METABOLISM AND NUTRITION

Use of re-esterified oils, differing in their degree of saturation and molecular structure, in broiler chicken diets

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ABSTRACT The aim of the present study was to investigate the potential use of re-esterified oils, differing in their degree of saturation and molecular structure, in comparison with their corresponding acid and native oils in broiler chicken diets. For this purpose, 144 one-d-old female broiler chickens were randomly distributed in 48 cages. Birds were fed a basal diet supplemented with 6% of native palm oil (**PN**), acid palm oil (**PA**), re-esterified palm oil low in mono- (**MAG**) and diacylglycerols (**DAG**) (**PEL**), re-esterified palm oil high in MAG and DAG (**PEH**), native soybean oil (**SN**), acid soybean oil (**SA**), re-esterified soybean oil low in MAG and DAG (**SEL**), or re-esterified soybean oil high in MAG and DAG (**SEH**), which resulted in a 2 × 4 factorial arrangement. Digestibility balances showed that the degree of saturation of fat generally exerted a greater impact than did the fat molecular structure. The dietary utilization of S sources was higher than that of P sources. However, the increased *sn*-2 saturated fatty acid (**SFA**) content of EL oils in the starter period and the increased MAG and DAG content of EH oils in the grower-finisher period yielded favorable effects on the SFA apparent absorption, especially in those birds fed re-esterified palm oils. The excreta acylglycerol and free fatty acid composition was mainly composed of free fatty acids, and their amount almost paralleled the results observed for SFA apparent absorption. For growth performance, birds fed S exhibited better feed conversion ratios and lower abdominal fat-pad weights than did those fed P. The fatty acid composition of abdominal adipose tissue was also mainly affected by the degree of saturation of dietary fat sources. We concluded that re-esterified oils, mainly from P sources, can be used in broiler chicken diets as alternative fat sources since they show similar or even higher total fatty acid apparent absorption than do their corresponding native and acid oils, with small changes in abdominal adipose tissue fatty acid composition.

Key words: degree of saturation, diacylglycerols, monoacylglycerols, re-esterified oil, *sn*-2 position

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INTRODUCTION

The use of supplemental fats in poultry diets is a widespread practice because of their high energy value. For this reason, the search for new, quality fat sources at competitive prices is of great practical interest. Acid oils, a by-product obtained from oil refining that usually contain a high proportion of free fatty acids (**FFAs**) and little triacylglycerols (**TAGs**), are an economically interesting alternative. However, the absorption of fatty acids (**FAs**), especially saturated ones, has been reported to be much lower when FAs are in free form than when they are part of TAGs (Young, 1961; Wiseman and Salvador, 1991; Vilà and Esteve-Garcia, 1996b). FFAs require a higher amount of bile acids to be incorporated into mixed micelles than monoacylglycerols (**MAGs**), because the former are more hydrophobic and have a higher ability to form insoluble soaps with divalent cations in the aqueous media of the intestine than do the latter (Small, 1991).

It has been hypothesized that the esterification of FFAs present in acid oils with glycerol (another by-product from biodiesel industry) would improve the nutritive value of acid oils, especially in young animals fed saturated fat sources, due to the increased amount of *sn*-2 saturated fatty acids (**SFAs**) and different proportions of MAGs and diacylglycerols (**DAGs**) that can

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be achieved in re-esterified oils. The FA positional distribution within acylglycerol molecules becomes important when the specificity of pancreatic lipase is considered. Pancreatic lipase preferentially hydrolyzes FA located at the *sn*-1,3 positions of acylglycerol molecules (Mattson and Beck, 1956). For this reason, long-chain SFA are better absorbed if situated in the *sn*-2 position than if located at the *sn*-1,3 positions of the acylglycerol molecules (Small, 1991; Bracco, 1994; Decker, 1996; Karupaiah and Sundram, 2007), because they are absorbed as 2-MAGs, instead as FFAs. Regarding the fat acylglycerol composition, until now MAG and DAG molecules have only been recognized as intermediates in the process of TAG digestion. However, they are amphiphilic molecules, able to act as emulsifying agents, and thus enhance FA incorporation into mixed micelles.

