Effect of replacing solvent-extracted canola meal with high-oil traditional canola, high-oleic acid canola, or high-erucic acid rapeseed meals on rumen fermentation, digestibility, milk production, and milk fatty acid composition in lactating dairy cows

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ABSTRACT

The objective of this experiment was to investigate the effects of replacing conventional, solvent-extracted canola meal (control; CTRL) with high oil content; conventional, mechanically extracted canola meal (CMEC); high-oleic, low polyunsaturated fatty acid (FA) canola meal (HOLL); and high-erucic acid, low-glucosinolate rapeseed meal (RPS) on rumen function, digestibility, milk production, and milk FA composition in lactating dairy cows. The experimental design was a replicated 4 × 4 Latin square with 8 lactating dairy cows. Four of the cows were ruminally cannulated. All oilseed meals were included at approximately 12 to 13% of dietary dry matter (DM). Crude protein and fat concentrations (% of DM) of the meals were 43 and 3.1%, 32.8 and 16.1%, 45.2 and 13.7%, and 34.3 and 17.9% for CTRL, CMEC, HOLL, and RPS, respectively. All diets were formulated to supply net energy of lactation in excess of requirements. The CMEC and RPS diets were predicted to be about 1% deficient in metabolizable protein. Relative to the CTRL, inclusion of high-oil seed meals in the diet lowered ruminal acetate concentration and the molar acetate:propionate ratio and decreased DM intake. Milk yield generally followed DM intake and was lower for CMEC and RPS than the CTRL. Treatments had no effect on milk composition, other than an increase in milk urea nitrogen concentration for HOLL. Fat-corrected milk (3.5%) feed efficiency was increased by HOLL and RPS compared with CTRL. Urinary urea nitrogen losses were increased by HOLL, which, as a consequence, increased the ammonia-emitting potential of manure. The ratio of milk N-to-N intake was greater for CMEC and RPS.

Replacing solvent-extracted canola meal with the high-oil meal decreased milk fat 12:0, 14:0, 16:0, and total saturated FA content and enhanced *cis*-9 18:1 and total monounsaturated FA concentrations. Relative to the CTRL, canola increased total *trans* FA in milk, whereas inclusion of HOLL in the diet increased *trans*-11 18:1 and *cis*-9, *trans*-11 CLA content. The RPS increased milk fat *cis*-13 22:1 content from 0.07 to 2.33 g/100 g of FA. In conclusion, HOLL or RPS, which are likely to come from small-scale biodiesel plants where oil is cold pressed without hexane extraction, fed at levels at or above 12 to 13% of dietary DM may decrease feed intake and milk production, but can be used to alter milk FA composition in lactating dairy cows.

Key words: canola meal, rapeseed meal, fatty acid, dairy cow

INTRODUCTION

Environmental concerns of burning fossil fuels and a desire to decrease fossil oil imports into the United States have generated greater interest in developing alternative fuels, including bioethanol and biodiesel. A high oil yield per acre makes canola and rapeseed ideal for biodiesel production. In addition, biodiesel made from canola and rapeseed oil has excellent quality characteristics, mainly improved cold flow, longer shelf life, and reduced mono-nitrogen oxides (NO_x) emissions compared with other feedstock oils (Brown, 2010; Zhang and Malhi, 2010).

Rapeseed has been grown as an oilseed crop in Europe since the Middle Ages, and the high erucic acid oil was used extensively as a steam engine lubricant during the Industrial Revolution. Concerns of high erucic acid in the human diet, however, resulted in the development by Canadian breeders of rapeseed cultivars (*Brassica napus* L. and *Brassica campestris* L.) with drastically decreased erucic acid and increased oleic acid concentration (i.e., canola). In 1974, the first canola cultivar

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(Tower) with both low erucic acid (less than 2%) in the seed oil and less than 30 $\mu\text{mol/g}$ of total glucosinolates in the seed meal was released for commercialization (Stefansson and Kondra, 1975). The low glucosinolate content of canola seed meal made this coproduct of canola crushing a suitable feed for inclusion in diets for dairy cows and beef cattle (Sharma et al., 1977; Lardy and Kerley, 1994). Recently, increased interest in biodiesel and other biodegradable and environmentally safe oil products (i.e., lubricants, surfactants, cutting fluids, among others) has renewed the demand for high-erucic acid oils from rapeseed. Breeding efforts in rapeseed have resulted in seed meals identical to that available from canola where seed meal glucosinolates have almost been eliminated (Brown et al., 1998).

Both canola and rapeseed oil contain high levels of *cis*-9 18:1 and *cis*-13 22:1 (Sakhno, 2010). Comparatively, canola has higher saturated fatty acid (FA) content (6 to 8%) than rapeseed (4%) and rapeseed is less abundant in polyunsaturated FA (PUFA; 20% compared with 30% in canola). Conventional canola oil, although low in saturated FA, is typically hydrogenated to avoid off-flavors during high temperature frying and to increase shelf life of the oil products. Rancidity and off-flavors in canola oil are caused by high PUFA content and, hence, products made from conventional canola cultivars are relatively high in *trans* FA. *Trans* FA are considered risk factors for cardiovascular disease (Mensink et al., 2003), which led to the development of canola-type cultivars with high oleic acid combined with low PUFA (**HOLL**; 18:2n-6 and 18:3n-3) content (Sakhno, 2010). Fry oil from these cultivars is oxidatively stable without hydrogenation and, hence, is *trans*-FA free (Orthofer, 2005). Traditional canola, HOLL canola, and low-glucosinolate rapeseed cultivars only differ in the composition of their seed oils, whereas the seed meal is low in glucosinolates and other toxins that could decrease their nutritive value in livestock (Hickling, 2001).

The type of fat in dairy cattle diets may have a significant effect on milk or tissue FA composition (Jenkins and McGuire, 2006). Many studies have examined the potential of oilseeds in the diet of lactating cows to lower milk fat 12:0, 14:0, and 16:0 content and increase *cis*-monounsaturated fatty acids (MUFA) and PUFA concentrations (Ney, 1991; Glasser et al., 2008; Shingfield et al., 2008). Canola oil, with its high MUFA and low PUFA content is a good candidate as a dietary ingredient to alter milk FA composition. Canola oil added to the diet of lactating cows (mixed with the diet or infused intraruminally) increased total 18:1 and decreased 16:0 content of milk fat (DePeters et al., 2001). Increases in milk 18:1 isomers and *cis*-9, *trans*-11 conjugated linoleic (**CLA**) have been reported in cows

fed diets supplemented with whole ground canola seeds or Ca salts of FA from canola oil (Chouinard et al., 2001; Ward et al., 2002; Chichlowski et al., 2005). Intermediates of ruminal lipid metabolism, including 9,11 and 10,12 isomers of CLA, have been shown to inhibit the growth of several human cancer cell lines and suppress chemically-induced tumor development in animal models (Ha et al., 1987; Parodi, 1999; Shingfield et al., 2008). Decreases in milk fat saturated FA because of supplementation with canola or rapeseed, however, are also accompanied by increases in milk *trans* FA concentrations (Collomb et al., 2004; Givens et al., 2009; Rego et al., 2009). The relative abundance of *cis*-9 18:1 and PUFA in plant oils is known to alter the distribution of *trans* FA in milk fat (Shingfield et al., 2008; Bernard et al., 2009; Rego et al., 2009) with the implication that high-residual oil canola or rapeseed meals of variable composition could be expected to alter the nutritional characteristics of milk fat.

The successful use of oilseeds as biodiesel feedstock depends heavily on use of the meal as animal feed. An economic analysis by Gavett and Van Dyne (1992) concluded that biodiesel produced from canola (or rapeseed) can only be economically competitive in the United States if government incentives are maintained and coproducts are successfully marketed as animal feed. Conventional, solvent-extracted, canola meal has very little residual oil (NRC, 2001) and has been successfully used as a protein feed in dairy diets (Schingoethe, 1996; Brito and Broderick, 2007; Mulrooney et al., 2009). Small-scale biodiesel facilities (i.e., 19 to 38 million-liter output) are proving to be more feasible compared with large-scale (380 million-liter) facilities that find it difficult to guarantee high quantities of raw oil feedstock. However, modern small-scale biodiesel facilities use mechanical oil extraction rather than hexane extraction, which results in seed meal coproducts with significantly higher oil content (Van Gerpen et al., 2005; Südekum, 2007). Plant oils and constituent PUFA, in particular, are known to elicit adverse effects on ruminal fermentation and may, in high amounts, lower ruminal fiber digestion (Palmquist and Jenkins, 1980; Nagaraja et al., 1997). Mechanically extracted canola and rapeseed seed meals contain high levels of oil rich in unsaturated FA (CRC, 1988), but research on the ruminal and production effects of these high-oil meals in dairy cows is lacking.

Therefore, the objective of this study was to investigate the effect of substitution of conventional, solvent-extracted canola meal (with low oil content) in the diet of lactating dairy cows with high-residual oil, mechanically extracted canola or rapeseed meals with identical seed meal glucosinolate content, but of variable oil FA composition. Our hypothesis was that high-oil canola

Table 1. Chemical¹ and fatty acid composition of the canola and rapeseed meals fed in the trial²

Composition, % of DM (or as indicated)	CTRL	CMEC	HOLL	RPS
CP	43.0	32.8	45.2	34.3
NDF	33.3	28.3	25.7	34.1
NFC	20.3	21.1	13.7	12.1
NE _L , ³ Mcal/kg	1.74	2.32	2.37	2.35
Ether extract	3.1	16.1	13.7	17.9
Fatty acid, ⁴ g/100 g of total fatty acids				
16:0	6.5	5.1	3.6	3.3
18:0	1.4	1.9	2.5	1.2
18:1	63.1	60.0	76.1	16.7
<i>cis</i> -9, <i>cis</i> -12 18:2	25.8	20.3	10.1	12.8
<i>cis</i> -9, <i>cis</i> -12, <i>cis</i> -15 18:3	2.7	9.0	3.5	6.4
<i>cis</i> -11 20:1	ND ⁵	1.2	1.5	9.8
<i>cis</i> -13 22:1	ND	0.1	0.1	42.0

¹As analyzed by Dairy One Inc. (Ithaca, NY).

²CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³Estimated by Dairy One Inc., based on NRC (2001) equations.

⁴Analyzed at the University of Idaho, Moscow (see Materials and Methods).

