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Influence of thermally oxidized vegetable oils and animal fats on energy and nutrient digestibility in young pigs[1]

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ABSTRACT: A total of 108 barrows (6.67 ± 0.03 kg BW) were assigned to 12 dietary treatments in a 4 × 3 factorial design plus a corn–soybean meal control diet to evaluate the effect of lipid source and peroxidation level on DE, ME, and apparent total tract digestibility (ATTD) of DM, GE, ether extract (EE), N, and C in young pigs. Main effects were lipid source (corn oil [CN], canola oil [CA], poultry fat [PF], and tallow [TL]) and peroxidation level (original lipids [OL], slow oxidation [SO] of lipids heated for 72 h at 95°C, or rapid oxidation [RO] of lipids heated for 7 h at 185°C). Pigs were provided ad libitum access to diets for 28 d followed by an 8-d period of controlled feed intake equivalent to 4% BW daily. Diets were formulated based on the ME content of CA with the standardized ileal digestible Lys, Met, Thr, Trp, total Ca, and available P:ME balanced relative to NRC (1998) recommendations. Lipid peroxidation analysis indicated that compared with the OL, SO and RO had a markedly increased concentrations of lipid peroxidation products, and the increase of peroxidation products in CN and CA were greater than those in PF and TL. Addition of lipids to diets increased ($P < 0.05$) ATTD of EE and tended to improve ($P = 0.06$) ATTD of GE compared with pigs fed the control diet. Feeding CN or CA increased ($P < 0.05$) ATTD of DM, GE, EE, N, and C compared with feeding TL, while feeding PF improved ($P < 0.05$) ATTD of GE and EE and tended to increase ($P = 0.06$) ATTD of C compared with TL. Pigs fed CN had increased ($P = 0.05$) percentage N retention than pigs fed TL. No peroxidation level effect or interaction between lipid source and peroxidation level on DE and ME was observed. Lipid source tended ($P = 0.08$) to affect DE but not ME values of experimental lipids ($P > 0.12$). Digestible energy values for CA (8,846, 8,682, and 8,668 kcal/kg) and CN (8,867, 8,648, and 8,725 kcal/kg) were about 450 kcal/kg greater than that of TL (8,316, 8,168, and 8,296 kcal/kg), with PF being intermediate (8,519, 8,274, and 8,511 kcal/kg), for OL, SO, and RO lipids, respectively, respectively. In conclusion, lipid source affected ATTD of dietary DM, GE, EE, N, and C, and N retention and tended to influence the DE value of the lipid but did not significantly affect their ME value. Rapid and slow heating of lipids used in this study increased lipid peroxidation products but had no detectable effects on nutrient and energy digestibility as well as DE and ME values of the various lipids.

Key words: energy, lipid source, nitrogen retention, oxidation level, young pigs

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INTRODUCTION

Energy is one of the most expensive components of swine diets. Lipids are commonly added to swine diets as concentrated energy sources to improve feed efficiency (Pettigrew and Moser, 1991). Better knowledge of the energy value of lipids will help to increase the ability of nutritionists to successfully use lipids in swine diets.

Several studies have characterized the quality of lipids as energy ingredients (Cera et al., 1988, 1989; Li et al., 1990; Jones et al., 1992). However, those research efforts have focused mainly on the effects of unsaturat-

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ed to saturated fatty acid ratio (Powles et al., 1993, 1994, 1995), fatty acid chain length (Hamilton and McDonald, 1969; Cera et al., 1989; Straarup et al., 2006), and FFA content (Sklan, 1979; Tso et al., 1981; DeRouchey et al., 2004). Few studies have evaluated the effect of lipid peroxidation products on energy value of lipids.

Most lipids are subjected to heating and potential oxidative processes before being supplemented in swine diets (Canakci, 2007). Lipids vary in susceptibility to peroxidation depending on their level of unsaturation (Frankel et al., 1984; Seppanen and Csallany, 2002). Therefore, lipids used in animal feeds may not only differ considerably in fatty acid composition but may also contain various concentrations of peroxidation products, which may affect their DE and ME content. Recently, DeRouchey et al. (2004) showed that increasing the rancidity of choice white grease did not affect fatty acid digestibility, but the DE or ME content of the lipids was not reported. The objective of the current experiment was to determine the effects of lipid source and peroxidation level on DE and ME content and on apparent total tract digestibility (**ATTD**) of DM, GE, ether extract (**EE**), N, and C in lipid-supplemented diets fed to young pigs.