Because there is limited information about the use of these technical fats in poultry nutrition, the aim of the present study was to investigate the potential use of re-esterified oils that differ in their degree of saturation and molecular structure in comparison with their corresponding acid (negative control) and native (positive control) oils in broiler chicken diets, with an examination of their effects on FA apparent absorption, excreta acylglycerol and FFA composition, growth performance, carcass fat depots, and FA composition of abdominal adipose tissue.

MATERIALS AND METHODS

Experimental Fats

Experimental fats were supplied by SILO S.p.a. (Florence, Italy). Re-esterified oils were produced using, as raw materials, palm or soybean acid oils (by products obtained from the refining process of crude oils, with a high FFA content) and glycerol (a by-product obtained from the methylation process applied to biodiesel production), which were processed in a reactor for 4 to 6 h under high vacuum conditions (1 to 3 mmHg), without chemical catalysts, and setting the temperature to around 190 to 250°C. According to the stoichiometric proportion of FFAs and glycerol, fats with the same FA profile, but with a different FA positional distribution, and TAG, DAG, and MAG proportions were obtained (Table 1).

Oil samples were analyzed in triplicate for moisture [Method 926.12 of the AOAC International (2005)], impurities (ISO 663:2007), unsaponifiable matter [Method 933.08 of the AOAC International (2005)], acylglycerol and FFA composition (ISO 18395:2005), MAG and DAG positional isomers (Sacchi et al., 1997), total FA composition (Guardiola et al., 1994), *sn*-2 FA composition [Commission Regulation (EEC) 2568/91 – Annex VII], and gross energy content (IKA-Kalorimeter system C4000; Staufen, Germany), as described in more detail in our previous report (Vilarrasa et al., 2014).

Animals and Diets

The study was performed at the animal experimental facilities of the Servei de Granges i Camps Experimentals (Universitat Autònoma de Barcelona; Bellaterra, Barcelona, Spain). The experimental procedure received prior approval from the Animal Protocol Review Committee of the same institution. All animal housing and husbandry conformed to European Union Guidelines (2010/63/EU).

A total of 144 one-d-old female broiler chickens of the Ross 308 strain were obtained from a commercial hatchery (Terra-Avant S.A., Anglès, Girona, Spain), where birds with extreme weights were discarded. On arrival, chicks were wing-banded, weighed (initial BW = 42.8 ± 2.02 g) and randomly assigned to one of 8 dietary treatments, with 3 chicks/cage and 6 cages/treatment. Birds were housed in wire-floor cages with excreta collection trays. Throughout the study, feed and water were supplied for *ad libitum* consumption, and animals were raised under controlled conditions of light and temperature, as recommended by the breeder.

Birds received a starter feed (in mash form) until day 20 and a grower-finisher feed (in pelleted form) from day 20 to day 40. The wheat- and soybean-meal-based diets were formulated to meet or exceed the requirements of Fundación Española para el Desarrollo de la Nutrición Animal (**FEDNA**) (2008) and to minimize basal fat levels. The 8 dietary treatments were the result of including 6% of one of the following experimental fats in the basal diet: native palm oil (**PN**), acid palm oil (**PA**), re-esterified palm oil low in MAG and DAG (**PEL**), re-esterified palm oil high in MAG and DAG (**PEH**), native soybean oil (**SN**), acid soybean oil (**SA**), re-esterified soybean oil low in MAG and DAG (**SEL**), or re-esterified soybean oil high in MAG and DAG (**SEH**). These 8 experimental diets resulted in a 2 × 4 factorial arrangement, with 2 levels of fat saturation degree [palm oil (P) and soybean oil (S)] and 4 types of fat molecular structure [native oil (N, as a positive control), acid oil (A, as a negative control), re-esterified oil low in MAG and DAG (EL), and re-esterified oil high in MAG and DAG (EH)]. The composition of the experimental diets is presented in Table 2. The manufacture of the experimental diets was carried out at the experimental station of IRTA Mas de Bover (Constantí, Tarragona, Spain).

Analytical determinations of feeds were performed according to the methods of the AOAC International (2005): dry matter (Method 934.01), ash (Method 942.05), crude protein (Method 968.06), crude fat (Method 2003.05), and crude fiber (Method 962.09). Gross energy was determined as described previously for fats, and the FA content was analyzed following the method of Sukhija and Palmquist (1988), adding nonadecanoic acid (C19:0, Sigma-Aldrich Chemical Co., St. Louis, MO) as an internal standard. The macronutrient and FA composition of the experimental diets are presented in Table 3.