⁵Not detected.

and rapeseed meals can successfully replace conventional canola meal when included up to 15% of the dietary DM and may have some beneficial effects on milk FA composition.

MATERIALS AND METHODS

Animals and Treatments

The experiment was conducted under the approval of The Pennsylvania State University Animal Care and Use Committee (IACUC# 29567) and involved 8 multiparous Holstein dairy cows, averaging 49 ± 2.1 kg of milk/d, 2.6 ± 0.32 lactations, 643 ± 21.9 kg of BW, and 109 ± 15.1 DIM at the beginning of the trial. The design of the trial was a replicated 4×4 Latin square. Four cows (first square) were fitted with soft plastic ruminal cannulas (Bar Diamond Inc., Parma, ID) and the other 4 cows (second square) were intact. Only the ruminally cannulated cows were used to generate rumen fermentation data. Experimental periods were 17 d in duration, including 12 d for adaptation to the diet and 5 d for sampling. This length of the experimental periods was chosen based on availability of experimental canola and rapeseed meals. The treatments included (1) conventional, solvent-extracted canola meal (control; **CTRL**); (2) conventional, high-oil mechanically extracted canola meal (**CMEC**); (3) high-oil mechanically extracted, high-oleic acid, low-PUFA canola meal (**HOLL**); and (4) high-oil mechanically extracted, low-glucosinolate rapeseed meal (**RPS**). The high-oil content seed meals (CMEC, HOLL, and RPS; Table

1) were produced at the J. W. Martin Laboratory by Joseph Thompson (Dept. of Biological and Agricultural Engineering, University of Idaho) with seed purchased from Pacific Northwest Farmers Cooperative, Genesee, ID (CMEC); Cargill Specialty Canola Oils (Idaho Falls, ID; HOLL); and the University of Idaho Canola and Rapeseed Program (Moscow, ID; RPS). Prior to mechanical seed crushing, the seed was heated to 50°C and during the crush process the seed meal reached temperatures no higher than 70°C. Seed meals were stored in waterproof metal storage bins until used in this study. The CTRL meal was purchased from a local grain and feed ingredient merchant (McGeary Grain Inc., Lancaster, PA).

Cows were housed in a tie-stall facility and were fed twice daily at approximately 0800 and 1600 h. Seed meals were added to the basal TMR at inclusion rates of 12 to 13% (DM basis; Table 2). The seed meals were top-dressed and mixed with a portion of the TMR, immediately before the a.m. and p.m. feedings, to ensure complete consumption. Feed was pushed up approximately 4 to 6 times daily. All diets were fed ad libitum to achieve approximately 5% refusals. Cows had access to fresh water throughout the duration of the trial. During the trial, cows were milked daily at 0530 and 1730 h and received recombinant bovine somatotropin (rBST) at 14-d intervals (Posilac; Elanco Co., Greenfield, IN; 500 mg, i.m.) beginning at 63 DIM. As the design of the experiment was a Latin square, we assumed that the effect of rBST was evenly distributed among treatments over the duration of the experiment and did not affect our results.

Table 2. Ingredient and chemical composition of the experimental diets¹

Item	CTRL	CMEC	HOLL	RPS
Ingredient, % of DM				
Corn silage ²	44.8	44.4	44.3	44.4
Alfalfa haylage ³	8.4	8.3	8.3	8.3
Grass hay ⁴	4.4	4.4	4.4	4.4
Corn grain, ground	11.2	11.1	11.1	11.1
SoyChoice ⁵	6.4	6.3	6.3	6.3
Cookie byproduct ⁶	6.7	6.6	6.6	6.7
Cottonseed hulls	3.0	3.0	3.0	3.0
CTRL	12.1	—	—	—
CMEC	—	12.9	—	—
HOLL	—	—	13.0	—
RPS	—	—	—	12.8
Mineral/vitamin premix ⁷	3.0	3.0	3.0	3.0
Composition, % of DM or as indicated ⁸				
CP	16.0	14.9	16.6	15.1
RDP	9.2	8.6	9.7	8.8
RUP	6.8	6.3	6.9	6.3
MP required, ⁹ g/d	3,164	3,042	3,048	2,962
MP supplied, ⁹ g/d	3,393	3,013	3,269	2,926
MP balance, ⁹ g/d	229	−29	221	−36
Ether extract	3.9	5.5	5.2	5.7
NDF	31.1	31.3	31.0	32.1
ADF	20.1	20.5	20.6	20.4
NE _L , Mcal/kg	1.48	1.55	1.56	1.57
NE _L balance, ⁹ Mcal/d	6.0	6.9	5.8	5.4
NFC	47.4	46.5	45.5	45.4
Ca	0.3	0.3	0.3	0.3
P	0.4	0.4	0.4	0.4

¹Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

²Corn silage was, on average, 36.4% DM and (as % of DM) 35.5% NDF, 7.3% CP, and 37.8% starch.

³Alfalfa haylage was, on average, 32.5% DM and (as % of DM) 22.1% CP and 38.4% NDF.

⁴Grass hay contained (as % of DM) 70.1% NDF and 7.5% CP.

⁵SoyChoice (expeller soybean meal from Wenger's Feed Mill Inc., Rheems, PA) contained (as % of DM) 47.7% CP, 46% RUP (as % of CP), 54% RDP (as % of CP), 16.3% NDF, and 27.5% NFC.

⁶Cookie byproduct (Bakery Feeds, Honey Brook, PA) contained (as % of DM) 12.8% CP, 9.2% ether extract, 59.8% NFC, and 14.1% NDF.

⁷The premix contained (% as-is basis) trace mineral mix, 0.88; MgO (54% Mg), 8.3; NaCl, 6.4; vitamin ADE premix, 1.73; limestone, 35.8; selenium premix, 1.09; and dry corn distillers grains with solubles, 45.8. Composition: Ca, 14.1%; P, 0.35%; Mg, 4.58%; K, 0.41%; S, 0.31%; Mn, 1,071 mg/kg; Cu, 358 mg/kg; Zn, 1,085 mg/kg; Fe, 181 mg/kg; Se, 6.67 mg/kg; Co, 5.4 mg/kg; I, 13.4 mg/kg; vitamin A, 262,101 IU/kg; vitamin D, 65,421 IU/kg; and vitamin E, 1,971 IU/kg.

⁸As estimated by NRC (2001), based on analyzed chemical composition of feedstuffs (Cumberland Valley Analytical Services, Maugansville, MD), or as specified in Materials and Methods, and amounts mixed in the TMR.

⁹As predicted by NRC (2001), based on actual milk production, milk composition, and nutrient intakes.

Sampling and Analyses

Feed intake was measured daily and samples from the basal TMR, individual feeds, the canola and rapeseed meals, and refusals were collected twice weekly and composited by week. Samples were dried for 48 h at 65°C in a forced-air oven and then ground in a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA) through a 1-mm screen for chemical analyses. Samples were then composited by period. When necessary, aliquots were pulverized at 30 Hz/s for 2 min using Mixer Mill MM 200 (Retsch GmbH, Haan, Germany) for N

analysis. Individual forages were sampled weekly and dried in a microwave oven to determine DM content. Weekly changes were made to the TMR if changes occurred in forage DM.

Rumen samples from the cannulated cows were collected on 2 consecutive days during the 5-d sampling period. Whole ruminal contents were collected at 0, 2, 4, and 6 h after the a.m. feeding from the rumen ventral sac, atrium, and 2 samples from the feed mat. Samples were filtered through 2 layers of cheesecloth and the filtrate was immediately placed on ice for further analyses.

Eight spot urine (approximately 300 mL each) and fecal (approximately 400 g each) samples were collected from each cow at 0900, 1500 and 2100 (d 1 of each sampling period), 0300, 0600, 1200, 1800 (d 2), and 0000 h (d 3). Urine samples were collected by massaging the vulva. Fecal samples were collected from the rectum or from the ground, if fresh. Urine was acidified (pH <3) using 2M H₂SO₄; the pH was verified using litmus paper. Acidified urine was diluted 1:10 with distilled water and stored frozen at -20°C. Fecal samples were oven-dried at 65°C and composited per cow and period on an equal DM basis. Aliquots of fresh urine (non-acidified) and feces were composited on a wet basis by cow and period and frozen immediately at -20°C for later analysis of ammonia and greenhouse gas emitting potential (EP) of manure.

Milk production was recorded daily and the milk yield during the 5-d sampling period was used in the statistical analysis. Samples for milk composition were collected 3 times during the sampling period (on d 1, 3, and 5). Morning and evening samples were analyzed separately so milk component concentration and yield could be weighed for a.m. and p.m. milk yields. Samples were preserved using 2-bromo-2-nitropropane-1,3-diol and analyzed for fat, true protein, lactose, and MUN [Pennsylvania DHIA, University Park; infrared spectroscopic method (method 927.16; AOAC, 2005); MilkoScan 4000; Foss Electric, Hillerød, Denmark]. At these times, unpreserved milk samples were also collected, composited according to yield, and stored at -20°C until submitted for FA analysis as outlined elsewhere (Hristov et al., 2009a). In brief, lipid in 1 mL of milk was extracted using a mixture of diethyl ether and hexane and transesterified to FA methyl esters using freshly prepared methanolic sodium methoxide. Methyl esters were quantified using a gas chromatograph (Model 6890; Hewlett-Packard, Wilmington, DE) equipped with a flame-ionization detector and a 100-m fused silica capillary column (i.d., 0.25 mm), coated with a 0.2-μm film of cyanopropyl polysiloxane (CP-SIL 88; Chrompack 7489, Middelburg, the Netherlands). Peaks were identified based on retention time comparisons with authentic standards (GLC #463 and GLC #606; Nu-Chek-Prep Inc., Elysian, MN). Methyl esters not contained in commercially available standards were formally identified by GC-MS analysis of 4,4-dimethylloxazoline FA (DMOX) derivatives prepared from FA methyl esters by incubation overnight with 2-amino-2-methyl-1-propanol under an N atmosphere at 150°C. Distribution of CLA isomers was determined by HPLC using 4 silver-impregnated silica columns (ChromSpher 5 Lipids, 250 × 4.6 mm; 5-μm particle size; Varian Ltd., Walton-on-Thames, UK) coupled in series, 0.1% (vol/vol) acetonitrile in heptane as the mobile phase and

monitoring column effluent at 233 and 210 nm. Milk FA composition was expressed as a weight percentage of total FA using theoretical relative response factors, whereas concentrations of specific CLA isomers were calculated based on proportionate peak area responses determined by HPLC and the sum of *trans*-7, *cis*-9 CLA; *trans*-8, *cis*-10 CLA; and *cis*-9, *trans*-11 CLA weight percentage determined by GC.

