truly digested in the stomach	42.9	46.4	32.5	38.2	31.1	5.7	0.38	0.46	0.10	0.57
Bacterial N, % of bacterial OM	8.29	8.20	8.50	6.92	8.30	0.43	0.53	0.15	0.10	0.26
NDF										
Intake, kg/d	3.06	4.85	4.57	5.18	5.07	0.10	0.01	0.01	0.09	0.41
Digestibility, % of intake										
Stomach	19.9	30.5	29.6	16.9	16.4	3.3	0.38	0.01	0.84	0.94
SI	4.88	4.16	–2.19	15.32	17.10	4.74	0.50	0.02	0.65	0.42
Total tract	25.1	34.1	33.0	29.1	42.5	3.3	0.04	0.56	0.11	0.07
SI, % of Duodenal flow	3.95	0.09	–3.05	20.42	18.05	8.00	0.60	0.05	0.96	0.74

[1]Control = No CS, RWCS = raw CS, and ROCS = roasted CS.

[2]Contrasts: control versus CS diets, raw versus roasted CS, whole versus ground CS (WCS and GCS, respectively), and interaction between heat treatment and particle size.

[3]True OM digestibility in the stomach = total flow of OM to the duodenum minus microbial OM flow to the duodenum divided by intake of OM.

[4]Small intestine.

[5]Nonammonia, nonbacterial N.

[6]RUP = (NANBN/N intake) × 100.

TABLE 5. Least squares means (means of all hours) for ruminal NH_3 N, VFA, and pH of cows fed cottonseed (CS) processed in different ways.

Item	Diet[1]					SE	Contrast[2]			
	Control	Whole RWCS	Ground RWCS	Whole ROCS	Ground ROCS		Control vs. CS	RWCS vs. ROCS	WCS vs. GCS	Interaction
							P			
NH_3 N, mg/dl	14.9	12.0	13.1	11.3	12.0	1.5	0.13	0.57	0.58	0.88
VFA, m*M*	114	112	114	108	115	3	0.73	0.69	0.21	0.42
VFA, mol/100 mol										
Acetate (A)	52.6	56.8	55.3	56.7	58.7	0.9	0.01	0.10	0.76	0.08
Propionate (P)	28.5	29.1	29.9	27.4	24.8	1.1	0.57	0.01	0.42	0.16
Isobutyrate	1.23	0.68	0.71	0.71	0.83	0.05	0.01	0.19	0.16	0.39
Butyrate	13.3	11.0	11.2	12.7	12.6	0.8	0.17	0.12	0.98	0.84
Isovalerate	2.46	1.36	1.14	1.20	1.97	0.17	0.01	0.09	0.02	0.16
Valerate	1.94	1.26	1.47	1.27	1.24	0.08	0.01	0.24	0.33	0.20
A:P	2.01	2.06	1.92	2.18	2.44	0.13	0.37	0.03	0.69	0.16
pH	5.91	6.00	5.88	6.07	6.08	0.42	0.04	0.01	0.17	0.13

[1]Control = No CS, RWCS = raw CS, and ROCS = roasted CS.

[2]Contrasts: control versus CS diets, raw versus roasted CS, whole versus ground CS (WCS and GCS, respectively), and interaction between heat treatment and particle size.

Roasted CS decreased ruminal propionate concentration. Pena et al. (23) found similar effects when ROCS was fed to lactating cows. This decrease in ruminal propionate corresponded to the decreased OM and NDF digestibilities in the stomach that were observed with ROCS (Table 4). However, in some studies (19, 28, 32), either no effect on ruminal propionate was found or an increase in ruminal propionate occurred with heat-treated SB (3). Ruminal concentration of butyrate was similar for all diets, but concentrations of isoacids were lower for cows fed the CS diets than for those fed the control diet. Isovalerate concentration for ROCS tended to be higher than that for RWCS. Glimp et al. (12) and Mielke and Schingoethe (18) obtained the same result using SB diets. Isovalerate also was lower for WCS than for GCS.