Table 1. Chemical analyses of experimental fats.[1]

Item		PN oil	PA oil	PEL oil	PEH oil	SN oil	SA oil	SEL oil	SEH oil
Moisture (%)		0.14	0.35	0.02	0.34	0.05	0.08	0.09	0.10
Impurities (%)		<0.50	<0.50	<0.50	<0.50	—	—	<0.50	<0.50
Unsaponifiable matter (%)		0.30	1.59	1.80	1.55	0.27	0.18	0.29	0.30
Fatty acid composition and distribution (%)									
C16:0	Total	41.9	45.0	40.1	40.2	10.7	10.8	11.4	10.9
	sn-2%[2]	7.89	12.4	20.3	15.3	1.59	1.70	4.36	9.00
C18:0	Total	4.63	5.82	8.46	8.57	4.42	4.39	4.15	3.93
	sn-2%[2]	9.35	15.5	24.3	18.2	1.59	1.30	4.83	12.1
C18:1 n-9	Total	36.4	37.1	39.5	39.5	21.2	22.6	21.3	22.1
	sn-2%[2]	49.6	10.0	31.7	16.8	34.1	15.1	28.6	19.4
C18:2 n-6	Total	11.5	8.57	8.05	7.74	54.2	53.4	53.6	54.5
	sn-2%[2]	64.4	16.0	34.6	16.6	43.0	19.4	37.3	21.5
C18:3 n-3	Total	0.56	0.26	0.18	0.15	7.68	6.72	7.83	6.75
	sn-2%[2]	39.3	38.5	33.5	21.7	30.8	15.2	28.7	19.8
Minor fatty acids		5.02	3.18	3.69	3.80	1.79	2.18	1.76	1.82
SFA	Total	48.1	52.7	50.9	51.2	15.2	15.5	15.6	15.0
	sn-2%[2]	8.36	12.7	20.5	15.3	1.69	1.71	4.61	9.82
MUFA	Total	38.2	38.4	40.8	40.9	22.9	24.4	23.0	23.8
	sn-2%[2]	48.0	9.88	31.7	16.8	32.2	14.2	27.3	19.2
PUFA	Total	13.7	8.84	8.24	7.89	61.9	60.1	61.4	61.2
	sn-2%[2]	62.7	16.7	34.6	16.7	41.4	19.0	36.2	21.3
Acylglycerol and FFA composition (%)									
TAG		84.5	29.8	58.8	22.0	98.2	45.0	78.6	34.6
DAG	Total	10.3	11.7	33.9	48.9	0.78	—	11.5	36.0
	1(3),2-DAG%[3]	28.6	39.1	32.5	26.7	50.0	—	29.2	28.9
MAG	Total	0.42	2.61	5.55	27.9	0.27	—	8.90	28.1
	2-MAG%[4]	33.3	11.8	14.3	7.26	50.0	—	7.41	6.63
FFA		4.79	55.8	1.75	1.17	0.75	55.0	0.95	1.32
Glycerol-to-fatty acid ratio[5](mol/mol)		0.34	0.17	0.41	0.58	0.33	0.15	0.40	0.56
Gross energy(kcal/kg)		9,305	9,361	9,328	8,917	9,465	9,437	9,280	8,955

[1]Native palm oil (PN oil), acid palm oil (PA oil), re-esterified palm oil low in MAG and DAG (PEL oil), re-esterified palm oil high in MAG and DAG (PEH oil), native soybean oil (SN oil), acid soybean oil (SA oil), re-esterified soybean oil low in MAG and DAG (SEL oil), and re-esterified soybean oil high in MAG and DAG (SEH oil).

[2]The proportion of a particular FA that is located at the acylglycerol*sn*-2 position (*sn*-2%) was calculated as follows: *sn*-2% = (*sn*-2 / Total) × *a* × 100, where *sn*-2 is the FA composition at the *sn*-2 position, Total is the total FA composition of the fat, and *a* is the ratio between the moles of FA located at the *sn*-2 position and the moles of total FA. *a*was 0.30, 0.12, 0.26, 0.16, 0.33, 0.15, 0.29, and 0.19 for PN, PA, PEL, PEH, SN, SA, SEL, and SEH oils, respectively.

