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Effect of toasting and decortication of oat on rumen biohydrogenation and intestinal digestibility of fatty acids in dairy cows

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ABSTRACT

This experiment quantified the effect of decorticated and toasted oat (*Avena sativa* L.) on fatty acid (FA) supply, ruminal biohydrogenation (BH) of FA, and intestinal digestibility of FA in 4 ruminal and intestinal cannulated Danish Holstein cows. Experimental diets containing untreated oat, decorticated oat, toasted oat, and decorticated and toasted oat were fed ad libitum to the cows in a 2 × 2 factorial arrangement in a Latin square design throughout 4 periods. Unless otherwise mentioned, the results of this study indicate the main effect of decortication and toasting. Decortication increased the intake of FA by 40.3 g/d and increased feed-ileum digested FA, whereas toasting decreased the intake of FA by 69.3 g/d. Toasting increased both feed-ileum and total-tract digestibility of FA by 59.8 and 67.4 g/kg of FA intake, respectively. The proportion of C18:2n-6 in FA intake increased, and the C18:3n -3 proportion in FA intake decreased due to decortication. Toasting resulted in a dramatic reduction of the C18:2n-6 proportion in FA intake, and it increased the proportions of C18:0 and C18:3n-3 in FA intake. Toasting reduced ruminal BH of C18:1n-9 and C18:2n -6 by 134 and 11.7 g/kg of FA intake, respectively, and toasting increased the proportion of unsaturated FA to saturated FA in the duodenal FA flow. Decortication decreased the ruminal BH of C18:3n-3 by 38.0 g/kg of FA intake. Decortication increased small intestinal digestibility of C12:0, C15:0, C20:0, and C22:0. Toasting increased the small intestinal digestibility of C15:0, C18:0, *trans*-C18:1, C20:0, and C24:0. Toasting reduced the small intestinal digestibility of C18:1n-9, C18:2n -6, and C20:1n-9. This study showed that decortication successfully increased the intake of FA and flow of FA at the duodenum and feed-ileum digested FA. However, toasting oat at 121°C caused a remarkable decline in FA concentration in oat, and thereby FA intake; therefore, toasting cannot be recommended.

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INTRODUCTION

Organic dairying has limited possibilities for external inputs, such as concentrate (Blanco-Penedo et al., 2012; Scollan et al., 2017), which may restrict milk production and affect milk fatty acid (**FA**) composition (Schwendel et al., 2015). Compared with most cereals, oat has a high content of crude fat with high levels of PUFA (Decker et al., 2014; Qi et al., 2017). Oat is commonly grown by Nordic organic dairy farmers and could be used as a fat source for cows. However, oat grain is covered with hull (husk) and is low in crude fat (Welch et al., 1983) and high in structural carbohydrates and lignin (Round, 1988; Decker et al., 2014). Therefore, removing the hull through decortication increases the concentration of crude fat in oat (on DM basis) when compared with the husked grain. Increasing the fat content in the diet through decorticated oat might compromise the supply of AA because fat is not fermented in the rumen (Brask et al., 2015). However, Panah et al. (2020a) reported an increase in both microbial protein and AA synthesis due to decortication, possibly as a consequence of the increased starch intake concurrent with the increased fat content of oat by decortication. Toasting can protect protein against rumen degradation and then counteract the negative effect of increased fat supply on the metabolizable protein supply to the cow (Panah et al., 2020a). Gonthier et al. (2005) reported that heat treatment of oilseeds can protect the protein matrix surrounding the fat droplets against rumen degradation, and thereby protect UFA against ruminal biohydrogenation (**BH**). Panah et al. (2020a) showed that toasting oat reduced the ruminal digestibility of AA and in situ degradability of CP, causing the increased flow of both CP and AA at the duodenum.

Upon entering the rumen, esterified FA undergo lipolysis by rumen microbes, and after lipolysis, UFA are extensively biohydrogenated in the rumen (Doreau

and Chilliard, 1997). Decortication is expected to make the UFA of the grain more susceptible to ruminal BH; therefore, partial protection against ruminal BH could increase the post ruminal appearance of UFA. Heat treatment was shown to be a successful approach in protecting UFA in different feeds from ruminal BH (Pires et al., 1997; Lashkari et al., 2015). This could also be applicable in oat because fat droplets are distributed throughout the endosperm together with starch and protein (Peterson and Wood, 1997). Therefore, the objective of this study was to investigate to what extent decortication could increase the FA supply, and if toasting could decrease ruminal BH of UFA.

MATERIALS AND METHODS

Animals and Experimental Design

This experiment complied with the Danish ethical requirements based on the Danish Ministry of Justice Law No. 726 (September 9, 1993). In a 4 × 4 Latin square design, 2 primiparous and 2 multiparous lactating Danish Holstein dairy cows, fitted with rumen cannulas and duodenal and ileal simple T-cannulas, received 1 of 4 experimental diets over 4 periods. Each period consisted of 22 d, in which d 1 to 13 were allocated for adaptation, and d 13 to 17 for collection of digesta (i.e., rumen, duodenum, ileum, feces). The experimental diets were offered as TMR including whole grain oat (Oat), decorticated oat (**D**), toasted whole oat (**T**), or decorticated toasted oat (**DT**). The main effect of decortication and toasting is reported in full terms (i.e., decortication: the main effect of decortication in D and DT diets; toasting: the main effect of toasting in T and DT diets). Animals were housed in tie-stalls, and beds were covered with rubber mats and sawdust. The average BW of cows at the onset of the experiment was 618 ± 47.9 kg (mean ± standard deviation); the cows were at 61.3 ± 49.9 d in milk, and their BCS was 3 ± 0.20 (mean ± standard deviation). On d 17 through 22, the enteric methane emission was measured in respiration chambers, as already reported by Panah et al. (2020a).

Diets and Feeding

For the variety of oat used in this experiment, we used the 'Dominik' cultivar of *Avena sativa* grown in Denmark in 2017. We used a mobile decorticator with 3 Bühler dehuller MHSA (Bühler AG, Uzwil, Switzerland) mounted on a truck for decortication on-farm by Gl. Buurholt ApS (Brønderslev, Denmark), with an efficacy of 83%, and the remainder was partially decorticated. Toasting at 121°C was done on-farm using a Bulldog Toaster (Mecmar S. p. a., Minerbe, Italy). The flow through the toaster was 2,500 kg/h, and the retention time was 35 s. Before adding to the ration, all 4 forms of oat were rolled by a MS 1325-4 roller (Skjold, Sæby, Denmark) with a 3-mm roller distance.

Formulation of the diet was based on NorFor (Volden, 2011), and the forage-to-concentrate ratio of the TMR was 60:40 on a DM basis (Table 1). The TMR consisted (g/kg of DM) of grass-clover silage (609), toasted fava beans (165), vitamin and mineral supplements (8.70), and oat (1 of the 4 forms; 217). Chemical composition of feedstuffs is presented in Table 2. The TMR was offered to the cows ad libitum twice daily at 0600 and 1630 h. Feed offered and residuals were recorded daily, and DM concentration of feed and residues was determined on d 12 through 17 in each period. Samples of all ingredients were taken in each period on a weekly basis. Analysis were performed on pooled samples for periods 1 and 2, and for 3 and 4, respectively.