Roasted CS decreased propionate and tended to increase acetate concentrations; therefore, the ratio of acetate to propionate (**A:P**) was higher for ROCS. Mohamed et al. (19) also obtained the same effect with roasted SB and ROCS, but, in other studies (23, 28, 32), heat treatment of oilseeds had no effect on A:P in the rumen. However, Block et al. (3) and Schingoethe et al. (27) found that A:P decreased when heat-treated SB were fed. Raw SB supplemented with tallow tended to decrease the molar proportion of acetate and increase the molar proportions of propionate in lactating cows (26).

Cows fed the control diet had a lower ruminal pH (Table 5) than did cows fed the CS diets, because the control diet was lower in fiber and higher in rapidly fermentable carbohydrates. The RWCS resulted in lower ruminal pH than did the ROCS, possibly because roasting decreased the degradability of the CS fiber (Table 4). This effect on ruminal pH was not consistent with other reports that showed no effect of heat treatment of SB or SB meal (3, 17, 19, 27, 28) or of solvent extraction of CS meal (13, 22).

Data for apparent digestibility of OM are presented in Table 4. Intake of OM was similar among CS diets during the last 4 d of each period. Discussion comparing the control and CS diets is minimized; although many differences occurred, the primary reason for including the control diet was to facilitate calculation of RUP. Roasting increased duodenal flows of OM, probably because of reduced NDF digestibility (Table 4). In contrast, Pena et al. (23) did not find any effect of ROCS on flow of digesta to the duodenum. Flows of bacterial OM were similar among all diets.

Roasting decreased apparent digestibility of OM in digestive compartments located prior to the small intestine (hereafter referred to as the stomach). True digestibility of OM in the stomach was similar among diets, ranging from 41.9 to 54.3%. This range was in agreement with the data reported by others in which ROCS (23) or roasted SB (32) were fed. An interaction between heat treatment and particle size occurred for total tract digestibility of OM; ROCS and GCS resulted in the highest total tract OM digestion, which was in contrast to results of some reports (19, 32) that failed to determine an effect of heat treatment on DM digestibility of SB. However, Pena et al. (23) found a significant decrease in total tract digestibility of OM when ROCS were fed.

Intake of N (Table 4) was not different among diets. Duodenal flows of N were significantly lower for

the control diet than for the CS diets, and duodenal flows were not affected by roasting. In contrast, Pena et al. (23) reported higher duodenal N flows for the diet containing ROCS than for the control diet. Flows of NAN and feed N (nonammonia, nonbacterial N) to the duodenum were lower for the control diet than for the CS diets, but the flow of bacterial N was not different among diets.

As expected, apparent digestibilities of N (percentage of intake) in the stomach and total tract were higher for the control diet than for the CS diets because of highly degradable protein sources. In the study by Tice et al. (32), apparent digestibility of N in the total tract was greater for cows fed a control diet than for those fed SB diets. There was no effect of roasting on total tract digestibility of N, but an interaction between heat treatment and particle size occurred; ground ROCS resulted in a higher increase in total tract digestibility of N than did ground RWCS. Grinding CS increased total tract digestibilities of N probably because of the increased surface area for contact with proteases. Digestibility of N (percentage of duodenal flow) in the small intestine was similar among diets.

The RUP concentrations measured in vivo were not significantly different among diets, but RUP was numerically highest for the ground ROCS diet. Roasting and grinding increased the RUP content of CS. Tice et al. (32) found that the roasting process and the larger particle sizes of SB resulted in higher RUP for SB measured in vivo. Perhaps the fiber from lint and hulls caused the intact seed to reside in the rumen longer than GCS, thereby increasing the degradability of CP. Efficiency of bacterial N synthesis (grams of bacterial N per kilogram of OM truly digested) ranged from 31.1 to 46.4 (Table 4) and was lower than efficiencies reported by Stern et al. (28) but higher than those reported by Tice et al. (32). Bacterial protein synthesis tended to be higher for WCS than for GCS, but N content of bacteria tended to be increased for GCS. Bacterial populations were apparently shifted, partially explaining the responses in bacterial N.