[3]The proportion of 1(3),2-DAG vs.1,3-DAG.

[4]The proportion of 2-MAG vs. 1(3)-MAG.

[5]Estimated calculation based on values of acylglycerol and FFA composition.

The symbol "—" indicates no measurable value.

DAG = diacylglycerols; FFA = free fatty acids; MAG = monoacylglycerols; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; SFA = saturated fatty acids; TAG = triacylglycerols.

Controls and Sampling

Feed consumption and BW were measured weekly to calculate the ADFI, ADG, and feed conversion ratio (**FCR**) throughout the experiment.

Two digestibility balances were carried out using the total excreta collection method (Bourdillon et al., 1990). Excreta were collected in the starter period from day 8 to day 12 and in the growing-finishing period from day 34 to day 36. On the last day of both balances, feed consumption was measured and total excreta were collected, weighed, and homogenized, and a representative sample was frozen at −20°C. Contaminants, such as feed, feathers, down, and scales, were removed. The excreta samples were freeze-dried, ground, and kept at 5°C until further analysis. Excreta samples were analyzed using the same methods as those described for feeds to determine the apparent absorption of FA and the AME of the diets. The apparent absorption coefficients of the nutrients were calculated as the difference between the amount ingested and the amount excreted, expressed as a percentage of the amount ingested. The AME was calculated from the product of apparent absorption of energy and its corresponding gross energy of feed.

The acylglycerol and FFA composition of excreta was analyzed according to ISO 18395:2005, in which TAGs, DAGs, MAGs, and FFAs are separated based on their molecular size by size exclusion HPLC. Prior to analysis, fat was extracted from excreta with diethyl ether after acidification with HCl 1N. Following this, the ether was evaporated in a rotary evaporator, and a solution containing approximately 10 mg fat/mL of tetrahydrofurane was injected into an Agilent 1100 series HPLC chromatograph (Agilent Technologies, Santa Clara, CA) equipped with a refractive index detector

Table 2. Ingredient composition of experimental diets.

Ingredients (%)	Starter diet (from 0 to 20 d)	Grower-finisher diet (from 20 to 40 d)
Wheat	55.30	62.86
Soybean meal 48%	31.44	26.05
Experimental fats[1]	6.00	6.00
Sunflower meal	3.31	-
Dicalcium phosphate	1.74	1.40
Calcium carbonate	0.93	2.56
Sodium chloride	0.40	0.35
Vitamin and mineral premix[2]	0.30	0.30
DL-methionine	0.23	0.19
L-lysine	0.22	0.18
L-threonine	0.05	0.04
Enzyme supplement[3]	0.05	0.05
Ethoxyquin 66%	0.02	0.02
Choline chloride	0.01	-

[1]Native palm oil (PN), acid palm oil (PA), re-esterified palm oil low in mono- and diacylglycerols (PEL), re-esterified palm oil high in mono- and diacylglycerols (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in mono- and diacylglycerols (SEL), or re-esterified soybean oil high in mono- and diacylglycerols (SEH).

[2]Provides per kilogram of feed: vitamin A (from retinol), 13,500 IU; vitamin D_3 (from cholecalciferol), 4,800 IU; vitamin E (from alfa-tocopherol), 49.5 IU; vitamin B_1, 3 mg; vitamin B_2, 9 mg; vitamin B_6, 4.5 mg; vitamin B_{12}, 16.5 μg; vitamin K_3, 3 mg; calcium pantothenate, 16.5 mg; nicotinic acid, 51 mg; folic acid, 1.8 mg; biotin, 30 μg; Fe (from $FeSO_4 \cdot 7H_2O$), 54 mg; I (from $Ca(I_2O_3)_2$), 1.2 mg; Co (from $2CoCO_3 \cdot 3Co(OH)_2 \cdot H_2O$), 0.6 mg; Cu (from $CuSO_4 \cdot 5H_2O$), 12 mg; Mn (from MnO), 90 mg; Zn (from ZnO), 66 mg; Se (from Na_2SeO_3), 0.18 mg; Mo (from $(NH_4)_6Mo_7O_{24}$), 1.2 mg.