Rumen, Digesta, and Fecal Sampling

Chromium oxide (Cr_2O_3; 10 g) and titanium dioxide (TiO_2; 13 g) were used as digestion markers. Markers were weighed in degradable coffee filter bags and placed into the rumen concurrent with milking times (0520 and 1545 h). Intestinal digesta and feces were sampled 12 times over 5 d (i.e., d 13–17: at 1000 h and 1800 h on d 13; 0200 h, 1200 h, and 2000 h on d 14; 0400 h, 1400 h, and 2200 h on d 15; 0600 h, 1600 h, and 2400 h on d 16; 0800 h on d 17). Plastic bags, mounted on L-shaped polyvinyl chloride pipe connectors, were used to collect duodenal (0.5-L) and ileal (0.2-L) samples

Table 1. Total mixed ration and nutrient composition of experimental diets, g/kg of DM unless otherwise noted

	Diet[1]			
Item	Oat	D	T	DT
Ingredient				
Whole oat grain	217.1	—	—	—
Decorticated oat grain	—	217.1	—	—
Toasted oat grain	—	—	217.1	—
Decorticated toasted oat grain	—	—	—	217.1
Toasted fava bean	165.2	165.2	165.2	165.2
Grass-clover silage	609	609	609	609
Mineral supplement	8.70	8.70	8.70	8.70
Nutrients				
DM, g/kg	540	540	563	561
Ash	77.6	77.4	77.8	77.4
Crude fat	43.9	48.1	40.5	45.1
CP	194	197	193	198
Starch	156	175	151	174
NDF	331	310	331	301

[1]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

from the T-cannula. Approximately 50 g of feces were collected either during defecation or from the rectum. The 12 samples for duodenal and ileal contents and feces were pooled by sample, by cow, and by period.

Microbes were isolated from the rumen fluid on d 17 at 1200 h. The isolation was carried out by collecting 2 L of rumen liquid from the ventral rumen. Liquid was filtered through 2 layers of cheese cloth into prewarmed thermos bottles. After being transferred to the laboratory, the samples were centrifuged twice at 500 × *g* for 5 min at 3°C to remove feed particles and protozoa. Afterward, the resultant supernatant was centrifuged at 17,300 × *g* for 20 min at 3°C. The precipitated pellet was resuspended in 200 mL of saline solution (0.9% NaCl) and centrifuged at 17,300 × *g* for 20 min at 3°C to harvest the pellet (microbial matter).

Chemical Analysis

Feed and digesta samples were stored frozen at −20°C and subsequently freeze-dried before laboratory analysis. Dry matter of analyzed samples was determined by oven-drying at 60°C for 48 h according to Åkerlind et al. (2011). The ash content of feed was measured by combustion at 525°C for 6 h. Chromium oxide in digesta and fecal output was oxidized to chromate and determined calorimetrically (Schürch et al., 1950). Titanium dioxide was digested with sulfuric acid, hydrogen peroxide was added, and absorbance was measured spectrophotometrically according to Myers et al. (2004), with the modification that 15 mL of 30% hydrogen peroxide was added instead of 10 mL, and an extra 5 drops of 30% hydrogen peroxide were added before absorbance measurement.

Microbial flow at the duodenum was estimated using purine as marker. Total purine was analyzed according to the method of Zinn and Owens (1986) with modification by Thode (1999).

Fat was extracted from 250 mg of feed ingredient and feces, and 500 mg of microbes and digesta, based on a modified HCl-Bligh and Dyer procedure (Bligh and Dyer, 1959; Jensen, 2008). After hydrolyzing the samples with 3 *M* HCl for 1 h at 80°C, a mixture of 3 mL of methanol, 1.5 mL of distilled water, and 3 mL of chloroform, containing 5 mg of C17:0 (hectadecanoic acid, Sigma-Aldrich, St. Louis, MO) as internal standard, was added. After shaking and phase separation by centrifugation, approximately 2 mL of the chloroform phase was transferred to tared tube, weighed, oven-dried at 100°C, and weighed for total fat determination. Fatty acids from milk samples (0.50-mL) were extracted in the same way without prior acidic hydrolysis. Approximately 1 mL of the residual chloroform phase was transferred to a new culture tube (Wheaton, Millville, NJ; 16 × 100 mm; culture C-tubes with cap, round-bottom), evaporated to dryness under a N_2 stream and methylated with 0.8 mL NaOH (2%) in methanol, sealed with argon gas (Ar), and placed in an oven for 15 min at 100°C. After cooling, 1 mL of boron trifluoride reagent was added with Ar and placed at 100°C for 45 min. Finally, FA methyl esters were extracted with 2 mL of heptane and 4 mL of saturated

Table 2. Chemical composition and fatty acid profile of diet ingredients (mean ± SD, n = 2), g/kg of DM unless noted

	Feedstuff					
Item	Grass-clover silage	Toasted fava beans	Oat	Decorticated oat	Toasted oat	Decorticated toasted oat
DM, g/kg of fresh weight	302 ± 0.84	946 ± 0.95	882 ± 0.74	881 ± 1.39	986 ± 1.14	975 ± 1.43
Ash	95.2 ± 0.20	38.0 ± 0.24	21.6 ± 0.04	20.5 ± 0.04	22.1 ± 0.08	20.5 ± 0.10
Crude fat	35.9 ± 12.4	16.2 ± 2.16	73.1 ± 0.30	90.3 ± 0.14	77.0 ± 1.09	84.0 ± 2.90
Fatty acids	15.8 ± 0.53	15.3 ± 0.60	54.5 ± 3.91	72.1 ± 0.39	41.6 ± 3.15	47.3 ± 1.62
Fatty acids, g/kg of FA						
C6:0	ND[1]	ND	ND	ND	0.99 ± 0.12	1.12 ± 0.20
C10:0	2.21 ± 0.18	0.05 ± 0.07	ND	ND	0.29 ± 0.00	0.29 ± 0.01
C14:0	4.96 ± 0.13	1.08 ± 0.03	1.63 ± 0.03	1.44 ± 0.03	2.34 ± 0.02	2.10 ± 0.01
C16:0	175 ± 3.74	136 ± 0.28	154 ± 2.05	152 ± 0.78	220 ± 0.77	220 ± 0.44
C18:0	21.1 ± 1.04	23.1 ± 0.02	18.4 ± 0.30	18.2 ± 0.34	26.6 ± 0.01	26.5 ± 0.37
C18:1n-9	18.6 ± 1.26	303 ± 0.12	417 ± 5.16	421 ± 3.20	457 ± 4.81	461 ± 1.28
C18:1n-7	3.96 ± 0.09	3.22 ± 0.06	6.78 ± 0.06	6.84 ± 0.14	8.24 ± 0.0	7.99 ± 0.06
C18:2n-6	153 ± 2.18	477 ± 2.62	376 ± 3.35	376 ± 1.83	244 ± 3.25	244 ± 2.78
C18:3n-3	572 ± 2.31	26.1 ± 0.47	12.6 ± 0.12	12.1 ± 0.23	10.5 ± 0.44	8.99 ± 0.17
C20:0	6.32 ± 0.69	10.8 ± 0.21	1.47 ± 0.03	1.32 ± 0.02	2.30 ± 0.0	2.02 ± 0.02
C20:1n-9	0.68 ± 0.18	5.44 ± 0.12	6.80 ± 0.7	6.64 ± 0.17	8.14 ± 0.44	7.84 ± 0.12
Other[2]	41.0 ± 4.86	13.9 ± 4.41	5.39 ± 0.74	4.94 ± 0.70	19.3 ± 3.41	18.7 ± 2.40

[1]Not detected.

[2]Sum of C8:0, C11:0, C12:0, C13:0, C14:1, C15:0, C16:1n-9, C16:1n-7, C17:1, *trans*-C18:1, C18:3n-6, C18:4n-3, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA, C20:2n-6, C20:3n-6, C20:4n-6, C20:3n-3, C20:5n-3, C22:0, C22:1n-11, C22:1n-9, C22:5n-6, C22:5n-3, C22:6n-3, C24:0, C24:1.