Blood samples were collected from the coccygeal tail vein or artery 2 h after feeding, on 2 consecutive days during each sampling period. Approximately 5 mL of blood was collected into an evacuated tube (Becton, Dickinson and Co., Franklin Lakes, NJ) containing 0.79 mg of sodium heparin. Tubes were placed immediately in ice and, within 1 h, centrifuged at 4°C at 1,500 × *g* for 15 min. Plasma was recovered and frozen at -20°C for analysis of plasma urea N (Stanbio Urea Nitrogen Kit 580; Stanbio laboratory Inc., San Antonio, TX).

Rumen cheesecloth filtrates were immediately analyzed for pH (pH meter 59000-60 pH Tester; Cole-Parmer Instrument Co., Vernon Hills, IL) and processed for analyses of ammonia (Chaney and Marbach, 1962), VFA (Yang and Varga, 1989), and total free AA (TFAA; ninhydrin procedure; Snell and Snell, 1954).

Ammonia, nitrous oxide, methane, and carbon dioxide EP of manure were analyzed in a steady-state gas emission system (Wheeler et al., 2007) as described by Hristov et al. (2010). Gases were analyzed on a photoacoustic gas analyzer (INNOVA Model 1412; AirTech Instruments, Ballerup, Denmark).

Dry matter intake was calculated by adjusting daily as-fed feed intake to DM content (measured for 48 h at 65°C) of the weekly diet and refusals composited samples. Feed samples were analyzed by wet chemistry for ether extract, Ca, and P and estimated NEL and NFC by Dairy One (Ithaca, NY) or Cumberland Valley Analytical Services (Maugansville, MD) (see Tables 1 and 2). Diet, feeds, refusals, and fecal composited samples were analyzed for NDF and ADF contents using the Ankom²⁰⁰ Fiber Analyzer (Ankom Technology, Macedon, NY) according to Van Soest et al. (1991) with heat-stable amylase (Ankom Technology) and sodium sulfite (Fisher Scientific, Waltham, MA) used in the NDF procedure. The N content of the TMR, feed, refusals, fecal, and freeze-dried urine samples was analyzed on a Costech ECS 4010 C/N/S elemental analyzer (Costech Analytical Technologies Inc., Valencia, CA; official method 990.03; AOAC, 1990) and multiplied by 6.25 to obtain CP values.

Apparent total tract digestibility of nutrients was estimated using indigestible NDF as an intrinsic digestibility marker. Indigestible NDF in diet and fecal samples was analyzed according to Huhtanen et al. (1994), with the exception that 25-μm pore size Ankom

filter bags were used for the rumen incubation. Diet, feeds, refusals, and fecal samples were ashed for 4 h at 600°C for analysis of OM.

Urinary purine derivatives (allantoin and uric acid) excretion was used to estimate duodenal microbial N flow (for equations see Hristov et al., 2009a). A ratio of purine N to total N in rumen microorganisms of 0.134 was assumed based on the data of Valadares et al. (1999).

Statistical Analysis

Data was analyzed using the PROC MIXED procedure of SAS (SAS Institute, 2003). Intake of nutrients, digestibility, urinary excretions, manure ammonia and greenhouse gas EP, and milk composition data were analyzed by ANOVA Latin square. The 3 milk composition samples collected during each sampling period were averaged per cow, and the average values were used in the statistical analysis and to calculate FCM, milk NE_L, and milk fat, protein, and lactose yields. The model used was

$$Y_{ijkl} = \mu + S_i + C(S)_{ij} + P_k + T_l + e_{ijkl},$$

where μ is the overall mean, S_i is the square, $C(S)_{ij}$ is the cow within square, P_k is the k th period, T_l is the l th treatment, with the error term e_{ijkl} assumed to be normally distributed with mean = 0 and constant variance. Square and cow within square were random effects and all others were fixed.

Ruminal pH, ammonia, TFAA, and VFA concentrations, plasma urea N, DMI, and milk yield data were analyzed as repeated measures using an autoregressive(1) covariance structure. The model used was

$$Y_{ijklm} = \mu + S_i + C(S)_{ij} + P_k + T_l + D_m + TD_{lm} + e_{ijklm},$$

where μ is the overall mean, S_i is the square, $C(S)_{ij}$ is the cow within square, P_k is the k th period, T_l is the l th treatment, D_m is the time effect, TD_{lm} is the treatment $\times$ time of sampling interaction with the error term e_{ijklm} assumed to be normally distributed with mean = 0 and constant variance. Square and cow within square were random effects and all others were fixed.

Statistical differences were declared at $P < 0.05$. Differences between treatments at $0.05 < P < 0.10$ were considered as a trend toward significance.

RESULTS

The meals used in this experiment differed in chemical composition and FA profile of the residual oil (Table

1). Compared with the CTRL [defatted (solvent-extracted) canola meal], the high-oil seed meals had a much greater residual oil content, which was reflected in the higher estimated NE_L values. The CP content of CMEC and RPS was about 75% of that of the CTRL, which, in the case of CMEC, was a result of its high oil content. Despite its high oil content, the HOLL had similar CP content to the CTRL. The proportion of NDF in the meal DM was lower for CMEC and HOLL compared with CTRL or RPS. The concentration of NFC was greater in the traditional canola meals (CTRL and CMEC) than HOLL and RPS. However, it should be noted that the seed used in these experiments were from different cultivars, which may have had different potentials to produce high protein or NDF. In addition, the seed used had different origins and were grown under different environmental conditions. Therefore, the compositional differences observed may have no association with the classes of oilseeds (i.e., CTRL, CMEC, HOLL, or RPS) selected for the study.

As would be expected, the FA profile of oils in the CTRL and CMEC meals was very similar and the 2 treatments differed only in the amount of oil in each meal. Seed oil in HOLL had lower concentration of 18:2n-6 and 18:3n-3 and a higher concentration of total 18:1, compared with the conventional canola meals. Rapeseed meal had a very low concentration of 18:1 and high content of *cis*-13 22:1 (erucic acid). It also contained about 10% of *cis*-11 20:1 (eicosenoic acid). The differences in chemical composition between the meals resulted in differences in the chemical composition of the diets (Table 2). As the objective of this experiment was to replace CTRL with equal amounts of experimental meals (and not to maintain the diets isonitrogenous and isoenergetic), the CP content of CMEC and RPS diets was lower than that of the CTRL and HOLL diets. At the actual level of DMI and milk production and composition of the cows, CMEC and RPS diets were about 1% deficient in MP (according to NRC, 2001). All diets supplied NE_L in excess of requirements (NRC, 2001). The experimental diets contained between 33% (HOLL) and 46% (RPS) more lipid than the CTRL diet. The estimated NFC and NDF contents were similar among diets. Thus, the only significant difference in the chemical composition between the CTRL and experimental diets was the marginal deficiency in MP for CMEC and RPS and the higher fat content and different FA profile of all experiment diets.

Ruminal pH was increased ($P = 0.041$) by HOLL compared with the CTRL and RPS (Table 3). The concentrations of ammonia, TFAA, total VFA, propionate, butyrate, isovalerate, and valerate were not affected by treatment. The acetate concentration was decreased ($P = 0.006$) by all high-oil meal diets compared with

Table 3. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on rumen fermentation in lactating dairy cows (LSM; n = 96,¹ rumen pH, ammonia, and VFA data; n = 32, purine derivatives excretion data)²

Item	CTRL	CMEC	HOLL	RPS	SEM	P-value
pH	6.25 ^b	6.34 ^{ab}	6.36 ^a	6.25 ^b	0.059	0.041 ³
Ammonia, mM	6.3	5.1	6.3	6.5	0.67	0.41 ³
TFAA, mM	1.7	1.2	1.4	1.8	0.25	0.18 ³
Total VFA, mM	125.4	120.9	115.8	119.7	5.37	0.27 ³
Acetate	74.7 ^a	68.8 ^b	65.6 ^b	69.5 ^b	2.28	0.006
Propionate	29.5	31.8	29.8	29.7	3.11	0.58
Isobutyrate	1.04 ^b	1.12 ^b	1.23 ^a	1.09 ^b	0.065	0.007
Butyrate	15.6	14.4	14.2	14.8	0.66	0.39
Isovalerate	2.10	2.00	2.28	2.06	0.137	0.19
Valerate	2.54	2.78	2.59	2.59	0.317	0.48
Acetate:propionate	2.59 ^a	2.28 ^b	2.33 ^b	2.41 ^b	0.198	0.003
Urinary purine derivatives (PD) excretion, mmol/d						
Allantoin	634	539	554	527	48.9	0.31
Uric acid	57.7	50.1	48.4	40.8	4.89	0.093 ⁴
Total PD	692	590	603	568	53.0	0.28
MN, ⁵ g/d	475	399	409	383	39.4	0.28

^{a,b}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³Treatment $\times$ time interactions: pH, $P = 0.94$; ammonia, $P = 0.27$; total free AA (TFAA), $P = 0.80$; VFA data, $P = 0.85$ to 0.99 .

⁴CTRL versus RPS, $P = 0.015$.

⁵Estimated ruminal microbial N flow based on urinary PD excretion (see Materials and Methods).

the CTRL. The concentration of isobutyrate was increased ($P = 0.007$) by HOLL compared with all other diets. The decreased acetate concentration resulted in lowered ($P = 0.003$) acetate:propionate ratio for all experimental diets compared with the CTRL. Urinary purine derivative excretion and the estimated microbial N flow were not statistically different among diets, although a numerical trend existed ($P = 0.093$ to 0.31) for decreased purine derivative excretion with all of the experimental diets compared with the CTRL.

Intakes of DM, OM, and fiber fractions were lower ($P = 0.003$ to <0.001) for the high-oil meal diets compared with the CTRL (Table 4). The same effect was observed for N intake ($P < 0.001$), except for HOLL because of the greater CP content of HOLL compared with the CTRL and RPS. The total tract apparent digestibilities of DM, OM, and N were not affected by treatment, but digestibilities of NDF and ADF were decreased ($P = 0.033$ and 0.026 , respectively) by HOLL compared with RPS and ADF digestibility was increased ($P = 0.026$) by RPS compared with the CTRL.