[3]Provides per kilogram of feed: β-glucanase 350 IU; xylanase 1,125 IU.

(set at 35°C) and two Styragel columns (Styragel HR 1 and Styragel HR 0.5) of 30 × 0.78 cm i.d., filled with a spherical styrene divinylbenzene copolymer of 5 μm particle size (Water Associates, Milford, MA) connected in series. The mobile phase consisted of 100% tetrahydrofurane. The acylglycerol and FFA molecules were quantified by internal normalization (percentage of area). Finally, these values were expressed as grams per 100 g of fat intake based on the values of apparent absorption of fat obtained for each digestibility balance.

At the end of the experimental period, the 40-d-old broiler chickens were fasted for 3 h, stunned, slaughtered, bled, plucked, and chilled at 4°C for 12 h in a local slaughterhouse (Gimave S.A., Ripollet, Barcelona, Spain). Carcasses (total BW excluding blood and feathers) were weighed, and the liver and abdominal fat pad (from the proventriculus surrounding the gizzard down to the cloaca) for each bird were removed and weighed. Abdominal fat pad and liver weights were expressed in absolute values and as a percentage of carcass weight. A representative sample of the abdominal fat pad was taken and frozen at −20°C. The FA composition of abdominal adipose tissue was determined by the method of Carrapiso et al. (2000).

Statistical Analysis

The normality of the data and homogeneity of the variance were verified. All data were subjected to a

Table 3. Analyzed[1] macronutrient content and fatty acid composition of experimental diets[2] for starter and grower-finisher periods.

	Starter diets (from 0 to 20 d)								Grower-finisher diets (from 20 to 40 d)							
Item	PN	PA	PEL	PEH	SN	SA	SEL	SEH	PN	PA	PEL	PEH	SN	SA	SEL	SEH
Macronutrient content (%)																
Dry matter	89.5	90.0	89.9	89.9	90.0	90.0	90.0	89.8	87.4	88.4	88.0	88.2	88.9	88.2	88.6	88.1
Crude protein	21.0	20.8	20.1	20.9	20.9	19.8	20.5	20.4	19.4	19.5	19.5	19.1	19.2	19.4	19.2	19.5
Crude fat	8.10	8.33	8.35	8.37	8.34	8.54	8.42	7.98	6.92	7.08	7.41	6.89	7.54	7.35	7.23	6.78
Crude fiber	3.73	3.79	3.65	3.74	3.57	3.72	3.82	3.54	3.77	3.56	3.86	3.80	3.61	3.75	3.63	3.48
Ash	6.03	5.90	6.02	6.05	6.06	5.97	5.80	5.80	5.15	5.22	5.18	5.24	5.28	5.13	5.24	5.09
Gross energy(kcal/kg)	4,263	4,266	4,264	4,240	4,272	4,271	4,261	4,242	4,142	4,145	4,143	4,118	4,151	4,150	4,140	4,121
Fatty acid composition (%)																
C12:0	0.80	1.20	1.41	0.63	0.69	0.73	0.61	0.80	0.90	1.57	1.42	1.47	0.89	0.98	0.76	0.85
C14:0	0.94	0.94	1.00	1.00	0.11	0.16	0.12	0.12	1.01	1.06	1.07	1.05	0.10	0.16	0.00	0.11
C16:0	30.9	34.1	29.9	29.7	12.3	12.2	12.7	13.0	33.2	33.3	32.7	32.5	12.5	12.5	12.8	13.3
C18:0	4.14	5.02	6.73	7.01	4.05	4.31	3.97	3.86	4.01	6.27	6.67	6.63	3.83	3.90	3.62	3.76
C18:1 n-9	30.9	31.5	32.1	32.2	21.1	21.9	21.2	21.3	31.4	32.7	33.1	32.7	20.5	21.5	20.7	20.8
C18:1 n-7	1.06	0.90	0.92	1.03	1.33	1.38	1.33	1.34	1.02	0.82	0.82	0.83	1.29	1.34	1.29	1.30
C18:2 n-6	26.0	23.2	24.1	25.0	52.3	51.6	51.7	51.8	23.2	21.3	21.1	21.9	52.8	52.0	52.5	52.2
C18:3 n-3	2.26	1.97	2.04	2.18	6.74	6.36	6.97	6.36	1.65	1.44	1.43	1.56	6.72	6.25	6.97	6.37
Minor fatty acids	2.99	1.26	1.78	1.18	1.41	1.41	1.40	1.43	3.62	1.57	1.64	1.37	1.37	1.38	1.34	1.38
SFA	37.8	42.1	40.3	39.0	18.2	18.4	18.4	18.8	40.1	43.3	43.1	42.6	18.4	18.6	18.2	19.0
MUFA	32.7	32.8	33.6	33.8	22.8	23.7	22.9	23.0	33.3	34.0	34.4	34.0	22.1	23.2	22.3	22.4
PUFA	29.5	25.2	26.1	27.2	59.0	57.9	58.7	58.1	26.6	22.7	22.5	23.4	59.5	58.2	59.5	58.5
UFA:SFA	1.65	1.38	1.48	1.56	4.49	4.43	4.43	4.31	1.49	1.31	1.32	1.35	4.43	4.38	4.49	4.26