NaCl solution, followed by centrifugation for 10 min at 2,000 × *g* (Jensen, 2008). Microbial FA were analyzed both with and without internal standard. The gas chromatograph (Hewlett Packard 6890, Agilent Technologies, Palo Alto, CA) was equipped with an automatic column injector (Hewlett Packard 7673), a capillary column of 30 m × 0.32 mm i.d., 0.25 μm thickness (Omegawax 320, Supelco, Sigma-Aldrich), and a flame ionization detector for quantifying FA as FA methyl ester. The primary temperature was set at 170°C, and the temperature was increased at a rate of 2°C/min to 200°C, held for 5 min, and finally raised to 220°C at a rate of 5°C/min. Peaks were identified by comparison of retention times with external standards (GLC 68C, Nu-Prep Chek, Elysian, MN) for FA.

Cows were milked 2 times a day at 0520 and 1545 h, and milk samples for FA analysis were taken from the evening on d 15 and morning on d 16. The samples were mixed proportionally to milk production. For analysis of milk FA, milk samples were immediately frozen and kept cryopreserved until the day of analysis.

Calculations and Statistical Analyses

Dry matter intake was determined on d 12 through 17, and DMI data were averaged per cow per period. Daily DMI was calculated as DM offered minus DM in refusals. From d 13 to d 17 in each period, digesta DM flows were calculated as average of flows for each marker. Digestibility in the rumen, small intestine, and total-tract was calculated from the respective intake and flow at the duodenum, ileum, and fecal output.

The effect of different treatments on intake, digestibility, fat and FA content, and FA composition was analyzed using R (version 3.6.0, http://www.R-project.org). The least squares means of response variables were measured using the Fit Linear Mixed-Effects Models procedure in R through *lmer* function in *lme4* package (Bates et al., 2015). The model was as below:

$$Y_{ijkl} = \mu + D_i + T_j + DT_{ij} + P_k + C_l + E_{ijkl},$$

where Y is the dependent variable and μ is the overall mean; the model includes the fixed effects of decortication (D_i), toasting (T_j), the interaction (DT_{ij}), and the kth period (P_k), the random effect of lth cow (C_l), and the random error (E_{ijkl}). The main effects of decortication are reported as the effect of decortication in D and DT vs. Oat and T diets, and the main effect of toasting is based on the effects of toasting in T and DT vs. Oat and D diets. For the effect of internal standard on quantification of FA, the same model was used for statistical analysis with the inclusion of the effect of quantifications methods. Values presented in Tables 3–9 and in Supplemental Tables S1–S4 (https://doi.org/10.3168/jds.2019-18125) are least squares means with corresponding standard error of the mean. Significance for main effects was declared at $P \leq 0.05$ and a tendency at $0.05 < P < 0.10$. Interaction at $P \leq 0.05$ was declared significant, and if significant, least squares means were compared using the Tukey-Kramer test at $\alpha = 0.05$.

RESULTS

Intake

Crude fat intake did not change, but FA intake increased due to decortication by 40.3 g/d (as a difference between decorticated oat and nondecorticated oat; $P = 0.02$), and toasting decreased FA intake by 69.3 g/d ($P < 0.01$; Table 3). Decortication increased the total-tract digested amount of fat ($P = 0.05$).

Decortication decreased the proportion of C10:0 and C14:0 intake in total FA intake and tended to decrease the C18:0 proportion, whereas toasting increased their proportion as well as the C16:0 proportion in total FA intake (Table 4). The proportion of C18:1n-9 in FA intake increased ($P < 0.01$) due to decortication and decreased ($P < 0.01$) by toasting. Decortication increased the proportion of C18:2n-6, and it decreased the C18:3n-3 proportion, and toasting reduced the proportion of C18:2n-6 and increased the C18:3n-3 proportion in FA intake. Decortication increased the ratio of UFA:SFA, and toasting decreased this ratio in FA intake.

Digested Amount and Digestibility

Feed-ileum digestibility of crude fat increased ($P = 0.01$) by decortication. The D diet showed higher feed-ileum digestibility of crude fat compared with Oat diet (559 vs. 501 g/kg of fat intake; interaction $P < 0.01$; Table 3). However, neither the total-tract nor the hindgut digestibility of crude fat were affected by treatments. Decortication tended to increase FA digested in the small intestine, and it increased the feed-ileum digested FA by 35.9 g/d ($P = 0.01$). The amount of feed-ileum digested FA was reduced by 29.0 g/d ($P = 0.03$) due to toasting. Total-tract digested FA increased by decortication ($P = 0.03$), and it decreased by toasting ($P = 0.04$). Toasting increased the small intestinal digestibility of FA by 67.0 g/kg of duodenal FA ($P < 0.01$), and increased the feed-ileum FA digestibility by 59.8 g/kg of FA intake ($P = 0.01$). Total-tract digestibility of FA was increased by 67.4 g/kg of FA intake ($P = 0.01$), owing to toasting.

Ruminal formation of C18:0 decreased by 71.3 g/d ($P < 0.01$) due to toasting (Table 5). Toasting reduced the ruminal disappearance of C18:1n-9 by 36.0 g/d ($P < 0.01$), and decortication increased it by 15.6 g/d ($P = 0.01$). The ruminal formation of *trans*-C18:1 was reduced by toasting ($P = 0.01$) and increased by decortication ($P = 0.04$). Toasting resulted in lower ruminal disappearance of C18:2n-6 by 58.0 g/d ($P < 0.01$).

Toasting reduced the ruminal BH of C18:1n-9 ($P < 0.01$) and C18:2n-6 ($P = 0.01$) by 134 and 11.7 g/kg of FA intake, respectively (Table 5). Decortication decreased the ruminal BH of C18:3n-3 by 38.0 g/kg of FA. The DT diet yielded the lowest BH for C18:1n-9 when compared with Oat, D, and T (interaction $P = 0.02$).

Decortication reduced the proportion of C15:0, C18:1n-9, C18:3n-3, C22:0, C24:0, and odd chain FA (**OCFA**) in the duodenal FA (Supplemental Table S1, https://doi.org/10.3168/jds.2019-18125). Toasting increased the proportion of C15:0, C16:0, C18:1n-9, C18:2n-6, C18:3n-3, C20:0, C22:0, C24:0, and OCFA, whereas it decreased C18:0 in the duodenal FA.

Decortication increased the small intestinal digestibility of C12:0, C15:0, C20:0, and C22:0, and tended to increase the C13:0 digestibility (Table 6). Toasting increased the small intestinal digestibility of C15:0, C18:0, *trans*-C18:1, C24:0, and C20:0, and tended to increase the C22:0 digestibility. Toasting reduced the small intestinal digestibility of C18:1n-9 and C18:2n-6. Compared with Oat, D, and T diets, DT resulted in the highest reduction of the small intestinal digestibility of C18:1n-9 and C18:2n-6; digestibilities were 759 and 838 g/kg, respectively. Toasting reduced the digested amount of *trans*-C18:1 in the small intestine, with a tendency to reduce it for C18:0 (Supplemental Table S2, https://doi.org/10.3168/jds.2019-18125).