As expected, intake of NDF (Table 4) was lower for the control diet than for the CS diets. The NDF intake was lower for RWCS than for ROCS and tended to be higher for WCS than for GCS. Although unexplainable, the digestibility of NDF in the stomach (percentage of intake) was higher for RWCS than for ROCS; however, NDF digestibilities in the small intestine (percentage of intake and duodenal flows) were higher for ROCS than for RWCS. Therefore, this higher digestibility in the small intestine compensated for the lower ruminal NDF digestibility such that total tract digestibility was similar among CS diets. Pena et al. (23) observed that ADF digestion in the stomach was lower for ROCS than for RWCS, but total tract digestibility was similar. Apparent total tract digestibility of NDF was lower for the control diet, perhaps because of greater negative associative effects. There was a tendency for an interaction between heat treatment and particle size for total tract digestibility of NDF. Grinding increased intestinal NDF digestibility.

There was no difference in FA intake among cows fed the various CS diets (Table 6). Intake of $C_{18:2}$, total C_{18}, and total FA were lower for cows fed the control diet than for cows fed the CS diets. Lower FA intake by cows fed the control diet resulted from lower DMI. The higher intake of $C_{18:0}$ by cows fed the control diet occurred because tallow was included in that diet but not in the CS diets. Because DMI was similar among cows fed all CS diets, none of the individual FA intakes were different among CS diets. In the control diet, $C_{18:1}$ was the predominant C_{18} FA consumed, but $C_{18:2}$ was the predominant FA consumed in the CS diets. The lower FA intake for cows fed the control diet tended to result in lower duodenal flow of FA compared with that for cows fed CS diets. Duodenal flow of total C_{18} was lower for cows fed the control diet than for cows fed the CS diets, primarily because of lower flows of $C_{18:0}$ (data not shown) and $C_{18:2}$. However, duodenal flows of total FA ($P = 0.08$), $C_{16:0}$, and $C_{18:2}$ were higher for cows fed ROCS than for cows fed RWCS even though total FA intake was similar among cows fed all CS diets. Also, the flow of $C_{18:2}$ was lower for cows fed WCS than for cows fed GCS, possibly because WCS might have spent more time in the rumen, therefore increasing the possibility of additional biohydrogenation. Sullivan et al. (30) also made this speculation when explaining possible causes of higher $C_{18:2}$ in milk when cracked Pima CS was fed than when whole linted CS was fed. Cows fed the control diet had less biohydrogenation than did cows fed the CS diets. Opposite results were found by Klusmeyer and Clark (15) and Wu et al. (41); in those studies, control diets with no additional fat had higher biohydrogenation than did diets containing supplemental fat. Conversely, Tice et al. (33) did not find significant differences in biohydrogenation among diets containing Ca soaps and SB. The ROCS decreased biohydrogenation compared with RWCS. In contrast, Tice et al. (33) found similar biohydrogenation levels when raw versus roasted SB were compared. Biohydrogenation tended to be lower with the GCS than with the WCS, possibly because the small CS particles spent less residence time in the rumen.

Total tract digestibility of total FA and $C_{16:0}$ tended to be lower for WCS than for GCS, indicating that grinding of CS influenced absorption of FA. Sullivan et al. (30) also observed higher apparent digestibility of ether extract in the total tract for cracked Pima CS than for whole Pima CS. Apparent digestibility of FA in the small intestine (percentage of duodenal flow) was higher for the control diet than for the CS diet. Also, an interaction between heat treatment and particle size for total FA, $C_{18:0}$, and total C_{18} occurred, such that grinding decreased FA digestibility in the small intestine for RWCS but not for ROCS. Digestibility of $C_{18:0}$ and total C_{18} in the small intestine tended to be lower with ROCS than with RWCS and lower with GCS than with WCS.

Data for milk production and DMI are presented in Table 7. The BW were similar for cows fed all treatments. Although DMI was lower for cows fed the control diet than for cows fed the CS diets, NE_L intakes were similar because of the higher dietary NE_L concentration for the control diet. The ROCS increased production of energy-corrected milk, but GCS had no effect on milk production or composition.