Urinary N losses, absolute or as proportion of N intake or total excreted N, were not different among diets (Table 5). Urinary urea N excretion (absolute and as percent of N intake) was decreased ($P = 0.029$) by CMEC and RPS compared with HOLL and was numerically lower ($P = 0.11$ to 0.12) compared with the CTRL. As a result of the lower N intake, absolute fecal N losses were decreased ($P = 0.005$) by all experimental diets compared with the CTRL. Total (fecal and urine)

N losses were lower ($P = 0.008$) for CMEC and RPS compared with the CTRL.

The trends in urinary urea N losses resulted in greater ($P < 0.001$) ammonia EP of manure from HOLL compared with all other diets and lower ammonia EP for RPS compared with the CTRL and HOLL (Table 6). Methane EP was lower ($P = 0.049$) for HOLL compared with the CTRL and CMEC. Carbon dioxide emissions were not affected by diet and nitrous oxide emissions were negligible within the timeframe of the manure gas emissions experiment.

The production effects of the diets are shown in Table 7. Because of decreased DMI, milk yield was decreased ($P = 0.047$) by CMEC and RPS compared with the CTRL. Feed efficiency was numerically increased ($P = 0.12$) by HOLL versus CTRL. The milk fat percentage was not affected by treatment, but was abnormally low in this experiment and was indicative of milk fat depression for all treatments. The yield of 3.5% FCM did not differ among diets, except it tended to be lower ($P = 0.11$) for CMEC versus CTRL. The FCM feed efficiency was increased ($P = 0.021$) by HOLL and RPS compared with the CTRL. The milk true protein concentration was not different among diets. Milk protein yield tended to be decreased ($P = 0.064$) by RPS compared with the CTRL. Milk N efficiency was greater ($P = 0.004$) for CMEC and RPS compared with the CTRL and HOLL. Milk lactose yield reflected milk yield and was decreased ($P = 0.049$) by CMEC and RPS compared with the CTRL. Milk NE_L yield was

Table 4. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on intake and total tract apparent digestibility of nutrients in lactating dairy cows (LSM; $n = 32^1$)²

Item	CTRL	CMEC	HOLL	RPS	SEM	<i>P</i> -value
Intake, kg/d						
DM	30.9 ^a	29.3 ^b	28.9 ^b	28.3 ^b	0.81	0.001
OM	29.0 ^a	27.4 ^b	27.1 ^b	26.7 ^b	0.67	0.003
N	0.792 ^a	0.710 ^b	0.773 ^a	0.699 ^b	0.0150	<0.001
NDF	10.9 ^a	10.1 ^b	9.9 ^b	10.0 ^b	0.25	<0.001
ADF	7.0 ^a	6.4 ^b	6.4 ^b	6.2 ^b	0.16	<0.001
Apparent digestibility, %						
DM	61.2	61.8	60.8	62.5	0.69	0.10 ³
OM	62.9	63.2	62.5	63.9	0.71	0.17
N	59.7	59.8	62.4	60.2	0.90	0.21
NDF	36.0 ^{ab}	36.0 ^{ab}	34.5 ^b	38.6 ^a	1.64	0.033
ADF	27.7 ^b	26.7 ^b	26.3 ^b	30.6 ^a	1.37	0.026

^{a,b}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³HOLL versus RPS, $P = 0.022$.

Table 5. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on urinary and fecal N losses in lactating dairy cows (LSM; $n = 32^1$)²

Item	CTRL	CMEC	HOLL	RPS	SEM	<i>P</i> -value
Urinary N						
g/d	218	192	230	178	18.1	0.21
As % of N intake	27.7	27.2	29.9	26.1	2.37	0.71
As % of total excreted N	39.6	39.8	43.6	38.2	2.10	0.35
Urea N, g/d	114.0 ^{ab}	89.9 ^b	132.8 ^a	89.0 ^b	10.61	0.029 ³
As % of total urine N	53.3 ^{ab}	47.1 ^b	57.8 ^a	50.1 ^b	2.25	0.034
Fecal N						
g/d	321 ^a	285 ^b	293 ^b	275 ^b	9.7	0.005
As % of N intake	40.3	40.1	37.6	39.7	0.90	0.21
Total N loss						
g/d	540 ^a	477 ^{bc}	524 ^{ab}	453 ^c	18.6	0.008
As % of N intake	68.0	67.4	67.6	65.8	2.04	0.86
N balance, ⁴ %	96	97	95	95	2.4	0.93

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³CTRL versus CMEC and CTRL versus RPS, $P = 0.12$ and 0.11 , respectively.

⁴Estimated as: $[(N \text{ excreted in urine and feces, g/d} + N \text{ secreted in milk, g/d}) \div N \text{ intake, g/d}] \times 100$.

Table 6. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on ammonia and greenhouse gas-emitting potential (mg/m^2 per h) of manure in lactating dairy cows (LSM; $n = 32^1$)²

Gas	CTRL	CMEC	HOLL	RPS	SEM	<i>P</i> -value
Ammonia	457 ^b	416 ^{bc}	550 ^a	408 ^c	25.1	<0.001
Nitrous oxide	5.8	5.6	5.7	5.5	0.10	0.30
Methane	110 ^a	105 ^a	82 ^b	89 ^{ab}	6.8	0.049
Carbon dioxide	9,001	8,950	8,831	8,782	98.3	0.41

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

Table 7. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk yield and composition, feed efficiency, and plasma urea N concentration in lactating dairy cows (LSM; plasma urea N, $n = 63$;¹ all other variables, $n = 32$)²

Item	CTRL	CMEC	HOLL	RPS	SEM	P-value
Milk yield, kg/d	47.1 ^a	44.9 ^b	46.7 ^{ab}	45.0 ^b	2.11	0.047
Milk ÷ DMI	1.52	1.53	1.62	1.60	0.097	0.12 ³
Milk fat, %	2.81	2.80	2.75	2.94	0.201	0.54
Yield, kg/d	1.32	1.25	1.28	1.31	0.104	0.51
3.5% FCM, kg/d	41.7	39.7	41.0	40.8	2.24	0.11 ⁴
3.5% FCM ÷ DMI	1.35 ^c	1.35 ^{bc}	1.41 ^{ab}	1.45 ^a	0.057	0.021
Milk true protein, %	2.98	3.00	2.95	2.93	0.053	0.32
Yield, kg/d	1.40	1.34	1.38	1.31	0.058	0.064 ⁵
N yield, g/d	220	210	216	206	9.5	0.09 ⁶
As % of N intake	27.7 ^b	29.6 ^a	27.9 ^b	29.5 ^a	1.19	0.004
Milk lactose, %	4.88	4.80	4.87	4.84	0.058	0.35
Yield, kg/d	2.30 ^a	2.16 ^c	2.28 ^{ab}	2.18 ^{bc}	0.103	0.049
Milk NE _L , Mcal/d	29.2 ^a	27.7 ^b	28.7 ^a	28.2 ^{ab}	1.39	0.027
NE _L intake, ⁹ Mcal/d	45.8	45.4	45.1	44.4	1.26	0.43
Milk NE _L , % of NE _L intake	63.8	60.8	63.5	63.8	2.22	0.13
Plasma urea N, mg/100 mL	17.2 ^b	17.0 ^b	19.3 ^a	16.2 ^b	1.16	0.023
MUN, mg/100 mL	13.3 ^b	12.6 ^b	14.7 ^a	12.6 ^b	0.87	<0.001

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³CTRL versus HOLL, $P = 0.048$.

⁴CTRL versus CMEC, $P = 0.019$.

⁵CTRL versus RPS, $P = 0.013$.

⁶CTRL versus RPS, $P = 0.021$.

⁷Milk true protein yield ÷ 6.38.

⁸Milk NE_L (Mcal/d) = kg of milk × (0.0929 × % fat + 0.0563 × % true protein + 0.0395 × % lactose) (NRC, 2001).

⁹Based on NE_L concentration of the TMR (Table 1) and DMI (Table 4).

also reflective of the effect of diet on milk volume and was decreased ($P = 0.027$) by CMEC compared with the CTRL. The concentration of plasma urea N and MUN were increased ($P = 0.023$ and <0.001 , respectively) by HOLL compared with the other diets.

Replacing CTRL with CMEC or RPS decreased ($P = 0.028$ to 0.001) milk fat 10:0, 12:0, 14:0, 16:0, and total saturated FA content, enhanced ($P = 0.01$ to 0.002) total 18:1 and MUFA, but had no effect on total PUFA concentrations (Table 8). Compared with the CTRL, decreases in saturated FA on the high-oil meals were associated with higher total milk *trans* FA concentrations, increases that were significant ($P = 0.025$) for CMEC and HOLL (Table 8). Inclusion of high-oil meals also resulted in quantitatively minor, but statistically significant ($P = 0.033$ to <0.001) decreases in the abundance of 11-cyclo-11:0, 14:0 *iso*, 15:0, 15:0 *anteiso*, 15:0 *iso*, 16:0 *iso*, *cis*-13 16:1, 17:0 *anteiso*, 18:0 *iso*, 20:4n-6, and 20:5n-3, and marginal increases ($P = 0.002$ to <0.001) in *trans*-6, -7, and -11 16:1 contents. As expected, supplementing the diet with RPS resulted in a relatively high enrichment ($P < 0.001$) of *cis*-13 22:1 in milk, but also enhanced ($P = 0.004$ to <0.001)

trans-15 22:1, 20:2n-6, 20:3n-3, and 20:4n-3 concentrations.

Inclusion of high-oil meals in the diet altered the distribution of 18:1 isomers and increased ($P = 0.013$) milk fat *cis*-9 18:1 contents (Table 9). Relative to the CTRL, CMEC enhanced ($P = 0.011$ to <0.001) *cis*-15 18:1 and *trans*-4 to -9, -12, -13, -14, and -16 18:1 concentrations, whereas RPS increased ($P = 0.011$ and <0.001 , respectively) *cis*-15 18:1 and *trans*-16 18:1, but lowered ($P < 0.001$) milk fat *cis*-12 18:1 content. Replacing CTRL with HOLL resulted in higher ($P = 0.009$ to <0.001) *trans*-4 to -9 18:1 and *trans*-11 to -14 18:1 and lowered ($P < 0.001$) milk fat *trans*-16 18:1 content.