The total-tract digestibility of C18:2n-9, C18:2n-6, and C18:3n-3 increased by decortication (Table 7). Toasting increased the total-tract digestibility of SFA, such as C12:0, C15:0, C16:0, C18:0, C20:0, C22:0, and C24:0, while it decreased that for UFA, such as C18:1n -9, C18:2n-6, and C18:3n-3. The hindgut digestibility of SFA, including C18:0, C20:0, and C24:0, was reduced

Table 3. Intake and rumen, intestine, hindgut, and total-tract digestibilities[1] of crude fat and total fatty acids and daily digested amounts

	Diet[2]					*P*-value[3]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
Intake								
DM, kg/d	21.7	20.7	22.0	21.9	2.07	0.25	0.08	0.25
Crude fat, g/d	896	913	892	943	89.0	0.19	0.59	0.49
FA,[4] g/d	521	577	468	491	53.1	0.02	<0.01	0.24
Digested crude fat, g/d								
Rumen	−954	−965	−1,006	−1,003	131	0.93	0.32	0.87
Small intestine	1,429	1,485	1,489	1,511	183	0.51	0.46	0.77
Hindgut	−91.0	−109	−136	−73.8	28.4	0.44	0.86	0.19
Total tract	384	411	347	434	49.0	0.05	0.76	0.24
Digestibility of crude fat, g/kg of fat								
Rumen	−1,103	−1,046	−1,129	−1,096	74.5	0.38	0.45	0.80
Small intestine	765	784	783	776	13.0	0.38	0.40	0.08
Feed-ileum	501[a]	559[b]	542[b]	528[ab]	23.1	0.04	0.56	<0.01
Hindgut	−236	−266	−333	−167	64.8	0.32	0.99	0.17
Total tract	378	442	389	448	33.4	0.10	0.81	0.94
Digested total FA, g/d								
Rumen	59.0	57.0	52.5	34.2	27.2	0.67	0.52	0.73
Small intestine	344	403	343	376	38.9	0.06	0.49	0.54
Feed-ileum	403	460	395	410	49.4	0.01	0.03	0.09
Hindgut	11.0	2.73	9.52	7.54	4.83	0.31	0.73	0.52
Total tract	414	462	403	416	50.6	0.03	0.04	0.16
Digestibility of total FA, g/kg of FA								
Rumen	102	97.9	106	64.3	44.0	0.58	0.68	0.65
Small intestine	739	771	822	822	18.7	0.29	<0.01	0.29
Feed-ileum	762	794	841	834	23.3	0.48	0.01	0.28
Hindgut	89.5	19.2	129	90.0	28.6	0.09	0.09	0.59
Total tract	781	797	863	850	22.0	0.92	0.01	0.39

[a,b]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Digestibility values in rumen, small intestine, hindgut, and total tract are reported in grams of digested fat or fatty acid (FA) per kg of fat or FA intake, duodenal flow, ileal flow, and intake, respectively. Negative digestibilities indicate a supply of crude fat in the respective section, for rumen digestibilities probably due to supply of bile acids.

[2]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[3]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[4]It was assumed that the FA content of the feed refusals equals FA content in the intake because diets were offered as TMR.

Table 4. Composition of total fatty acid (FA) intake (g/kg of FA intake)

	Diet[1]					*P*-value[2]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
C10:0	0.89[b]	0.77[a]	1.13[d]	1.08[c]	0.01	<0.01	<0.01	<0.01
C14:0	2.91[b]	2.63[a]	3.38[d]	3.21[c]	0.02	<0.01	<0.01	0.02
C16:0	161[b]	158[a]	190[c]	191[d]	0.27	0.21	<0.01	<0.01
C18:0	20.0[b]	19.7[a]	23.7[c]	23.8[c]	0.06	0.08	<0.01	<0.01
C18:1n-9	245[ab]	271[c]	239[a]	253[b]	2.87	<0.01	<0.01	0.05
C18:1n-7	5.27[a]	5.51[b]	5.70[c]	5.72[c]	0.03	<0.01	<0.01	0.01
C18:2n-6	297[b]	308[c]	231[a]	231[a]	0.65	<0.01	<0.01	<0.01
C18:3n-3	239[b]	207[a]	268[d]	253[c]	2.78	<0.01	<0.01	0.02
C20:0	4.41[b]	3.92[a]	5.14[d]	4.86[c]	0.03	<0.01	<0.01	0.01
FA groups								
ΣC16[3]	164[b]	161[a]	194[c]	195[c]	0.28	0.09	<0.01	<0.01
Other[4]	20.6[b]	18.2[a]	28.5[c]	27.7[c]	0.32	<0.01	<0.01	0.05
UFA	797[b]	803[c]	759[a]	758[a]	0.39	<0.01	<0.01	<0.01
Ratio								
UFA:SFA	3.94[b]	4.07[c]	3.15[a]	3.14[a]	0.01	<0.01	<0.01	<0.01

[a–d]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[2]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[3]Σ(C16:0, C16:1n-9, C16:1n-7).

[4]Sum of C6:0, C8:0, C11:0, C12:0, C13:0, C14:1, C15:0, C17:1, *trans*-C18:1, C18:3n-6, C18:4n-3, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA, C20:1n-9, C20:2n-6, C20:3n-6, C20:4n-6, C20:3n-3, C20:5n-3, C22:0, C22:1n-11, C22:1n-9, C22:5n-6, C22:5n-3, C24:0, C22:6n-3, C24:1.

Table 5. Ruminal disappearance[1] (g/d) and fatty acid (FA) biohydrogenation[2] (g/kg of FA intake)

	Diet[3]					*P*-value[4]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
Ruminal disappearance								
C10:0	0.35	0.34	0.40	0.38	0.03	0.16	<0.01	0.59
C12:0	−1.08	−1.37	−1.23	−1.21	0.16	0.19	0.94	0.14
C13:0	0.40[b]	0.26[a]	0.34[ab]	0.31[ab]	0.06	<0.01	0.85	0.03
C14:0	−1.98	−2.89	−2.05	−2.60	0.48	0.01	0.60	0.40
C18:0	−258	−297	−198	−214	4.65	0.10	<0.01	0.45
C18:1n-9	104[b]	130[c]	78.9[a]	83.5[bc]	26.3	0.01	<0.01	0.04
C18:1n-7	−8.04	−10.5	−7.83	−8.58	12.4	0.02	0.07	0.12
trans-C18:1[5]	−7.30	−8.09	−5.98	−6.85	0.93	0.04	0.01	0.91
C18:2n-6	129	149	80.7	80.9	1.09	0.13	<0.01	0.13
C18:3n-3	111	107	112	110	12.1	0.19	0.32	0.65
C20:0	−1.36	−1.85	−0.99	−1.19	10.3	0.13	0.04	0.50
C20:1n-9	1.80[ab]	2.12[b]	1.51[a]	1.46[a]	0.24	0.14	<0.01	0.05
FA groups								
ΣC16[6]	7.20	5.73	11.8	8.02	4.74	0.50	0.38	0.76
ΣC18[7]	69.1	69.9	60.1	45.4	22.3	0.72	0.40	0.69
Other[8]	−23.8	−24.3	−23.9	−23.7	2.36	0.87	0.78	0.74
Biohydrogenation								
C18:1n-9	802[b]	833[b]	701[a]	668[a]	13.2	0.92	<0.01	0.02
C18:2n-6	954	955	945	940	4.40	0.59	0.01	0.36
C18:3n-3	789	762	785	736	10.4	0.01	0.19	0.31

[a–c]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Ruminal disappearance was measured as: FA intake − duodenal FA flow.

[2]Ruminal biohydrogenation: (FA intake – FA in duodenal flow)/FA intake.

[3]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[4]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[5]All *trans*-C18:1, mainly vaccenic acid.

[6]Σ(C16:0, C16:1n-9, C16:1n-7).

[7]Σ(C18:0, C18:1n-9, C18:1n-7, *trans*-C18:1, C18:2n-6, C18:3n-6, C18:3n-3, C18:4n-3, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA).