Production of milk, milk fat, milk protein, 4% FCM, and energy-corrected milk were lower for cows fed the control diet than for cows fed the CS diets. Milk protein percentage was also lower for cows fed the control diet. Milk protein production and percentage were increased by ROCS, possibly because of the numerically higher intake of RUP.

Some studies (4, 6, 37) suggested that roasting SB might offer a greater potential for increasing milk production when diets are based on alfalfa silage because of the high degradability of the protein in alfalfa. Therefore, use of corn silage as the only forage in our diets might have caused production responses to be lower than if alfalfa silage had been fed. Other reasons might also explain the lack of response from

TABLE 6. Intakes, duodenal flows, biohydrogenation, and apparent digestibilities of fatty acids (FA) by cows fed cottonseed (CS) processed in different ways.

	Diet[1]						Contrast[2]			
Item	Control	Whole RWCS	Ground RWCS	Whole ROCS	Ground ROCS	SE	Control vs. CS	RWCS vs. ROCS	WCS vs. GCS	Interaction
							P			
Intake, g/d										
Total FA	665	753	739	778	819	31	0.01	0.16	0.68	0.41
16:0[3]	136	143	141	148	154	7	0.21	0.24	0.77	0.60
18:0	77.9	18.2	19.5	19.4	20.8	2.9	0.01	0.70	0.67	0.97
cis-18:1	198	127	127	127	135	9	0.01	0.67	0.68	0.63
18:2	133	373	394	411	429	28	0.01	0.27	0.52	0.97
Total 18	425	535	559	575	605	36	0.01	0.29	0.48	0.92
Duodenal flow, g/d										
Total FA	654	702	697	816	761	41	0.08	0.08	0.49	0.57
16:0	139	136	131	156	146	7	0.67	0.04	0.29	0.75
18:2	21.5	28.8	38.0	45.9	53.4	2.7	0.01	0.01	0.02	0.76
Total 18	469	543	535	596	585	27	0.03	0.17	0.76	0.95
Biohydrogenation[4]	74.6	84.6	82.5	81.4	79.3	1.1	0.01	0.02	0.10	0.98
Total tract digestibility, % of intake										
Total FA	74.2	73.4	74.3	71.0	76.5	1.6	0.84	0.96	0.09	0.19
16:0	77.2	77.0	77.8	73.4	78.4	1.4	0.73	0.36	0.08	0.18
Total 18	71.5	71.4	74.4	70.7	75.5	2.8	0.66	0.94	0.20	0.75
Small intestinal digestibility, % of duodenal flow										
Total FA	77.6	76.8	72.2	72.7	74.2	0.90	0.01	0.31	0.13	0.01
16:0	80.1	70.3	77.5	79.9	79.6	5.5	0.60	0.36	0.54	0.52
18:0	73.7	79.1	68.1	67.4	69.4	2.0	0.25	0.05	0.06	0.01
18:2	81.9	74.1	82.5	76.8	84.4	3.5	0.54	0.56	0.06	0.91
Total 18	78.4	81.6	73.2	72.3	74.9	1.6	0.16	0.07	0.12	0.01

[1]Control = No CS, RWCS = raw CS, and ROCS = roasted CS.

[2]Contrasts: control versus CS diets, raw versus roasted CS, whole versus ground CS (WCS and GCS, respectively), and interaction between heat treatment and particle size.

[3]Number of carbons:number of double bonds.

[4]Calculated as $100 - [100 \times ((D18:1 + (D18:2 \times 2) + (D18:3 \times 3))/D18)/(I18:1 + (I18:2 \times 2) + (I18:3 \times 3))/I18]$, where D = duodenal flow, I = intake, and 18 = total C_{18} FA. Individual C_{18} FA were expressed as percentages of total C_{18} FA; biohydrogenation is expressed as the percentage of unsaturated bonds in FA that became saturated in the rumen (33).

TABLE 7. Body weight, intake, and milk production and composition data of cows fed cottonseed (CS) processed in different ways.