MATERIALS AND METHODS

All animal use procedures were reviewed and approved by the University of Minnesota Institutional Animal Care and Use Committee.

Animals, Experimental Design, and Diets

General procedures regarding lipid peroxidation, diet formulation, and animal management have been described previously (Liu et al., 2013a,b,c). In brief, 2 or 3 pigs from the same dietary treatment were housed in a single pen with ad libitum access to feed and water for 28 d.

After the 28-d diet adaptation phase, pigs were weighed (BW = 13.98 ± 2.37 kg) and moved to individual metabolism crates on d 29. Pigs were fed an amount of diet equivalent to 4% of their BW twice daily (2% at 0700 h and 2% at 1900 h) for an additional 5 d (i.e., d 29 to 34) followed by a 3-d total urine and fecal collection period. During the metabolism crate portion of the experiment, all pigs had constant feed intake and fecal output starting during the adaptation period through the end of the collection period and ad libitum access to water. Thus, a time-based total collection was used rather than marker-to-marker methodology for this experiment. Feces and urine were collected for 72 h beginning on the evening at 1900 h of d 34 and ending on the evening at 1900 h of d 37. During the collection period, fecal samples were collected daily at 0700 and 1900 h and stored at –18°C. At the end of the collection period, fecal samples from each pig were pooled, weighed, and dried in a forced-draft oven at 55°C for 3 d. After drying, fecal samples were ground through a 1-mm screen and a homogeneous subsample was obtained for subsequent analysis. Total urine output was collected in plastic containers located under the metabolism cages at the same time as fecal collection. To limit microbial growth and reduce ammonia loss, 30 mL of 6 *N* HCl was added to the urine collection containers during the 3-d collection period. Urine volume was recorded twice daily and a subsample consisting of 20% of the urine excreted from each pig was collected and stored in a freezer at approximately –18°C. At the end of the collection period, urine samples were pooled by mixing thawed urine samples from each pig and a subsample was obtained for subsequent analysis. Any unconsumed feed was removed, dried, and weighed and subtracted from the amount added to determine net feed consumption.

Chemical Analysis

Gross energy of lipids, diets, feces, and urine samples were determined using an isoperibol bomb calorimeter (Model 1281; Parr Instrument Co., Moline, IL) with benzoic acid used as a standard. Each sample was analyzed in duplicate. For urinary GE, 3 mL of filtered urine subsample was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 72 h. The urinary energy was calculated by subtracting the energy measured in cellulose from the energy in the samples containing both urine and cellulose. From these data, the DE and ME content of all the diets were calculated by subtracting the GE excreted in feces and urine from GE intake over the 3-d collection period. Within a specific assay diet, the concentrations of DE or ME for the specific lipid was calculated by subtracting the DE or ME contributed by the control diet from the DE or ME of the lipid containing diet and then dividing by the inclusion rate of that specific lipid.

Ether extractions of the experimental diets and feces were analyzed in duplicate using an accelerated solvent extraction system (ASE 350; Thermo Scientific, Waltham, MA). Briefly, the sample was dispersed in sand and loaded into an extraction cell. The cell was filled with petroleum ether and then heated and pressurized. The solvent containing the extract was pumped out, using additional solvent, into a preweighed glass vial. The extraction process was repeated 2 more times for each sample, with the solvent being collected into the same vial each time. When all cells had been extracted, the solvent was evaporated using a N_2 evaporation system (Multivap Model 118; Organomation Associates Inc., Berlin, MN). The glass vial was then reweighed and the percentage of EE was calculated.

Carbon, N, and S were analyzed by thermocombustion (VarioMAX CNS; Elementar Analysensysteme GmbH, Hanau, Germany), which uses catalytic tube combustion to volatilize the sample. The analyzer cleaned up the target gases by removing the unwanted substances and converted them to N_2, CO_2, and SO_2, which were separated from each other using adsorption columns and, after heating, were measured using a thermal conductivity detector.

Apparent total tract digestibility of DM, GE, EE, N, C, and S in each diet was calculated using the following equation: ATTD = [(Nt – Nf)/Nt] × 100%, in which Nt = the total consumption of DM (g), energy (kcal), or nutrient over the 3-d fecal total collection period and Nf = the total fecal excretion of DM (g), energy (kcal), or nutrient during the 3-d fecal total collection period.