Substitution of CTRL with CMEC and RPS decreased ($P < 0.05$) milk 18:2n-6 content and altered the abundance of minor non-methylene interrupted 18:2 isomers (Table 10). Relative to the CTRL, both CMEC and HOLL increased ($P < 0.001$ and 0.001) *trans*-11, *cis*-15 18:2 and *trans*-11, *trans*-15 18:2 content, with CMEC also enhancing ($P = 0.004$) *cis*-12, *cis*-15 18:2 in milk. In contrast, RPS decreased ($P = 0.019$) *trans*-9, *cis*-12 18:2 concentrations. Replacing

Table 8. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk fatty acid composition (g/100 g of total fatty acids) in lactating dairy cows (LSM; n = 32)¹)²

Fatty acid	CTRL	CMEC	HOLL	RPS	SEM	P-value
4:0	2.76	2.58	2.71	2.56	0.131	0.547
6:0	1.64	1.46	1.50	1.47	0.112	0.391
8:0	0.99	0.84	0.86	0.86	0.080	0.205
10:0	2.39 ^a	1.93 ^b	1.94 ^b	1.94 ^b	0.159	0.028
<i>cis</i> -9 10:1	0.21	0.18	0.19	0.18	0.013	0.120
11-cyclo 11:0	0.12 ^a	0.10 ^c	0.11 ^b	0.09 ^d	0.004	<0.001
12:0	2.93 ^a	2.38 ^b	2.40 ^b	2.39 ^b	0.142	0.002
<i>cis</i> -9 12:1	0.07 ^a	0.05 ^b	0.05 ^b	0.05 ^b	0.004	0.003
<i>trans</i> -9 12:1	0.07 ^a	0.06 ^b	0.06 ^b	0.06 ^b	0.003	0.002
13:0 <i>iso</i>	0.03	0.03	0.03	0.03	0.003	0.150
13:0 <i>anteiso</i>	0.01	0.01	0.01	0.01	0.000	0.170
14:0	10.5 ^a	9.26 ^b	9.13 ^b	8.96 ^b	0.202	0.001
14:0 <i>iso</i>	0.08 ^a	0.06 ^b	0.06 ^b	0.06 ^b	0.005	0.005
<i>cis</i> -9 14:1	0.97	0.94	0.93	0.84	0.044	0.330
<i>trans</i> -9 14:1	0.01	0.01	0.01	0.01	0.001	0.741
15:0	0.99 ^a	0.88 ^{bc}	0.90 ^b	0.83 ^c	0.020	<0.001
15:0 <i>iso</i>	0.19 ^a	0.16 ^{bc}	0.17 ^{ab}	0.15 ^c	0.008	0.002
15:0 <i>anteiso</i>	0.44 ^a	0.38 ^{bc}	0.40 ^b	0.36 ^c	0.010	<0.001
<i>cis</i> -9 15:1	0.01	0.01	0.01	0.01	0.001	0.563
<i>trans</i> -5 15:1	0.03 ^a	0.03 ^{bc}	0.03 ^b	0.02 ^c	0.001	0.002
<i>trans</i> -6 15:1	0.01	0.01	0.01	0.01	0.001	0.973
Σ 15:1	0.06 ^a	0.06 ^{ab}	0.06 ^a	0.05 ^b	0.002	0.021
16:0	24.9 ^a	23.4 ^b	22.9 ^b	21.0 ^c	1.302	<0.001
16:0 <i>iso</i>	0.23 ^a	0.19 ^b	0.19 ^b	0.18 ^b	0.014	0.033
<i>cis</i> -9 16:1	1.42	1.41	1.33	1.18	0.063	0.110
<i>cis</i> -10 16:1	0.03 ^a	0.02 ^a	0.02 ^a	0.02 ^b	0.001	0.004
<i>cis</i> -11 16:1	0.08 ^a	0.07 ^{ab}	0.07 ^{ab}	0.06 ^b	0.005	0.036
<i>cis</i> -12 16:1	0.03 ^b	0.03 ^b	0.03 ^b	0.03 ^a	0.001	0.002
<i>cis</i> -13 16:1	0.09 ^a	0.07 ^b	0.06 ^b	0.06 ^b	0.004	0.003
<i>trans</i> -4 16:1	0.01 ^a	0.01 ^{ab}	0.009 ^b	0.01 ^a	0.001	0.043
<i>trans</i> -5 16:1	0.01	0.02	0.02	0.01	0.001	0.054
<i>trans</i> -6,-7 16:1	0.04 ^c	0.05 ^b	0.05 ^b	0.06 ^a	0.004	<0.001
<i>trans</i> -8 16:1	0.05	0.07	0.06	0.06	0.013	0.735
<i>trans</i> -9 16:1	0.07	0.08	0.10	0.07	0.011	0.052
<i>trans</i> -10 16:1	0.02 ^b	0.02 ^b	0.02 ^b	0.03 ^a	0.001	0.001
<i>trans</i> -11 16:1	0.04 ^b	0.05 ^b	0.05 ^b	0.06 ^a	0.004	0.002
<i>trans</i> -12 16:1	0.17 ^b	0.17 ^b	0.18 ^b	0.25 ^a	0.010	<0.001
<i>trans</i> -13 16:1	0.03 ^c	0.03 ^b	0.03 ^{bc}	0.04 ^a	0.002	<0.001
Σ <i>cis</i> 16:1	1.64	1.60	1.51	1.35	0.065	0.071
Σ <i>trans</i> 16:1	0.44 ^c	0.50 ^b	0.52 ^b	0.59 ^a	0.036	<0.001
Σ 16:1	2.08	2.10	2.03	1.94	0.082	0.585
17:0	0.51 ^a	0.44 ^c	0.47 ^b	0.47 ^b	0.007	<0.001
17:0 <i>iso</i> ³	0.33 ^a	0.31 ^{ab}	0.33 ^a	0.30 ^b	0.006	0.017
17:0 <i>anteiso</i>	0.23 ^a	0.19 ^b	0.21 ^b	0.20 ^b	0.005	0.006
<i>cis</i> -7 17:1	0.02 ^a	0.02 ^{bc}	0.02 ^{ab}	0.01 ^c	0.001	<0.001
<i>cis</i> -8 17:1	0.01 ^b	0.01 ^b	0.01 ^b	0.02 ^a	0.001	<0.001
<i>cis</i> -9 17:1	0.18	0.17	0.17	0.17	0.012	0.650
<i>cis</i> -11 17:1	0.01	0.01	0.01	0.01	0.001	0.393
Σ 17:1	0.22	0.20	0.21	0.21	0.014	0.722
18:0	11.2 ^b	12.5 ^a	11.9 ^{ab}	11.6 ^b	0.253	0.009
18:0 <i>iso</i>	0.06 ^a	0.05 ^b	0.05 ^b	0.05 ^b	0.002	<0.001
10-OH-18:0	0.03 ^b	0.04 ^a	0.03 ^{ab}	0.02 ^c	0.002	0.012
10-O-18:0	0.07	0.10	0.08	0.07	0.010	0.060
13-O-18:0	0.01	0.01	0.01	0.01	0.001	0.352
Σ <i>cis</i> 18:1	22.6 ^b	24.7 ^a	25.4 ^a	24.9 ^a	0.574	0.024
Σ <i>trans</i> 18:1	6.64 ^b	8.17 ^a	8.34 ^a	6.43 ^b	0.717	0.002
Σ 18:1	29.2 ^b	32.8 ^a	33.7 ^a	31.4 ^{ab}	0.893	0.01
Σ 18:2 ⁴	3.59	3.56	3.37	3.34	0.243	0.159
Σ CLA	0.87 ^{bc}	0.94 ^b	1.17 ^a	0.69 ^c	0.064	0.001
18:3 n-3	0.36 ^a	0.36 ^a	0.30 ^b	0.36 ^a	0.022	<0.001
18:3 n-6	0.024 ^a	0.021 ^b	0.020 ^b	0.018 ^c	0.0011	0.001
<i>cis</i> -9, <i>trans</i> -11, <i>cis</i> -15 18:3	0.02	0.01	0.01	0.01	0.002	0.274
19:0	0.06 ^a	0.06 ^{ab}	0.05 ^b	0.06 ^a	0.002	0.010

Continued

Table 8 (Continued). Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk fatty acid composition (g/100 g of total fatty acids) in lactating dairy cows (LSM; $n = 32^1$)²

Fatty acid	CTRL	CMEC	HOLL	RPS	SEM	P-value
20:0	0.16 ^b	0.17 ^b	0.18 ^b	0.62 ^a	0.013	<0.001
Σ 20:1	0.32 ^b	0.36 ^b	0.40 ^b	2.11 ^a	0.080	<0.001
20:2 n-6	0.03 ^b	0.03 ^b	0.03 ^b	0.06 ^a	0.003	<0.001
20:3 n-3	0.01 ^b	0.01 ^b	0.01 ^b	0.04 ^a	0.002	<0.001
20:3 n-6	0.10 ^a	0.08 ^c	0.10 ^{ab}	0.08 ^{bc}	0.001	0.008
20:4 n-3	0.02 ^b	0.02 ^b	0.01 ^b	0.04 ^a	0.004	<0.001
20:4 n-6	0.14 ^a	0.11 ^c	0.11 ^{ab}	0.13 ^{bc}	0.005	0.004
20:5 n-3	0.03 ^a	0.02 ^b	0.02 ^b	0.02 ^b	0.001	0.003
21:0	0.03	0.03	0.03	0.03	0.001	0.160
22:0	0.05 ^b	0.05 ^b	0.05 ^b	0.20 ^a	0.018	<0.001
<i>trans</i> -15 22:1	0.01 ^b	0.01 ^b	0.01 ^b	0.12 ^a	0.006	<0.001
<i>cis</i> -13 22:1	0.07 ^b	0.01 ^b	0.01 ^b	2.33 ^a	0.136	<0.001
22:4 n-6	0.03 ^a	0.02 ^b	0.02 ^{ab}	0.03 ^a	0.001	0.007
22:5 n-3	0.06 ^a	0.04 ^c	0.05 ^{ac}	0.05 ^{ab}	0.002	0.002
22:6 n-3	0.003	0.003	0.003	0.003	0.0006	0.595
23:0	0.017 ^b	0.014 ^c	0.015 ^{bc}	0.023 ^a	0.0009	<0.001
24:0	0.024 ^{ab}	0.019 ^c	0.023 ^{bc}	0.029 ^a	0.0018	0.006
25:0	0.005	0.004	0.004	0.005	0.0005	0.146
26:0	0.007 ^a	0.004 ^b	0.007 ^a	0.003 ^b	0.0005	0.001
Σ unidentified	0.16	0.16	0.16	0.15	0.014	0.332
Σ saturated fatty acids	61.2 ^a	57.7 ^b	56.8 ^b	54.6 ^b	1.35	0.004
Σ <i>trans</i> fatty acids ⁵	8.10 ^b	9.83 ^a	9.97 ^a	8.92 ^{ab}	0.830	0.025
Σ MUFA ⁶	33.3 ^c	36.8 ^b	37.7 ^{ab}	40.0 ^a	1.10	0.002
Σ PUFA ⁶	5.27	5.23	5.23	5.02	0.313	0.524

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³Contains *cis*-7 16:1 as a minor component.