[8]Sum of C6:0, C8:0, C11:0, C14:1, C15:0, C17:1, C18:3n-6, C18:4n-3, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA, C20:2n-6, C20:3n-6, C20:4n-6, C20:3n-3, C20:5n-3, C22:0, C22:1n-11, C22:1n-9, C22:5n-6, C22:5n-3, C24:0, C22:6n-3, C24:1.

Table 6. Small intestinal digestibility of fatty acids (g/kg of duodenal fatty acid flow)

	Diet[1]					*P*-value[2]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
C11:0	824	735	655	715	50.0	0.79	0.09	0.17
C12:0	606	684	651	665	21.5	0.05	0.50	0.15
C13:0	462	533	438	529	42.2	0.09	0.75	0.82
C14:0	742	757	752	771	14.9	0.28	0.46	0.89
C15:0	772	806	817	830	10.3	0.04	0.01	0.34
C16:0	807	837	830	828	11.0	0.21	0.53	0.16
C16:1n-9	822	755	813	751	76.8	0.38	0.93	0.97
C16:1n-7	967	982	903	955	32.3	0.33	0.19	0.58
C17:1	923	930	913	928	7.36	0.16	0.40	0.55
C18:0	688	726	826	831	27.4	0.29	<0.01	0.40
C18:1n-9	874[b]	892[b]	798[a]	759[a]	8.33	0.24	<0.01	0.01
C18:1n-7	843	876	875	878	9.87	0.11	0.14	0.18
trans-C18:1[3]	839	871	907	908	16.1	0.28	0.01	0.31
C18:2n-6	857[ab]	880[b]	858[ab]	838[a]	8.91	0.93	0.05	0.04
C18:3n-3	858	874	858	867	9.44	0.22	0.76	0.73
C20:0	602	663	694	736	23.5	0.04	0.01	0.63
C20:1n-9	749	892	553	695	89.7	0.13	0.05	1.00
C20:3n-6	953	969	971	973	9.61	0.28	0.18	0.38
C20:4n-6	965	971	953	954	15.2	0.72	0.20	0.84
C20:5n-3	970	956	957	969	20.0	0.95	0.98	0.52
C22:0	535	590	586	647	25.3	0.05	0.06	0.91
C22:5n-3	956	971	972	966	12.7	0.68	0.65	0.38
C24:0	488	560	565	634	34.5	0.06	0.05	0.96
C24:1	731	798	641	822	123	0.32	0.78	0.63
Other[4]	490	584	672	699	100	0.53	0.16	0.72

[a,b]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[2]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[3]All *trans*-C18:1, mainly vaccenic acid.

[4]Sum of C6:0, C8:0, C10:0, C14:1, C18:3n-6, C18:4n-3, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA, C20:2n-6, C20:3n-3, C22:1n-11, C22:1n-9, C22:5n-6, C22:6n-3.

by decortication. Toasting increased hindgut digestibility of C18:1n-9 and *trans*-C18:1 (Supplemental Table S3, https://doi.org/10.3168/jds.2019-18125). The major part of fecal FA consisted of C16:0 and C18:0, 170 and 605 g/kg of fecal FA, respectively (data are not presented).

Microbial and Duodenal Fatty Acid Composition

Decortication had a tendency to reduce the proportion of C18:3n-3 in microbial FA (Table 8). Toasting decreased the proportion of C18:0 with a tendency to reduce C18:1n-9, while it increased the proportion of C18:3n-3 ($P < 0.01$) and OCFA in microbial FA. The n-6:n-3 ratio increased ($P = 0.03$) with decortication and decreased ($P < 0.01$) with toasting, due to possible oxidation.

Supplemental Table S4 (https://doi.org/10.3168/jds.2019-18125) shows the quantification of microbial FA with and without adjustment for the native amount of C17:0 as internal standard. No significant difference was found in the amount of C16:0 and C18:0, with and without adjustment for the native amount of C17:0. Similarly, the quantities of C18:1n-9, C18:2n-6, and C18:3n-3 were not affected by adjustment for the native amount of C17:0.

Milk Fatty Acid Composition

There tended to be an interaction between decortication and toasting, resulting in an increased proportion of C18:3n-6 in milk FA in DT (Table 9). Decortication increased the proportion of C20:2n-6 ($P < 0.01$) in milk FA.

DISCUSSION

Intake

Intake of FA increased by decortication due to removal of the hull with low FA concentration. Oat hull accounts for 25 to 30% of the whole grain DM (Butt et al., 2008), and according to Welch et al. (1983), it contains only 10.0 to 22.0 g of crude fat and 1.70 to 4.70 g

Table 7. Total-tract digestibility[1] of fatty acids (FA; g/kg of total FA intake)

	Diet[2]					*P*-value[3]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
C10:0	943	941	935	922	5.58	0.15	0.02	0.26
C12:0	−239	−295	−93	−135	46.5	0.15	<0.01	0.82
C13:0	810	828	823	799	21.0	0.89	0.70	0.31
C14:0	348	164	342	246	92.1	0.09	0.61	0.55
C14:1	439	351	539	494	47.2	0.04	<0.01	0.43
C15:0	−1,090	−1,269	−901	−877	102	0.47	0.03	0.35
C16:0	818	831	856	845	12.3	0.91	0.04	0.26
C16:1n-9	415	437	614	578	69.7	0.90	0.02	0.61
C16:1n-7	958[a]	975[ab]	989[b]	977[ab]	5.57	0.68	0.02	0.03
C17:1	363	496	389	397	39.9	0.13	0.40	0.17
C18:0	−6,802	−6,424	−2,080	−2,187	925	0.85	<0.01	0.73
C18:1n-9	981[c]	986[c]	963[b]	946[a]	1.72	<0.01	<0.01	<0.01
18:1n-7 *cis*	275	372	422	384	92.5	0.65	0.24	0.31
C18:2n-6	984[c]	987[c]	978[b]	969[a]	1.00	0.01	<0.01	<0.01
C18:3n-3	993[b]	993[b]	993[b]	991[a]	0.27	0.03	<0.01	0.02
C20:0	408	404	634	627	49.3	0.85	<0.01	0.95
C22:0	556	577	659	647	22.2	0.74	<0.01	0.27
C24:0	380	393	564	538	39.9	0.79	<0.01	0.42
Others[4]	683	685	822	797	27.0	0.57	0.04	0.49
SFA	12.1	55.7	524	503	103	0.89	<0.01	0.68
UFA	951[b]	956[b]	945[ab]	935[a]	3.08	0.29	<0.01	0.02

[a–c]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Total-tract digestibility of FA: (FA intake – FA in fecal output)/FA intake × 1,000.

[2]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[3]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[4]Sum of C6:0, C8:0, C11:0, C18:3n-6, C18:4n-3, *trans*-C18:1, *cis*-9,*trans*-11 CLA, *trans*-10,*cis*-12 CLA, C20:1n-9, C20:3n-3, C20:5n-3, C20:2n-6, C20:3n-6, C20:4n-6, C22:1n-11, C22:1n-9, C22:5n-6, C22:6n-3.

of FA per kg of DM. The C16:0 and Cl8:0 proportions of FA were higher, and the proportions of C18:1n-9 and C18:2n-6 were lower in oat hull compared with the grain in the study by Welch et al. (1983). Therefore, the FA composition in hull compared with whole oat explains the effect of decortication on FA composition of diets containing undecorticated oat. In agreement with the present findings, Panah et al. (2020b) also reported an increased FA content in decorticated oat. Therefore, decortication of oat is a tool to increase the concentration of FA in the ration.