Statistical Analysis

All data were analyzed using the MIXED procedure of SAS 9.2 (SAS Inst. Inc., Cary, NC). Two-way ANOVA was conducted to evaluate the main effects of lipid source (corn oil [**CN**], canola oil [**CA**], poultry fat [**PF**], and tallow [**TL**]), lipid peroxidation level (original lipids [**OL**], slow oxidation [**SO**], and rapid oxidation [**RO**]), and any 2-way interactions in a 4 × 3 factorial arrangement. The corresponding statistical model included the fixed effects of lipid source, peroxidation level, and lipid source × peroxidation level interactions. One-way ANOVA was conducted to evaluate the differential effect between the control diets and lipid containing diets on all response criteria. Individual pig was used as the experimental unit for all other responses. Group was included as a random effect. All results are reported as least squares means. Mean comparisons were achieved by the PDIFF option of SAS with the Tukey-Kramer adjustment. The significance level chosen was $\alpha = 0.05$. Treatment effects were considered significant if $P < 0.05$, whereas values of $0.05 \leq P \leq 0.10$ were considered statistical trends.

RESULTS

Characterization of Experimental Lipids

The various characteristics of the experimental lipids have been described in detail previously (Liu et al., 2013b). In brief, the concentration of crude fat, moisture, insolubles, and unsaponifiables were similar among the 12 experimental lipids. As expected, CN and CA had greater concentrations of unsaturated fatty acids than TL, with PF being intermediate. Averaged among lipid sources, both SO and RO decreased the linoleic acid and linolenic acid concentrations compared with the OL, but changes in concentration of other major fatty acids were not observed. Lipid peroxidation tests indicated that all of the OL were relatively unoxidized, but SO and RO led to a marked increase in the production of primary and secondary peroxidation products, and the production of these peroxidation products caused by SO and RO in CN and CA was much greater than that in PF and TL (Liu et al., 2013b).

Lipid Digestible and Metabolizable Energy Content

No effect of peroxidation level or lipid source × peroxidation level interaction was detected for lipid DE (Table 1). Lipid source tended to affect ($P = 0.08$) the DE content on an as-fed basis, where the DE content of CN and CA (8,747 and 8,732 kcal/kg, respectively) were numerically greater than TL (8,260 kcal/kg), with PF being intermediate (8,435 kcal/kg).

No lipid source, peroxidation level, or lipid source × peroxidation level interaction effects were observed for ME content of the different lipids (Table 1). The ME content of different lipids had similar trends relative to their DE content, with the CN and CA (8,453 and 8,456 kcal/kg, respectively) having the greatest ME, PF being intermediate (8,167 kcal/kg), and TL having the lowest ME (7,978 kcal/kg).

Apparent Total Tract Digestibility of DM, GE, Ether Extract, N, C, and S

Lipid Diets versus Control. Pigs fed diets supplemented with lipids had a greater ($P < 0.01$) ATTD of EE and tended to have a greater ($P = 0.06$) ATTD of GE compared with pigs fed the control diet. No differences in ATTD of DM, N, C, and S or in percentage N retention between pigs fed the control diet and pigs fed the diets containing lipids were observed (Table 2).

Among Lipids. There was no peroxidation level or lipid source × peroxidation level interaction noted for ATTD of DM, GE, EE, N, C, and S among diets containing various lipid sources (Table 2). Lipid source affected ATTD of DM, GE, EE, N, and C ($P < 0.01$) but did not affect ATTD of S. Pigs fed diets containing either CN or CA had increased ATTD of GE (main effect mean of CN or CA vs. main effect mean of TL was 88.78 or 88.57 vs. 86.50, respectively), EE (main effect mean of CN or CA vs. main effect mean of TL was 83.73 or 83.15 vs. 79.52, respectively), N (main effect mean of CN or CA vs. main effect mean of TL was 89.15 or 88.78 vs. 85.95, respectively), and C (main effect mean of CN or CA vs. main effect mean of TL was 89.29 or 89.11 vs. 87.26, respectively) compared with pigs fed diets containing TL ($P < 0.05$). Pigs fed diets containing PF also had a greater ATTD of GE and EE ($P < 0.05$) and tended to have a greater ATTD of C ($P = 0.06$) compared with pigs fed diets supplemented with TL.