⁴Sum of 18:2 excluding isomers of conjugated linoleic acid (CLA).

⁵Sum of *trans* fatty acids excluding isomers of CLA.

⁶MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids.

CTRL with CMEC or RPS had no effect on milk fat total CLA content, whereas HOLL resulted in a 0.2 g/100 g of FA enrichment ($P = 0.001$; Table 8) because of increases ($P = 0.003$ and 0.002) in *cis*-9, *trans*-11 CLA and *trans*-7, *cis*-9 CLA concentrations (Table 10). Inclusion of CMEC had relatively minor effects on milk CLA isomer composition other than an increase ($P = 0.026$ to 0.002) in *trans*-7, *cis*-9 CLA; *trans*-11, *trans*-13 CLA; and *trans*-12, *trans*-14 CLA abundance. In contrast, RPS decreased ($P = 0.004$ to <0.001) milk fat *cis*-9, *trans*-11 CLA; *trans*-11, *cis*-13 CLA; *trans*-9, *trans*-11 CLA; *trans*-10, *trans*-12 CLA; and *trans*-11, *trans*-13 CLA concentrations and increased ($P = 0.003$) *cis*-9, *cis*-11 CLA content, compared with the CTRL.

Substitution of CTRL with CMEC and RPS had no effect on the abundance of 20:1 isomers in milk, whereas HOLL enhanced ($P < 0.001$) milk *cis*-9 to -14 20:1 and *trans*-8 to -15 20:1 content (Table 11).

DISCUSSION

The main effect of diet on ruminal fermentation was the shift in the acetate:propionate ratio in response to

the high-oil meals (CMEC, HOLL, and RPS). The classic explanation for a decrease in acetate concentration is a depression in the activity and growth of ruminal fibrolytic species (Steward et al., 1997). Dietary fat in general and specifically plant oils rich in PUFA are known to exert inhibitory effects on rumen fibrolytic bacteria (Palmquist and Jenkins, 1980; Smith et al., 1993). Rapeseed oil (fed at 700 to 1,400 g/d) increased the molar proportion of propionate, but had no effect on rumen acetate in a series of experiments conducted at the Oskar Kellner Institute (Jentsch et al., 1972). Supplementation of whole canola seeds, which more than doubled the fat content of the diet, had no effect on rumen acetate but decreased (trend at $P = 0.07$) the total VFA concentration in a study by Chichlowski et al. (2005). A similar lack of effect of various oilseeds (including canola) on rumen VFA profile was reported by Beauchemin et al. (2009). Although not statistically different, the numerical decrease in urinary purine derivative excretion (and estimated microbial protein synthesis in the rumen) in the current experiment appears to be biologically significant and in agreement with the

Table 9. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk 18:1 content (g/100 g of total fatty acids) in lactating dairy cows (LSM; n = 32)^{1,2}

Fatty acid	CTRL	CMEC	HOLL	RPS	SEM	P-value
<i>cis</i> -9 18:1 ³	20.7 ^b	22.7 ^a	23.5 ^a	23.1 ^a	0.57	0.013
<i>cis</i> -11 18:1	0.98	1.00	0.98	0.96	0.070	0.862
<i>cis</i> -12 18:1	0.50 ^a	0.51 ^a	0.48 ^a	0.38 ^b	0.018	<0.001
<i>cis</i> -13 18:1	0.14	0.17	0.16	0.13	0.011	0.057
<i>cis</i> -15 18:1	0.14 ^b	0.19 ^a	0.18 ^{ab}	0.21 ^a	0.025	0.011
<i>cis</i> -16 18:1 ⁴	0.11	0.12	0.12	0.12	0.006	0.586
<i>trans</i> -4 18:1	0.05 ^{bc}	0.06 ^a	0.07 ^a	0.04 ^c	0.004	<0.001
<i>trans</i> -5 18:1	0.04 ^{bc}	0.05 ^a	0.06 ^a	0.03 ^c	0.003	<0.001
<i>trans</i> -6,-7,-8 18:1	0.53 ^b	0.78 ^a	0.83 ^a	0.53 ^b	0.066	<0.001
<i>trans</i> -9 18:1	0.45 ^b	0.60 ^a	0.63 ^a	0.52 ^{ab}	0.045	0.001
<i>trans</i> -10 18:1	1.50	2.12	1.85	1.57	0.414	0.375
<i>trans</i> -11 18:1	1.55 ^b	1.61 ^{ab}	2.13 ^a	1.10 ^b	0.193	0.009
<i>trans</i> -12 18:1	0.58 ^c	0.70 ^{ab}	0.70 ^a	0.63 ^{bc}	0.036	0.003
<i>trans</i> -13,-14 18:1	1.03 ^b	1.26 ^a	1.18 ^a	1.03 ^b	0.074	0.001
<i>trans</i> -15 18:1	0.53	0.56	0.54	0.56	0.018	0.543
<i>trans</i> -16 18:1 ⁵	0.37 ^b	0.41 ^a	0.35 ^c	0.42 ^a	0.006	<0.001

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³Contains *cis*-10 18:1 as a minor component.

⁴Co-elutes with *cis*-9, *trans*-12 18:2 and *trans*-8, *cis*-12 18:2.

⁵Contains *cis*-14 18:1 as a minor isomer.

rumen pH and VFA data. This decrease (from about 15 to 20%, compared with the CTRL) can be explained mainly as a result of lowered DMI of experimental meals and possibly a negative effect of dietary fat on the microbial populations. Indeed, NRC (2001) predicted a decreased in microbial protein synthesis of up to 15% with HOLL (compared with the CTRL). Our study is in agreement with the concept that dietary fat may negatively affect, through various mechanisms, feed intake in dairy cows (Allen, 2000). This effect will depend on the level of fat supplementation but is not consistent among studies. In several reports, DMI was not affected by canola (seeds or oil) supplementation (Bayourthe et al., 2000; Chichlowski et al., 2005; Beauchemin et al., 2009). The classic work by Jentsch et al. (1972), summarizing 32 metabolism trials, concluded that rapeseed oil affected negatively feed and total energy intake in dairy cows. These authors recommended that rapeseed oil should not be fed to dairy cows. In the current experiment, however, results for rapeseed meal containing very low glucosinolate concentrations, combined with high erucic acid in the seed oil, were not different from conventional high-oil canola meal.

Despite the decreased acetate proportion in ruminal VFA, total tract fiber digestibility did not appear to be affected by the experimental diets. The numerical trend for decreased NDF digestibility with HOLL and the increased fiber digestibility with RPS is difficult to explain. The HOLL contained less 18:2n-6 and 18:3n-

3, but higher total 18:1 concentrations, which may have resulted in greater inhibition of ruminal fibrolysis compared with the other meals (the effect on acetate concentration was numerically greatest for HOLL). The effect of RPS could also be related to the low concentration of 18-carbon unsaturated FA in this meal. Meals used in the study all had very low concentrations of total meal glucosinolate content (<20 $\mu\text{mol/g}$ of de-fatted seed meal) and these compounds would not have any effect on ruminal fermentation (Hristova et al., 2009). However, the inverse relationship between DMI and nutrient digestibility (Robertson and Van Soest, 1975) cannot be ignored and may also explain some of the effects on fiber digestibility, particularly with RPS, observed in this experiment.

Urine N output data were quite variable and the numerically greater N output from the HOLL (and CTRL) treatments did not approach statistical significance. The urinary urea N excretion data, however, reflected rather well the greater N concentration in HOLL and CTRL meals and the higher overall intake of N with these diets. These data agreed well with the increased plasma urea N and MUN concentrations of cows consuming HOLL. The differences in fecal and total N losses were also in a similar direction. These results were expected, as, despite of the overall low (by industry standards; Hristov et al., 2006) CP content of the diets, CTRL and HOLL provided MP in excess of requirements and CMEC and RPS were close to MP

Table 10. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk 18:2 content (mg/100 g of total fatty acids) in lactating dairy cows (LSM; $n = 32^1$)²