The proportion of C16:0, C18:0 and C18:1 increased in Oat due to toasting in agreement with Molteberg et al. (1995), who reported that heat treatment increased the proportion of C18:0 in total FA of oat and decorticated oat, mainly due to the nonenzymatic oxidation of PUFA and the destruction of antioxidants during the heat treatment. Despite a slightly increased DMI, toasting decreased the FA intake mainly due to the reduction of C18:2n-6 and C18:3n-3 concentrations in toasted oat (both T and DT; as a difference between toasted oat and nontoasted oat) with an average of 12.9 and 0.35 g/kg of DM, respectively (Table 1). This reduction of C18:2n-6 and C18:3n-3 due to toasting was not expected because we anticipated that toasting, by denaturing the protein matrix around the fat droplets, would encapsulate the UFA (Kennelly, 1996; Gonthier et al., 2005), as a big portion of oat fat is stored in the endosperm in combination with protein (Peterson and Wood, 1997). Martin (1958) reported that oat fat is susceptible to heat-induced oxidation, owing to its high levels of UFA. Accordingly, Lampi et al. (2015) showed that when raising the temperature from 110 to 130°C during heat treatment (extrusion), the oat flour promoted a nonenzymatic oxidation of oat lipids followed by a decrease in total FA (15.2%), C18:1n-9 (11.1%) and C18:2n-6 (21.1%) concentrations, and accumulation of oxidation byproducts during prolonged storage. Likewise, in the present study, toasting oat decreased the total FA (18.8 g/kg of DM) and C18:2n-6 (132 g/kg of FA). The concentration of C18:1n-9 also decreased in DM; however, due to the serious decrease, especially in C18:2n-6, the proportion of C18:1n-9 in total FA increased (40.0 g/kg of FA) by toasting.

Molteberg et al. (1995) showed that in corn flakes, the antioxidant activity of tocopherols hindered the oxidation of FA in extruded corn flakes. It was later confirmed that heat treatment at 120, 160, and 200°C was associated with a significant reduction of vitamin E in wheat, barley, rye, and oat (Hall, 2010), leading to nonenzymatic oxidation during storage (Martin, 1958). Nonetheless, there is a void of studies about the effect

Table 8. Ruminal microbial synthesis of fat and fatty acid (g/d), and microbial fatty acid (FA) composition

Item	Diet[1]				SEM	*P*-value[2]		
	Oat	D	T	DT		Dec	Toa	Dec × Toa
Crude fat	183	203	216	227	30.2	0.34	0.11	0.77
FA	64.0	79.9	70.2	74.9	11.9	0.13	0.92	0.38
Crude fat, g/kg of microbial DM	71.7	72.9	75.0	68.8	5.42	0.66	0.94	0.51
FA, g/kg of microbial DM	25.4	28.6	23.4	22.9	2.17	0.52	0.10	0.39
FA, g/kg of microbial FA								
C8:0	2.13	1.79	1.52	2.67	0.67	0.56	0.84	0.30
C10:0	1.17	0.97	1.52	1.46	0.11	0.25	0.01	0.55
C11:0	0.88	0.77	1.28	1.22	0.07	0.25	<0.01	0.72
C12:0	12.9	12.3	16.4	17.2	1.10	0.95	<0.01	0.54
C13:0	4.22	4.10	5.04	4.82	0.40	0.63	0.06	0.88
C14:0	24.3	27.5	28.5	33.0	3.76	0.12	0.06	0.75
C14:1	6.45	6.27	7.17	6.25	1.04	0.17	0.36	0.34
C15:0	56.5	51.8	64.2	62.9	4.43	0.43	0.04	0.66
C16:0	314	306	338	340	13.7	0.78	0.05	0.65
C16:1n-9	7.65	5.19	8.64	9.84	1.43	0.58	0.04	0.14
C16:1n-7	1.94[a]	1.87[a]	2.28[a]	3.03[b]	0.15	0.05	<0.01	0.02
C17:0	18.8	18.8	24.8	19.7	1.53	0.07	0.02	0.07
C17:1	3.84	3.69	3.13	3.76	0.75	0.75	0.67	0.61
C18:0	359	382	321	306	22.6	0.85	0.03	0.41
C18:1n-9	40.8	38.4	35.2	38.5	2.35	0.75	0.08	0.08
C18:1n-7	34.6	38.3	34.0	40.0	1.89	0.01	0.64	0.36
trans-C18:1[3]	7.56	7.32	7.49	7.96	0.92	0.85	0.64	0.56
C18:2n-6	61.6	57.6	52.5	58.2	2.90	0.78	0.18	0.13
C18:3n-6	1.63	1.82	1.68	1.79	0.33	0.59	0.97	0.89
C18:3n-3	20.6	17.0	26.6	25.1	2.42	0.07	<0.01	0.40
cis-9,*trans*-11 CLA	0.29	0.14	0.39	0.0	0.22	0.26	0.93	0.60
trans-10,*cis*-12 CLA	0.56	0.60	0.24	0.88	0.31	0.30	0.95	0.36
C20:0	4.48	4.45	4.13	4.11	0.34	0.92	0.24	1.00
C20:1n-9	2.24	2.86	4.14	2.11	1.38	0.48	0.57	0.21
C20:2n-6	1.50	1.03	0.27	1.31	0.46	0.55	0.32	0.14
C22:0	3.45	2.92	3.43	3.33	0.46	0.46	0.64	0.60
C22:1n-11	0.29	0.57	0.33	0.49	0.22	0.28	0.94	0.75
C24:0	2.04	1.57	2.47	1.44	0.41	0.10	0.73	0.50
C24:1	1.62	1.07	2.16	1.08	0.36	0.06	0.47	0.48
FA groups								
OCFA[4]	84.3	79.2	98.5	92.4	4.15	0.17	0.01	0.88
Ratios								
n-6:n-3	3.22	3.67	2.15	2.50	0.23	0.03	<0.01	0.70
UFA:SFA	0.24	0.23	0.23	0.25	0.01	0.73	0.43	0.09

[a,b]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[2]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[3]All *trans*-C18:1, mainly vaccenic acid.

[4]OCFA = odd-chain FA.

of toasting oat on its FA concentration during the application of heat treatment because the main focus has been the effect of heat on oat lipids during storage of oat products for human consumption. Therefore, in the present study, it is difficult to attribute the reduced total FA, and especially C18:2n-6, to either nonenzymatic oxidation of FA or inactivation of antioxidants or both during toasting. However, the decrease in FA concentration in this study was large enough to make toasting at temperatures required for protein protection irrelevant for oat, as the potential gain in protein value (Panah et al., 2020a) is overruled by the decrease in crude fat and FA, and thereby energy value, of oat.

Digested Amount and Digestibility

Although toasting increased the FA digestibility in the small intestine and in both the feed-ileum and total-tract, it decreased the amount of feed-ileum and total-tract digested FA due to reduced FA intake by toasting. The observed values for feed-ileum digestibility of FA were numerically lower than those for total-tract digestibility of FA. Hindgut digestibility values for FA were higher than zero ($P = 0.05$) for all diets except for D, indicating that there is an overall digestion of FA in the hindgut. Other studies reported discrepancies between feed-ileum and total-tract digest-

Table 9. Milk fatty acids (FA) composition (g/kg of milk FA)