Table 1. Energy values of vegetable oils and animal fats of differing oxidation status fed to growing pigs[1]

Item	Control diet	Corn oil			Canola oil			Poultry fat			Tallow				*P*-value[3]		
		OL	SO	RO	OL	SO	RO	OL	SO	RO	OL	SO	RO	SEM	SOU	PER	SOU × PER
Obs[2]	6	9	9	9	8	8	8	8	8	8	9	8	8	–	–	–	–
Energy content, kcal/kg as-fed basis																	
GE	3,813	9,435	9,434	9,328	9,454	9,362	9,401	9,386	9,348	9,356	9,412	9,337	9,352	–	–	–	–
DE	3,293	8,846	8,682	8,668	8,867	8,648	8,725	8,519	8,274	8,511	8,316	8,168	8,296	268	0.08	0.60	0.99
ME	3,173	8,522	8,417	8,429	8,551	8,371	8,436	8,324	7,960	8,217	8,033	7,891	8,009	287	0.12	0.63	0.98

[1]Data are least squares mean ($n = 6$ for control and $n = 8$ or 9 for lipid diets). OL = original lipids (lipids were stored as received without antioxidants or heating); SO = slow oxidation (SO lipids were heated for 72 h at 95°C with constant compressed air flow rate at 12 L/min); RO = rapid oxidation (RO lipids were heated for 7 h at 185°C with constant compressed air flow rate at 12 L/min). Data for the control represents the control diet while data for all lipid sources represents the energy of the lipid itself.

[2]Obs = number of observations per treatment.

[3]SOU = lipid source; PER = oxidation level; SOU × PER = lipid source × oxidation level interaction.

Nitrogen Retention

There was no peroxidation level or lipid source × peroxidation level interaction observed for percentage N retention ($P > 0.05$). The only difference in N retention among lipid sources was for pigs fed diets containing CN having greater N retention ($P < 0.05$) than pigs fed diets containing TL.

DISCUSSION

General

Lipids are commonly added to swine diets to serve as concentrated energy sources and, consequently, to improve feed efficiency (Pettigrew and Moser, 1991). Large quantities of lipids produced from the rendering industry as well as food processing facilities and restaurants are subjected to heating processes and are used exclusively in animal feeds (Canakci, 2007). However, because the lipids are normally heated for a considerable length of time at a high temperature (Frankel et al., 1984), these lipids are highly susceptible to peroxidation. Therefore, lipids used in animal diets not only differ in their fatty acid profile but also contain various concentrations of toxic peroxidation products, which may contribute to differences in energy concentrations as well as have effects on digestibility of other nutrients. In the current study, 4 different sources of lipids (CN, CA, PF, and TL) were evaluated. These sources differed in fatty acid composition and lipid peroxidation status (OL lipids, SO, and RO lipids) as described by Liu et al. (2013b).

Lipids were included in the diet at 10% to maximize differences between pigs fed the control and lipid containing diets, to maximize differences in fatty acid composition and peroxidation levels among lipid sources, and to minimize errors associated with determining energy values of lipids when using the difference method for DE and ME determinations. Previous studies have demonstrated that the apparent digestibility of various lipids in nursery pigs increases with age, stabilizing around 4 wk of age (Hamilton and McDonald, 1969; Frobish et al., 1970; Cera et al., 1988). As a result, a 28-d adaptation to diets was allowed to improve the accuracy of estimates of the maximum energy potential of the various lipids evaluated.

Digestible Energy and ME

For comparative purposes, the DE and ME of the basal diet used in Phase 2 was 3,293 and 3,173 kcal/kg (as-fed basis), respectively, which were similar to values calculated based on NRC (1998) ingredient values. Close agreement of our experimental values with NRC (1998) values suggests good collection and analytical methods used in the current experiment. All of the experimental

lipids had similar GE values of 9,384 ± 43 kcal/kg and were close to average GE value of 9,410 ± 121 kcal/kg of 8 lipids including 3 animal fats, 2 soybean oils, 1 palm oil, 1 palm mix oil, and 1 vegetable oil byproduct reported by Jorgensen and Fernandez (2000). Similar GE values were expected considering that results from most published experiments show that lipids contain a high concentration of EE (above 96%) and low amounts (usually less than 3%) of moisture, impurities, and unsaponifiables. The nearly equal GE values of lipids used in the current experiment suggest that neither the fatty acid composition nor the different concentrations of lipid peroxidation products were related to the GE value of lipids.