Fatty acid	CTRL	CMEC	HOLL	RPS	SEM	P-value
<i>cis</i> -9, <i>cis</i> -12 18:2 ³	2,785 ^a	2,581 ^b	2,451 ^b	2,520 ^b	174.0	0.004
<i>cis</i> -12, <i>cis</i> -15 18:2	14.3 ^b	18.9 ^a	14.4 ^b	11.8 ^b	1.22	0.004
<i>cis</i> -9, <i>trans</i> -13 18:2 ⁴	344	403	378	370	28.8	0.405
<i>cis</i> -9, <i>trans</i> -14 18:2	147	169	151	160	8.2	0.277
<i>trans</i> -9, <i>cis</i> -12 18:2	36.1 ^a	35.1 ^a	34.0 ^a	29.0 ^b	4.21	0.019
<i>trans</i> -11, <i>cis</i> -15 18:2	114 ^b	171 ^a	157 ^a	112 ^b	26.7	<0.001
<i>trans</i> -12, <i>cis</i> -15 18:2	42.4	46.5	43.1	44.5	3.45	0.356
<i>trans</i> -9, <i>trans</i> -12 18:2	25.8 ^{ab}	30.8 ^a	27.8 ^a	22.1 ^b	2.62	0.002
<i>trans</i> -9, <i>trans</i> -13 18:2	64.9 ^{ab}	75.9 ^a	85.1 ^a	53.8 ^b	4.00	<0.001
<i>trans</i> -11, <i>trans</i> -15 18:2	22.0 ^b	28.4 ^a	25.8 ^a	21.8 ^b	0.94	0.001
CLA ⁵ isomer						
<i>cis</i> -8, <i>cis</i> -10	0.61	0.69	0.79	1.00	0.147	0.220
<i>cis</i> -9, <i>cis</i> -11	2.33 ^b	2.24 ^b	2.82 ^b	3.97 ^a	0.344	0.003
<i>cis</i> -12, <i>cis</i> -14	1.00	1.32	1.01	1.38	0.181	0.442
<i>cis</i> -8, <i>trans</i> -10	5.87	6.02	7.72	5.80	0.647	0.071
<i>cis</i> -9, <i>trans</i> -11	668 ^b	680 ^b	907 ^a	492 ^b	57.0	0.003
<i>cis</i> -11, <i>trans</i> -13	1.35	1.55	1.34	1.46	0.192	0.877
<i>cis</i> -12, <i>trans</i> -14	0.49 ^b	0.69 ^{ab}	0.45 ^b	1.20 ^a	0.204	0.033
<i>trans</i> -7, <i>cis</i> -9	92.3 ^b	131 ^a	141 ^a	94.2 ^b	13.49	0.002
<i>trans</i> -8, <i>cis</i> -10	5.43	5.30	6.36	5.21	0.352	0.089
<i>trans</i> -9, <i>cis</i> -11	26.7	34.7	32.8	27.4	6.24	0.570
<i>trans</i> -10, <i>cis</i> -12	11.7	13.6	11.3	14.2	1.65	0.515
<i>trans</i> -11, <i>cis</i> -13	3.45 ^a	3.18 ^a	3.54 ^a	2.34 ^b	0.293	0.002
<i>trans</i> -12, <i>cis</i> -14 ⁶	4.65	6.62	5.21	5.35	0.687	0.296
<i>trans</i> -13, <i>cis</i> -15	0.34	0.61	0.46	0.69	0.192	0.602
<i>trans</i> -7, <i>trans</i> -9	2.68 ^b	3.15 ^{ab}	4.06 ^a	2.60 ^b	0.304	0.026
<i>trans</i> -8, <i>trans</i> -10	3.99	4.81	4.24	3.91	0.302	0.229
<i>trans</i> -9, <i>trans</i> -11	12.6 ^a	12.4 ^a	13.8 ^a	8.61 ^b	0.602	<0.001
<i>trans</i> -10, <i>trans</i> -12	8.22 ^a	7.43 ^a	7.73 ^a	5.33 ^b	0.320	<0.001
<i>trans</i> -11, <i>trans</i> -13	11.4 ^b	13.7 ^a	12.0 ^{ab}	9.10 ^c	0.993	0.004
<i>trans</i> -12, <i>trans</i> -14	4.92 ^b	6.35 ^a	5.32 ^b	5.72 ^{ab}	0.268	0.026
<i>trans</i> -13, <i>trans</i> -15	0.57 ^a	0.64 ^a	0.39 ^b	0.52 ^a	0.036	0.003

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

³Contains *cis*-9, *trans*-15 18:2, *cis*-8 19:1, and *cis*-9 19:1 as minor components.

⁴Contains *cis*-10, *trans*-14 18:2 as a minor component.

⁵Conjugated linoleic acid.

⁶Contains *cis*-13, *trans*-15 CLA as a minor component.

requirements. The fact that, compared with the CTRL, a numerically greater proportion of N was lost in urine than feces with HOLL, tends to be in agreement with the numerically higher digestibility of HOLL canola meal CP versus the CTRL. These differences are, however, only trends and must be interpreted with caution.

The higher urinary urea N excretion with HOLL was undoubtedly the reason for the greater ammonia EP of HOLL manure compared with the other diets. Similarly, numerical trends for increased urinary urea N excretion for the CTRL can explain the higher ammonia EP with this manure compared with RPS, for example. Urinary N (mostly urea N) is the primary and immediate source of ammonia formation and losses from cattle manure (Hristov et al., 2009b, 2011). In this study, the relationship between urinary urea N excretion and the

ammonia EP of manure was quadratic and relatively strong ($r^2 = 0.61$, $P < 0.001$, $n = 28$; 4 observations were identified as outliers based on an absolute studentized residual value >2 and removed from the data set, PROC REG of SAS). A recent study suggested MUN may be a good indicator for predicting ammonia emission from dairy manure (van Duinkerken et al., 2011). In our data set, the relationship between MUN and ammonia EP of manure was weak and explained only 24% of the variability in ammonia EP. The nitrous oxide EP of manure was negligible in this experiment. This is not surprising, as nitrous oxide emission is insignificant on the barn floor or from simulated storage systems (Adviento-Borbe et al., 2010; Arriaga et al., 2010) because of the lack of nitrifying and denitrifying microorganisms in cattle feces (Dowd et al., 2008). In addition, longer-

Table 11. Effect of replacing solvent-extracted canola meal with high-oil, mechanically extracted canola or rapeseed meals on milk 20:1 content (g/100 g of total fatty acids) in lactating dairy cows (LSM; n = 32)¹

Fatty acid	CTRL	CMEC	HOLL	RPS	SEM	P-value
<i>cis</i> -9 20:1	0.14 ^b	0.15 ^b	0.56 ^a	0.17 ^b	0.012	<0.001
<i>cis</i> -11 20:1	0.08 ^b	0.10 ^b	0.87 ^a	0.12 ^b	0.056	<0.001
<i>cis</i> -13 20:1	0.02 ^b	0.01 ^b	0.25 ^a	0.01 ^b	0.014	<0.001
<i>cis</i> -14 20:1	0.001 ^b	0.001 ^b	0.016 ^a	<0.001	0.001	<0.001
<i>cis</i> -15 20:1	0.03	0.04	0.05	0.04	0.008	0.482
<i>trans</i> -8,-9 20:1	0.01 ^b	0.01 ^b	0.06 ^a	0.01 ^b	0.003	<0.001
<i>trans</i> -10 20:1	<0.001 ^b	0.001 ^b	0.034 ^a	0.002 ^b	0.002	<0.001
<i>trans</i> -11 20:1	0.01 ^b	0.01 ^b	0.08 ^a	0.01 ^b	0.005	<0.001
<i>trans</i> -12 20:1	0.02 ^b	0.02 ^b	0.07 ^a	0.02 ^b	0.003	<0.001
<i>trans</i> -13 20:1	0.01 ^b	0.01 ^b	0.07 ^a	0.01 ^b	0.002	<0.001
<i>trans</i> -15 20:1	0.002 ^b	0.005 ^b	0.052 ^a	0.003 ^b	0.008	<0.001

^{a,b}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹Number of observations used in the statistical analysis.

²Diets contained: CTRL = conventional, solvent-extracted canola meal; CMEC = conventional, mechanically extracted canola meal; HOLL = high-oleic, low-polyunsaturated fatty acid, mechanically extracted canola meal; RPS = low-glucosinolate, mechanically extracted rapeseed meal.

term measurements of nitrous oxide emission may be necessary. For example, Külling et al. (2001) observed significant decrease of nitrous oxide emission from slurry from cows fed low dietary CP concentration during a 3-wk manure storage experiment. The decreased methane EP of HOLL manure in this experiment is difficult to explain. Formation of methane and carbon dioxide in manure occurs as a result of decomposition of fecal OM and heterotrophic microbial respiration in an anaerobic manure environment (Smith and Conen, 2004). Methane emission from farm animal waste is dependent to a large extent on diet composition (Hashimoto et al., 1981), but also on various factors such as manure type, manure composition, and bedding (Massé et al., 2008). In the current experiment, fecal OM and NDF concentrations were not different between treatments (data not shown). Feces were not analyzed for starch or FA content and differences in these nutrients may have caused the decrease in methane EP with HOLL.

The response in milk yield observed in this experiment was entirely a result of decreased DMI with the experimental, high-oil meals. Through palatability or energy intake regulation, the experimental meals lowered feed intake in these high-producing cows and consequently, with the exception of HOLL, decreased milk yield. This effect is not surprising, bearing in mind previous reports with rapeseed oil (Jentsch et al., 1972). Thus, it can be concluded that inclusion of high-oil canola (or rapeseed) meals from small-scale biodiesel plants at or above 12 to 13% of dietary DM may decrease feed intake and milk production in dairy cows. As stated earlier, however, the effect of plant oils on DMI and, consequently, milk yield is not consistent. Solvent-extracted canola (or rapeseed) meal is an excellent, high in Met (Schingoethe, 1996) protein source and can successfully replace solvent-extracted soybean meal

in dairy cow diets (Shingfield et al., 2003; Brito and Broderick, 2007; Südekum, 2007). High-oil, mechanically extracted canola or rapeseed meals, however, have to be included in dairy rations with caution (Südekum, 2007). Others (Ward et al., 2002; Chichlowski et al., 2005) did not observe any negative effects on milk production and some studies reported an increase in DMI (and milk yield, in some cases) with full-fat canola seeds or oil supplementation (Bayourthe et al., 2000; DePeters et al., 2001; Beauchemin et al., 2009).

Milk fat content was low for all treatments in this experiment, which can be attributed to the high starch content of the corn silage, the relatively high inclusion rate of corn silage in the basal diet, and the high DMI. Starch-rich diets are known to lower milk fat synthesis with the decreases in mammary lipogenesis, typically being greater in cows fed high-starch, low-fiber diets containing high proportions of PUFA (Shingfield and Griinari, 2007; Shingfield et al., 2010). The lack of effect of the high-oil meals on milk fat synthesis is consistent with no substantial changes in milk fat *trans*-10 18:1, *trans*-9, *cis*-11 CLA, and *trans*-10, *cis*-12 CLA that, based on studies involving post-ruminal infusions, have been implicated in the etiology of milk fat depression (Shingfield and Griinari, 2007; Shingfield et al., 2010).