	Diet[1]					*P*-value[2]		
Item	Oat	D	T	DT	SEM	Dec	Toa	Dec × Toa
C6:0	33.4	33.9	33.4	33.0	1.51	0.87	0.46	0.49
C8:0	19.1	18.5	18.7	18.9	1.45	0.67	1.00	0.35
C10:0	41.8	39.6	39.7	41.4	4.42	0.78	0.89	0.11
C11:0	1.13	1.00	1.11	1.39	0.27	0.61	0.20	0.16
C12:0	47.4	44.0	44.5	46.9	5.03	0.77	0.99	0.10
C13:0	1.69	1.53	1.71	1.98	0.26	0.73	0.17	0.21
C14:0	142	138	140	140	4.82	0.27	0.84	0.18
C14:1	11.9	12.8	12.5	12.3	1.03	0.36	0.98	0.16
C15:0	16.3	15.5	16.5	18.3	1.23	0.59	0.14	0.19
C16:0	368	375	363	372	13.0	0.35	0.61	0.89
C16:1n-9	1.18	1.17	1.12	1.14	0.12	0.82	0.25	0.73
C16:1n-7	18.2	20.4	18.9	18.8	2.16	0.17	0.52	0.13
C17:1	3.03	3.11	3.02	3.12	0.21	0.45	0.98	0.93
C18:0	78.2	77.0	81.9	74.5	8.02	0.43	0.91	0.57
C18:1n-9	165	168	172	164	13.0	0.67	0.73	0.32
C18:1n-7	2.12	1.98	2.34	2.16	0.28	0.29	0.19	0.85
trans-C18:1[3]	8.12	8.10	9.18	8.21	1.51	0.48	0.41	0.50
C18:2n-6	18.1	17.3	17.5	17.7	1.29	0.65	0.93	0.54
C18:3n-6	3.62	3.33	2.95	3.75	0.34	0.32	0.60	0.06
C18:3n-3	7.70	7.70	7.51	7.65	0.68	0.85	0.75	0.85
cis-9,*trans*-11 CLA	1.15	1.40	1.22	1.17	0.30	0.54	0.41	0.22
trans-10,*cis*-12 CLA	0.23	0.25	0.26	0.23	0.09	0.83	0.91	0.56
C20:0	0.99	0.94	0.96	0.97	0.07	0.65	0.97	0.53
C20:1n-9	3.24	3.30	3.67	3.35	0.56	0.59	0.33	0.44
C20:2n-6	0.16	0.51	0.19	0.39	0.07	<0.01	0.56	0.32
C20:3n-6	0.68	0.69	0.70	0.76	0.06	0.46	0.36	0.62
C20:4n-6	1.19	1.17	1.10	1.16	0.12	0.80	0.49	0.57
C22:0	0.70	0.61	0.60	0.56	0.07	0.35	0.25	0.67
C22:1n-11	0.56	0.41	0.42	0.46	0.09	0.54	0.58	0.31
C22:5n-3	0.57	0.57	0.51	0.53	0.06	0.77	0.33	0.82
C22:6n-3	0.40	0.28	0.31	0.39	0.07	0.75	0.88	0.18
C24:0	0.97	0.91	0.87	0.85	0.12	0.63	0.33	0.77
FA groups[4]								
OCFA	20.4	19.6	20.6	22.8	1.49	0.56	0.16	0.36
SCFA	143	137	137	142	12.3	0.81	0.89	0.15
MCFA	563	568	557	568	15.2	0.41	0.79	0.73
LCFA	294	295	306	290	20.6	0.48	0.77	0.43
SFA	752	747	743	751	16.5	0.81	0.74	0.29
UFA	248	253	257	249	16.5	0.81	0.74	0.29
MUFA	213	219	223	214	15.4	0.78	0.71	0.24
PUFA	35.0	34.2	33.6	34.9	2.26	0.82	0.74	0.32
n-9	169	172	177	169	13.6	0.66	0.71	0.32
n-6	23.7	23.0	22.5	23.7	1.53	0.76	0.76	0.23
n-3	9.86	9.72	9.44	9.74	0.73	0.86	0.64	0.62
Ratios								
n-6:n-3	2.44	2.39	2.40	2.46	0.12	1.00	0.91	0.64
UFA:SFA	0.33	0.34	0.35	0.33	0.03	0.75	0.63	0.27

[1]Oat = whole grain oat; D = decorticated oat; T = toasted oat; DT = decorticated and toasted oat.

[2]Dec = effect of decortication; Toa = effect of toasting; Dec × Toa = interaction between toasting and decortication.

[3]All *trans*-C18:1, mainly vaccenic acid.

[4]OCFA = odd-chain FA, SCFA = short-chain FA (C6 to C12), MCFA = medium-chain FA (C14 to C17), LCFA = long-chain FA (≥C18).

ibility of FA, supposedly due to microbial BH of UFA, possible absorption of FA in the hindgut (Glasser et al., 2008), and de novo FA synthesis by the hindgut microbes (Boerman et al., 2015). The reduced hindgut digestibility of SFA, such as C18:0, C20:0, and C24:0, and total SFA by decortication could be an explanation for the possible BH of their unsaturated isomers in hindgut. In addition, hindgut digestibility of C18:1n-9 increased by toasting, which could also be due to BH or absorption (Glasser et al., 2008). However, the hindgut absorption of FA was negligible based on our results, implying that for the true digestibility of individual FA, the feed-ileum digestibility is more representative than total-tract digestibility, which agrees with Boerman et al. (2015). The results of total-tract FA digestibility obtained from the current study were in the same range

as those of other studies (Møller, 1989; Avila et al., 2000; Loor et al., 2002). The increased total-tract digestibility of FA due to toasting was the consequence of increased total-tract digestibility of SFA such as C16:0, C18:0, C20:0, C22:0, and C24:0.

The tendency of decortication to increase the small intestinal digested FA could be explained by the increased FA flow at the duodenum due to decortication. The increased FA digestibility in the small intestine (g/kg of duodenal FA) by toasting might be a result of an increased UFA:SFA ratio of duodenal FA. A higher intestinal digestibility of UFA than of SFA in ruminants has also been found in earlier studies (Jenkins and Jenny, 1989; Weisbjerg et al., 1992c). Based on a meta-analysis, the increased quantity of C16:0 reaching the small intestine positively influences small intestinal digestibility of FA, whereas increased flow of FA at the duodenum has a negative effect on it (Boerman et al., 2015). Accordingly, in our study the duodenal flow of FA decreased with a consequent increase in small intestinal digestibility by toasting, although the proportion of C16:0 in the intake FA was reduced.

Decortication increased the C18:1n-9 proportion in the FA intake and increased its ruminal disappearance due to BH. This could also be seen from the reduced proportion of C18:1n-9 in the duodenal FA and increased ruminal formation of *trans*-C18:1 isomers. This is consistent with Weisbjerg et al. (1992a),who reported an increased ruminal BH of C18:1n-9 upon its increased intake. Accordingly, it was previously shown that the in vitro BH of C18:1n-9 was associated with the formation of several positional isomers such as *trans*-C18:1, rather than only C18:0 (Mosley et al., 2002; Lejonklev et al., 2013). As FA generally are not fermented in the rumen, increasing the levels of FA intake results in a higher concentration of FA at the duodenum (Børsting et al., 1992; Doreau and Ferlay, 1994).