The DE or ME content of each source of lipids determined in the current experiment were similar to those for CN (8,755 and 8,405 kcal/kg, respectively), CA (8,760 and 8,410 kcal/kg, respectively), PF (8,520 and 8,180 kcal/kg, respectively), and TL (8,000 and 7,680 kcal/kg, respectively) as reported in the NRC (1998). This is encouraging given that the DE content of various lipids reported by the NRC (1998) were estimated based on an equation accounting for the concentration of FFA and the unsaturated:saturated fatty acid ratio and ME was predicted as 96% of DE (Powles et al., 1995).

Nutrient and GE Digestibility

The different DE or ME content of various lipids in the current experiment were consistent relative to their corresponding EE digestibility. Regardless of peroxidation level, CN and CA had the greatest ATTD of EE, with PF being intermediate and the TL having the lowest ATTD of EE. Lipid digestibility can be affected by several factors. Because unsaturated fatty acids more easily form micelles for absorption compared with saturated fatty acids, the concentration of various fatty acids and the ratio of unsaturated to saturated fatty acids are important factors in lipid digestibility (Freeman et al., 1968; Stahly, 1984; Powles et al., 1995). In addition, chain length of fatty acids also plays an important role in lipid digestibility, because fatty acids with a chain length of less than 14 carbons have a greater digestibility than those with a longer chain length (Cera et al., 1988; Straarup et al., 2006). Free fatty acid concentrations may also affect lipid digestibility (NRC, 1998). Free fatty acids are less water soluble than monoglycerides or diglycerides and lipids with a greater FFA concentration have a lower incorporation rate into micelles leading to reduced absorption efficiency (Sklan, 1979; Tso et al., 1981). However, results from a recent study suggest that FFA concentrations of at least 53% do not adversely affect utilization of choice white grease in nursery pigs (DeRouchey et al., 2004). In the current experiment, the various DE and ME values among different lipid sources

Table 2. Apparent total tract digestibility (ATTD) of DM, GE, ether extract (EE), N, C, and S and N retention (NR) of diets (as-fed basis)[1]

		Corn oil			Canola oil			Poultry fat			Tallow				*P*-value[3]			
Item	Control	OL	SO	RO	OL	SO	RO	OL	SO	RO	OL	SO	RO	SEM	S	O	S × O	CON vs LPD
Obs[2]	6	9	9	9	8	8	8	8	8	8	9	8	8	–	–	–	–	–
ATTD, %																		
DM	86.78	88.66	88.42	88.76	88.76	88.21	87.35	87.35	88.00	87.51	86.83	86.66	86.21	0.74	<0.01	0.42	0.91	0.29
GE	86.35	88.92	88.59	88.84	89.35	88.67	87.69	88.44	87.56	87.81	86.83	86.53	86.15	0.78	<0.01	0.23	0.91	0.06
EE	21.50	83.34	85.02	82.82	84.94	83.55	80.96	83.59	82.27	82.49	80.04	78.33	80.19	1.50	<0.01	0.23	0.24	<0.01
N	86.81	88.73	89.34	89.39	88.63	89.24	88.47	87.76	86.59	87.86	85.57	86.46	85.83	1.30	<0.01	0.90	0.81	0.83
C	87.34	89.41	89.07	89.39	89.86	89.28	88.20	89.01	88.34	88.33	87.56	87.43	86.79	2.30	<0.01	0.22	0.88	0.13
S	73.16	72.24	73.61	71.20	72.50	69.11	71.71	71.28	71.63	71.49	72.34	72.18	71.4	2.30	0.90	0.91	0.93	0.58
NR, %[4]	62.08	64.14	65.66	64.95	64.81	62.76	63.07	64.29	60.05	63.17	56.32	60.44	58.20	4.00	0.05	0.99	0.89	0.95

[1]Data are least squares mean (n = 6 for control and n = 8 or 9 for lipid diets); OL = original lipids (lipids were stored as received without antioxidants or heating); SO = slow oxidation (SO lipids were heated for 72 h at 95°C with constant compressed air flow rate at 12 L/min); RO = rapid oxidation (RO lipids were heated for 7 h at 185°C with constant compressed air flow rate at 12 L/min).

[2]Obs = number of observations per treatment.

[3]SOU = lipid source; PER = oxidation level; SOU × PER = lipid source by oxidation level interaction; CNT vs. LPD = control versus lipids.