The decrease in milk NE_L, true protein, and lactose yields observed for some of the experimental meals in this study was a result of the decreased milk volume, rather than changes in milk composition. Feed efficiency was numerically or significantly (3.5% FCM feed efficiency) increased by some of the experimental meals (HOLL and RPS). Most of this effect was simply a consequence of the decreased DMI with the experimental meals (Robertson and Van Soest, 1975), but may also reflect more efficient ruminal fermentation. Jentsch et al. (1972), for example, estimated a 2 to

2.5% decrease in feed digestible energy losses due to a decrease in rumen methane production with rapeseed oil. Methane production was not measured in this experiment, but it is possible that the increased feed efficiency with HOLL or RPS was, at least in part, due to a decrease in ruminal methane production and a more efficient use of feed digestible energy. Recent studies have demonstrated that the inclusion of about 9% crushed canola seeds in the diet results in a 16% decrease in ruminal methane production (per unit of DMI) in lactating cows (Beauchemin et al., 2009). In the current experiment, the diets based on low-CP meals (CMEC and RPS) increased milk N efficiency of the cows. This was expected and is usually the result of lower N intake (through a decrease in dietary CP concentration), when milk protein yield is maintained or even slightly decreased (Huhtanen and Hristov, 2009).

Substituting solvent-extracted rapeseed with high-oil meals in the diet decreased milk fat 10:0, 12:0, 14:0, 16:0, and total saturated FA (SFA) content, consistent with the known effects of rapeseed oil or rapeseeds in the diet on milk FA composition (Glasser et al., 2008; Shingfield et al., 2008). Milk fat 16:0 concentrations are consistently lowered in response to inclusion of rapeseed oil or processed rapeseeds in the diet, whereas the effects on 10:0, 12:0, and 14:0 content tend to be much more variable. A decrease in milk fat medium-chain SFA concentrations to supplementation with high-oil meals can be attributed to an increase in the amount of long-chain unsaturated FA available for absorption (Murphy et al., 1987; Loor et al., 2002; Chelikani et al., 2004) leading to an inhibition of de novo FA synthesis in the mammary gland (Shingfield et al., 2010).

Dietary rapeseed supplements typically enhance milk fat 18:0 content (Glasser et al., 2008; Shingfield et al., 2008) because of an increase in 18:0 at the duodenum (Murphy et al., 1987; Loor et al., 2002; Chelikani et al., 2004). Replacing solvent-extracted canola meal with conventional, but not high-oleic acid or high-erucic acid, high-oil meals increased milk 18:0 concentrations. However, changes in milk fat 18:0 enrichment to rapeseed and canola high-oil meals compared with solvent-extracted canola meal were marginal compared with the differences in estimated 18-carbon FA intake. A lack of substantial increase in the secretion of 18:0 in milk tends to suggest an incomplete digestion and absorption of 18:0 in the small intestine in cows fed high-oil canola or rapeseed meals. Previous studies have provided evidence that the bioavailability of lipid is lower for whole rapeseeds compared with processed rapeseeds or rapeseed oil (Bayourthe et al., 2000; Givens et al., 2009).

Experimental treatments resulted in comparable decreases in medium-chain and total milk SFA despite

the relatively large difference in the lipid composition of high-oil rapeseed and canola meals. Several studies have examined the effects of high-oleic acid canola oil on milk fat composition (Jenkins, 1998; Loor et al., 2002), but direct comparisons with conventional sources of canola or rapeseed oil are limited. Recent investigations demonstrated that high-oleic acid rapeseed resulted in marginally lower milk fat 16:0 concentrations compared with conventional rapeseeds (Kliem et al., 2011), but no significant difference existed between CMEC and HOLL treatments in this experiment. Furthermore, comparisons of milk fat composition responses to conventional, HOLL and RPS also suggest that supplementing the diet with lipids rich in *cis*-13 22:1 are equally as effective as oils abundant in *cis*-9 18:1 and 18:2n-6 in lowering the de novo synthesis of FA in the mammary gland.

Replacing solvent-extracted rapeseed meal with high-oil rapeseed or canola meals enhanced the concentrations of MUFA in milk fat due, at least in part, to an increase in *cis*-9 18:1 content consistent with the known effects of processed rapeseeds or rapeseed oil in the diet on milk FA composition (Glasser et al., 2008; Shingfield et al., 2008). An increase in milk *cis*-9 18:1 content to the inclusion of high-oil meals may arise because of increased ruminal escape of *cis*-9 18:1 in the diet or via desaturation of 18:0 in the mammary gland. In this experiment, differences in *cis*-9 18:1 intake between conventional, high-oleic, and high-erucic acid meals were not reflected by milk fat *cis*-9 18:1 enrichment. Furthermore, no clear relationship existed between milk fat *cis*-9 18:1 and 18:0 concentrations ($Y = -0.515x + 28.6$, $n = 32$, $r^2 = 0.08$), suggesting that both mechanisms contributed, to a variable extent, to the increase in milk *cis*-9 18:1 secretion with high-oil rapeseed or canola meals in the diet.

The CMEC, HOLL, and RPS also increased milk fat *cis*-15 18:1 content. Earlier investigations have shown that the relative abundance of one or more *cis*-18:1 isomers with double bonds at $\Delta 11$ to $\Delta 16$ can be altered in response to milled or ground rapeseeds (Collomb et al., 2004; Givens et al., 2009; Kliem et al., 2011), milled high-oleic acid rapeseeds (Kliem et al., 2011), and rapeseed oil (Givens et al., 2009; Rego et al., 2009) inclusion in the diet.

Inclusion of all high-oil meals resulted in higher milk *trans*-16:1 concentrations and both conventional and high-oleic acid meals enhanced milk fat *trans*-18:1 and total *trans* FA content. Rapeseed-based supplements are known to alter the relative abundance of specific *trans* FA in bovine milk fat (Givens et al., 2009; Rego et al., 2009; Kliem et al., 2011), changes that arise because of the incomplete hydrogenation of *cis*-9 16:1, *cis*-9 18:1, 18:2 n-6, and 18:3 n-3 in the rumen. In this experiment,

trans-10 18:1 and *trans*-11 18:1 represented the major *trans* FA in milk fat. In most diets, *trans*-11 18:1 is the most abundant *trans* FA in milk fat (Shingfield et al., 2008), whereas ruminal formation and appearance of *trans*-10 18:1 in milk is known to be increased in high-starch, low-fiber diets containing unsaturated FA that cause milk fat depression (Loor et al., 2005; Shingfield and Grinari, 2007; Shingfield et al., 2010). A relatively high concentration of *trans*-10 18:1 in milk for all experimental diets is consistent with the low milk fat content.

Relative to the CTRL, HOLL, but not CMEC, increased milk fat *trans*-11 18:1 content, which is difficult to explain, based on the relative concentrations of *cis*-9 18:1 and PUFA in the experimental meals. Supplementing the diet with canola or rapeseed oil or processed seeds has been reported to enhance milk *trans*-11 18:1 content in some (Loor et al., 2002; Chelikani et al., 2004; Chichlowski et al., 2005), but not all studies (Collomb et al., 2004; Givens et al., 2009; Rego et al., 2009).

Even though replacing CTRL with high-oil canola meal or RPS increased dietary 18:2 n-6 intake, the concentration of 18:2 n-6 in milk was decreased. Earlier studies have also shown that rapeseed oil or processed rapeseeds in the diet tend to lower milk fat 18:2n-6 content (Collomb et al., 2004; Givens et al., 2009; Rego et al., 2009). Experimental treatments had relatively minor effects on the abundance of non-methylene interrupted 18:2 isomers in milk fat. An increase in milk *cis*-9, *trans*-13 18:2 content is a typical response to rapeseed oil (Givens et al., 2009; Rego et al., 2009), or processed rapeseeds (Collomb et al., 2004; Givens et al., 2009; Kliem et al., 2011) inclusion in the diet. The high-oil meals had no effect on *cis*-9, *trans*-13 18:2 concentrations, but the abundance of this isomer in milk fat was relatively high across all treatments in this experiment.

High-oleic acid canola meal enhanced milk fat CLA content due, in the most part, to an increase in *cis*-9, *trans*-11 CLA that is consistent with the corresponding increase in milk *trans*-11 18:1 concentrations. *Trans*-7, *cis*-9 CLA was the second most abundant CLA isomer in milk fat in all diets. Both conventional and high-oleic acid canola meals enhanced *trans*-7, *cis*-9 CLA in milk, consistent with previous investigations examining the effects of rapeseed-based feeds on milk fat composition (Givens et al., 2009; Rego et al., 2009; Kliem et al., 2011). These findings indicate that both conventional and high-oleic acid canola meals increased ruminal formation of *trans*-7 18:1, because *trans*-7, *cis*-9 CLA in milk is exclusively synthesized endogenously in the mammary gland (refer to Shingfield et al., 2010). Substituting solvent-extracted rapeseed meal with high-oil rapeseed or canola meals had relatively minor effects on

the distribution of other CLA isomers in milk fat, with the changes due to treatment reflecting differences in 18:2n-6 and 18:3n-3 intake and the formation of specific CLA isomers in the rumen during incomplete biohydrogenation of dietary PUFA (Jenkins et al., 2008; Shingfield et al., 2010).

Replacement of CTRL with RPS increased milk fat *cis*-13 22:1, *trans*-15 22:1, and 22:0 content, indicating that *cis*-13 22:1 is partially hydrogenated or isomerized in the rumen and that 22-carbon biohydrogenation intermediates and end-product FA are absorbed and utilized in the synthesis of milk fat in the bovine mammary gland.

CONCLUSIONS

In this study, inclusion of high-oil, mechanically extracted canola and rapeseed meals decreased ruminal acetate concentration, but had no other effects on ruminal fermentation or total tract nutrient digestibility in dairy cows. Urinary urea losses and ammonia emission from manure were increased by some meals as a result of the higher protein content of these meals and dietary N intake. All meals decreased feed intake and with most, this resulted in decreased milk yield. Thus, high-oil canola (or rapeseed) meals, fed at levels at or above 12 to 13% of dietary DM may decrease intake and milk yield in high-producing dairy cows. More research is needed to determine the optimal dietary inclusion level of these feedstocks to maximize dairy cow productivity. The high-oil meals had no effect on milk components and FCM feed efficiency was increased by some meals. The high-oil meals had a profound effect on milk FA composition, decreasing the concentration of total saturated FA and generally increasing the sum of monounsaturated and *trans* fatty acids. In conclusion, high-oil canola or rapeseed meals, which are likely to come from small-scale biodiesel plants where oil is cold pressed without hexane extraction, may decrease feed intake and milk production, but can be used to alter milk fatty acid composition in lactating dairy cows.

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