The reduced formation (g/d) of C18:0 in the rumen by toasting is mainly a reflection of the reduced UFA intake due to toasting because unsaturated C18 FA are precursors for the C18:0 formation. Another reason for this reduction could be due to the reducing effect of toasting on ruminal BH of C18:1n-9 and C18:2n-6 (Reddy et al., 1994), resulting in an increased UFA:SFA ratio in the duodenal FA. The flow of FA from the rumen mainly comprises C18:0 because the majority of C18:2n-6 and C18:3n-3 is reduced to minor proportions due to extensive BH (Noble, 1978). The *trans*-C18:1 isomers, mainly vaccenic acid, mostly originate from microbial activity as an intermediate of C18:2n-6 BH (Doreau and Ferlay, 1994), as well as the isomerization of other C18:1 FA (He et al., 2012). Toasting reduced the digested amount of *trans*-C18:1 isomers in the small intestine as a consequence of its decreased ruminal formation, possibly due to the declined BH. Heat treatment was shown to protect UFA against ruminal BH (Privé et al., 2010; Lashkari et al., 2017; Chowdhury et al., 2018), probably by inducing denaturation of the protein matrix around the fat droplets and making a protecting encapsulation against ruminal BH, resulting in an increased supply of PUFA to the small intestine (Kennelly, 1996). Conjugated linoleic acids (i.e., *cis*-9,*trans*-11 and *trans*-10,*cis*-12) entering the small intestine mainly originate from microbial BH of C18:2n-6 (Noble, 1978; Buccioni et al., 2012). Although ruminal BH of C18:2n-6 was reduced by toasting, the unaffected CLA proportion in the duodenal FA could be due to the reduced C18:2n-6 proportion in the FA intake due to toasting. This also makes it difficult to derive a realistic conclusion about the reducing effect of toasting on the extent of ruminal BH of oat FA because a considerable amount of UFA was already lost due to toasting before entering the rumen. In addition, toasting decreased the ruminal disappearance of C18:1n-9 in both amount and proportion (BH).

Aligned with the reduced BH due to toasting, the duodenal proportion of C18:1n-9 increased, although its proportion in FA intake was reduced, by toasting. Despite the unaffected ruminal BH of C18:3n-3 by toasting, the proportion of C18:3n-3 in the duodenal FA increased. This was probably because toasting increased the proportion of C18:3n-3 in the FA intake, raising its proportion in the duodenal FA. Decortication decreased the rumen BH of C18:3n-3 and reduced its proportion in the duodenal FA, mainly due to the reduced intake of C18:3n-3. Some C18:3n-3 was removed with the hull, causing a decline in the C18:3n-3 proportion of the FA intake. Despite the effect of treatments, unexpected lower BH of C18:3n-3 compared with C18:2n-6 in our study could be due to the nature of the oat fat, which is rich in phospholipids (Kaimainen et al., 2012), as BH of C18:3n-3 was shown to be lower when esterified to phospholipids (Lashkari et al., 2019).

The small intestinal digestibility of some SFA, such as C12:0, C15:0, C20:0, and C22:0, increased by decortication, possibly due to the removal of hull. Welch et al. (1983) reported that oat hull mainly contains SFA, and as hulls have low degradability, this might also reduce the digestibility of the FA in the hulls. The results of our study indicated that toasting reduced the small intestinal digestibility of C18:1n-9 and C18:2n-6 with the same trend seen for their ruminal BH. Børsting et al. (1992) suggested that UFA are more likely to form micelles inside the small intestine when compared with SFA. In addition, Weisbjerg et al. (1992a) showed that the small intestinal digestibility of C18:1n-9 and C18:2n-6 is independent from the intake level. Therefore, it might be the case that toasting of oat, in addition to

reducing the FA concentration, also overprotected the remaining C18:1n-9 and C18:2n-6, reducing their small intestinal digestibility and significantly increasing their concentration in ileal flow (results are not presented). The increased flow of C18:1n-9 and C18:2n-6 at the ileum could explain their increased hindgut digestibility. Toasting reduced the ruminal digestibility of oat AA (Panah et al., 2020a) and ruminal BH of C18:1n-9 and C18:2n-6. The protection by toasting against ruminal BH might also have resulted in the reduced digestibility of C18:1n-9 and C18:2n-6 in the small intestine, supplying a large amount of BH in the hindgut. Bainbridge and Kraft (2016) also reported that hindgut digestibility of PUFA from protected echium oil increased as a result of their increased flow to the hindgut. However, the concurrent increased hindgut digestibility of *trans*-C18:1 as a BH intermediate and unchanged C18:0 hindgut digestibility due to toasting did not support increased BH in the hindgut. The interaction between decortication and toasting indicated that the effect of toasting on the small intestinal digestibility was stronger in decorticated oat for both C18:1n-9 and C18:2n-6. Toasting increased the small intestinal digestibility of SFA, including C15:0, C18:0, C20:0, and C24:0, and tended to increase it for C22:0. This might be an effect of an increased UFA proportion in the duodenal FA due to toasting because UFA facilitate the solubility of SFA and micelle formation in the small intestine (Jenkins and Jenny, 1989; Børsting et al., 1992; Bauchart, 1993). Although toasting increased the proportion of C18:0 in the FA intake, it resulted in increased small intestinal digestibility of this FA. This is in conflict with the findings of Weisbjerg et al. (1992a), who reported that small intestinal digestibility of C18:0 decreases with increased intake level. The reason for this difference could be due to the increased UFA in the duodenal FA of the present study, in accordance with Børsting et al. (1992) and Boerman et al. (2015).

In agreement with Weisbjerg et al. (1992a), the results of the present study showed that the small intestinal digestibility of SFA increased from C12:0 to C16:0, and then decreased with increasing chain length, regardless of treatment. Furthermore, the small intestinal digestibility of FA increased with the higher level of unsaturation. Unlike other studies (Weisbjerg et al., 1992a; Boerman et al., 2015), in our study, C18:3n-3 had a lower small intestinal digestibility than C18:2n-6.

Microbial Fatty Acid Synthesis and Composition

Microbial synthesis of fat and FA were not affected by the diets. However, toasting tended to reduce the FA concentration in the microbial biomass, which is possibly a reflection of a reduced FA intake by toasting. Consistent with Weisbjerg et al. (1992b), the results of the present study indicate that, except for C18:0, the abundance of other FA in microbial fat depends on their intake levels. This could be seen from the increased proportions of C10:0, C14:0, C16:0, and C18:3n-3 in the FA intake due to toasting, increasing these FA in the microbial FA. The tendency of toasting to reduce the proportion of C18:1n-9 in the microbial FA is also a reflection of a reduced proportion of C18:1n-9 in the FA intake. Weisbjerg et al. (1992b) showed that C16:0 and C18:0 constitute the major proportion of microbial FA, consistent with the results of the present study. Bauchart et al. (1990) reported that due to extensive BH, there was no correlation between the C18:3n-3 and C18:2n-6 intakes and their incorporation into microbial FA. However, in our study, the increased proportion of C18:3n-3 in microbial FA was in line with its increase in the FA intake by toasting. Likewise, the tendency for decortication to decrease C18:3n-3 in the microbial FA could be related to the reduced proportion of C18:3n-3 in the FA intake. Toasting also increased the proportion of OCFA in the microbial FA. Microbial OCFA are formed via elongation of propionate or valerate (Emmanuel, 1974). However, Panah et al. (2020a) did not observe any changes in the propionate and valerate production due to toasting in the present experiment.

C17:0 as an Internal Standard

Choice of appropriate internal standard for FA analysis of feed and digesta samples has been challenging due to potential errors in determination of the FA content or composition (Jenkins, 2010). In the present study, the applicability of C17:0 as an internal standard on FA quantification was tested because rumen microbes contain around 20 g/kg of FA of C17:0, which could compromise the use of C17:0 as an internal standard. However, the test showed that the use of C17:0 as an internal standard had no significant effect on FA quantification. Therefore, it can also be concluded that in samples with a lower C17:0 proportion (i.e., milk; 5.4–7.2 g/1,000 g of FA; Glasser et al., 2008), the effect of C17:0 as an internal standard will have less of an effect on FA quantification.

CONCLUSIONS

Decortication of oat increased the supply and digested amount of FA in the small intestine and feed-ileum. Toasting of oat severely decreased the concentration of UFA in the diet, but also reduced the ruminal BH of UFA and increased the small intestinal digestibility of the total FA. Decortication of oat seems to be a proper technology to increase the FA supply in dairy cows,

whereas toasting cannot be recommended due to the high loss of C18:2n-6 and total FA.

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