[4]Nitrogen retention as a percentage of N intake.

can be explained by their different concentrations of unsaturated fatty acids, given that only 10% of each lipid was added to the diet and the range in FFA was only from 0.28 to 3.65% among lipid sources.

In addition to the influence of lipid source on apparent EE digestibility, ATTD of DM, GE, N, and C were also affected. The greater ATTD of GE and C in pigs fed diets containing CN, CA, and PF compared with pigs fed diets containing TL can be attributed to a greater ATTD of EE in diets supplemented with CN, CA, and PF compared with pigs fed diets containing TL. In the current experiment, ATTD of N in pigs fed diets containing CN or CA was greater compared with pigs fed diets containing TL. One of the important functions of dietary lipids is to serve as an essential structural component of biological membranes, and as such, dietary lipids may affect composition of the enterocyte cell membrane. Consequently the physiological integrity of the membranes may change when dietary lipid source changes (Jorgensen and Fernandez, 2000). This concept is supported by Lindley et al. (1995), who reported that rats fed diets containing polyunsaturated fatty acids had improved absorptive functions. Thus, the greater apparent N digestibility in pigs fed diets containing CN or CA compared with pigs fed diets containing TL in the current experiment might have resulted from the greater concentration of polyunsaturated fatty acids in the CN or CA compared with that in TL, which contributed to increased intestinal absorptive function. Another reason for the greater apparent N digestibility in pigs fed diets CN or CA compared with pigs fed diets containing TL might have resulted from the differential impact of lipid source on microflora in the large intestine. Bacterial protein synthesis in the large intestine plays an important role in altering apparent N digestibility (Li and Sauer, 1994). However, the detailed mechanism of the effects of lipid source on microflora in the large intestine is unknown.

A key objective of the current experiment was to evaluate the effects of peroxidation level in lipids on their DE and ME content. However, no effect of peroxidation level (OL vs. SO lipids vs. RO lipids) on the DE or ME content was observed. The lack of an effect of peroxidation on DE or ME content among OL and SO lipids and RO lipids were agreement with their corresponding ATTD of EE, which was also not affected by peroxidation level. Similar to our results, DeRouchey et al. (2004) showed that pigs fed diets supplemented with choice white grease with different levels of peroxidation had similar ATTD of EE. Overall, these results indicated that thermal oxidation processes that increased lipid peroxidation product concentration have little to no effects on lipid digestibility and consequently did not influence their DE or ME values. In contrast, it may be possible that digestibility coefficients and/or DE and ME determinations may not be sensitive enough to detect the effects lipid peroxidation on pig performance and gene expression (Liu et al., 2013a) or intestinal barrier function and immunity (Liu et al., 2013c).

The ratio of unsaturated to saturated fatty acids is recognized as one of the important indicators of the lipid digestibility (Powles et al., 1993, 1994, 1995). In the current experiment, lipid peroxidation methods used resulted in significant changes in various peroxidative measures of the lipids used in this study, but had little effect on the composition of major fatty acids or the subsequent unsaturated to saturated fatty acid ratio. This observation suggests that measures of lipid peroxidation may not be as sensitive as the unsaturated to saturated fatty acid ratio in predicting lipid digestibility and subsequent DE and ME values.

Pigs fed diets supplemented with lipids had greater ATTD of EE and tended to have greater ATTD of GE compared with pigs fed control diet. This was expected because the majority of dietary lipids in the control diet were bound lipids (lipids existing within cell membranes) while most of the dietary lipids in the lipid-supplemented diets were unbound lipids. These results agree with those reported by others (Adams and Jensen, 1984; Li et al., 1990; Kil et al., 2010) in which pigs fed diets containing supplemental lipids had greater ATTD of EE compared with pigs fed diets containing only bound lipids. In addition, increased dietary fat helps to delay gastric emptying (Hunt and Knox, 1968), which may result in a slower rate of passage of the diet in the small intestine resulting in greater carbohydrate, AA, and EE digestibility in lipid-supplemented diets (Li and Sauer, 1994). Therefore, the improved ATTD of GE in pigs fed the lipid supplemented diets in the current experiment could be a consequence of an overall enhancement in nutrient digestibility.

In conclusion, the increase in lipid peroxidation products produced by heating of lipids did not affect the ATTD of various nutritional components and had no effect on subsequent DE or ME of the lipids evaluated. In addition, results from this study support the notion that nutrient and energy digestibility, and consequently DE and ME values, are mainly dependent on their fatty acid composition rather than their level of peroxidation.

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