Item	Diet[1]						Contrast[2]			
	Control	Whole RWCS	Ground RWCS	Whole ROCS	Ground ROCS	SE	Control vs. CS	RWCS vs. ROCS	WCS vs. GCS	Interaction
							P			
BW, kg	508	517	504	526	524	8	0.34	0.13	0.38	0.57
DMI, kg/d	12.6	14.3	14.0	13.9	14.5	0.5	0.03	0.91	0.73	0.41
DMI, % of BW	2.53	2.76	2.80	2.64	2.83	0.13	0.16	0.01	0.05	0.02
NE_L Intake,[3] Mcal/d	23.6	24.7	24.7	23.9	25.8	1.0	0.33	0.91	0.41	0.41
Milk, kg/d	17.6	18.7	18.9	19.8	19.8	0.7	0.05	0.16	0.91	0.87
Fat, %	3.44	3.76	3.61	3.55	3.83	0.21	0.32	0.97	0.77	0.36
Fat, g/d	612	697	667	711	788	50	0.09	0.28	0.64	0.32
Protein, %	3.05	3.19	3.15	3.28	3.25	0.04	0.01	0.07	0.32	0.88
Protein, g/d	539	589	580	659	667	12	0.01	0.01	0.95	0.50
4% FCM, kg/d	16.3	17.8	17.5	18.9	20.3	0.9	0.05	0.12	0.59	0.39
ECM,[4] kg/d	17.6	19.3	18.9	20.7	21.9	0.8	0.02	0.07	0.67	0.37

[1]Control = No CS, RWCS = raw CS, and ROCS = roasted CS.

[2]Contrasts: control versus CS diets, raw versus roasted CS, whole versus ground CS (WCS and GCS, respectively), and interaction between heat treatment and particle size.

[3]NE_L Intake calculated from energy concentrations in the feed offered and orts.

[4]Energy-corrected milk = (7.2 × kilograms per day of protein) + (12.95 × kilograms per day of fat) + (0.327 × kilograms per day of milk), based on an equation developed by Tyrrell and Reid (34) with factors modified to use 3.5% milk fat (instead of 4%) and 3.2% of protein as the basis for standardization.

processing of CS. The main objective of this trial was primarily to collect digestibility data; therefore, duration of the periods (2 wk) were too short to allow adequate adaptation for milk production and composition responses. Also, the cows were in late lactation, which might have caused a smaller response, and the milk production of cows was low relative to CP intakes for observing effects of ROCS or GCS. Therefore, caution should be used when conclusions are made based on milk production.

Cottonseeds are high in $C_{18:2}$. The concentration of $C_{18:2}$ in milk was 1.79, 2.50, 2.89, 3.33, and 3.71% of total FA for control, whole RWCS, ground RWCS, whole ROCS, and ground ROCS, respectively. The $C_{18:2}$ was lower in the control diet than in the CS diets because of lower intake of $C_{18:2}$. Diets with ROCS increased $C_{18:2}$ in milk, and GCS tended (P = 0.06) to increase the proportion of $C_{18:2}$ in milk. Although intake of $C_{18:2}$ was similar for RWCS and ROCS, ROCS increased $C_{18:2}$ in milk because of the lower ruminal biohydrogenation that occurred for ROCS (Table 6). Higher intestinal digestibility of $C_{18:2}$ for GCS versus WCS, or possibly even the slightly lower biohydrogenation with GCS, likely contributed to the tendency for an increase in milk $C_{18:2}$ with GCS.

CONCLUSIONS

The processing of oilseeds influences their utilization by dairy cows. Ruminal A:P and pH increased when CS were roasted. The potential for increasing RUP from CS by heat treatment appears to be less than that from SB. Roasting decreased digestibility of OM in the stomach but did not affect total tract digestibility. Grinding increased total tract digestibilities of OM and N and appeared to be more beneficial for ROCS than for RWCS. Roasting shifted the digestibility of the NDF in CS from the stomach to the intestine. Roasting tended to increase milk protein percentage and production. Long-term studies, especially with high producing cows in early lactation, are needed to elucidate any sound production responses to the processing of CS. Also, improvement in equipment to handle linted CS is needed to facilitate widespread application of these processes.

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