[1]All samples were analyzed at least in duplicate.

[2]Diets with 6% of native palm oil (PN), acid palm oil (PA), re-esterified palm oil low in MAG and DAG (PEL), re-esterified palm oil high in MAG and DAG (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in MAG and DAG (SEL), or re-esterified soybean oil high in MAG and DAG (SEH).

DAG = diacylglycerols; MAG = monoacylglycerols; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; SFA = saturated fatty acids; UFA = unsaturated fatty acids.

2-way ANOVA using the GLM procedure of SAS (version 9.2, SAS Institute Inc., Cary, NC). The models included the degree of saturation of fat (P, S) and the fat molecular structure (N, A, EL, EH) as the main factors, and the 2-way interaction. Differences between treatment means were tested using Tukey's correction for multiple comparisons. The cage served as the experimental unit, so that there were 6 replicates per treatment. For abdominal fat pad and liver weights, the broiler carcass weight was included as a covariate in the model in order to correct these variables for variations not related to dietary treatment effect. Results in tables are reported as least-square means, and differences were considered significant at $P < 0.05$.

RESULTS AND DISCUSSION

Characterization of Experimental Fats

The chemical analysis of the experimental fats is presented in Table 1. P oils were high in palmitic (41.8 ± 2.29%) and oleic (38.1 ± 1.61%) acids, and S oils in linoleic (53.9 ± 0.51%) and oleic (21.8 ± 0.67%) acids. The average unsaturated-to-saturated FA proportions were 49:51 wt/wt and 85:15 wt/wt for P and S oils, respectively. Little variability was observed among oils of the same degree of saturation.

The specific distribution of FA within the acylglycerol molecules found in N oils was in agreement with that reported by Mattson and Volpenhein (1963). SFAs were preferentially esterified at the *sn*-1,3 positions, and unsaturated fatty acids (**UFAs**) at the *sn*-2 position in N oils. The chemical esterification process involved a certain redistribution of FAs in the acylglycerol molecules. Although this process did not result in a completely random distribution of FAs (i.e., 33% of each FA should appear in the *sn*-2 position), re-esterified oils showed a higher percentage of SFAs located at the *sn*-2 position and, therefore, a lower percentage of mono- (**MUFAs**) and polyunsaturated fatty acids (**PUFAs**) located at this position when compared with their corresponding N oils. In most case, the reason why EH oils showed a lower proportion of *sn*-2 FAs than did EL oils was their higher 1(3)-MAG and 1,3-DAG content, as will be discussed subsequently in more detail. In this sense, A oils, owing to their high FFA content and, therefore, low moles of FAs located at the *sn*-2 position, showed low proportions of *sn*-2 FAs.

Regarding acylglycerol and FFA composition, native oils (N), as positive controls, were mainly composed of TAGs (91.4 ± 9.69%), whereas acid oils (A) from chemical refining, as negative controls, had a high content of FFAs (55.4 ± 0.57%). However, in general, PN and PA oils showed lower TAG and higher DAG, MAG, and FFA contents than did SN and SA oils, respectively. Re-esterified oils showed variable amounts of TAGs, DAGs, and MAGs and low levels of FFAs. Broadly speaking, EH oils showed a higher amount of MAGs and DAGs and a lower amount of TAGs than did EL oils. Although EL and EH oils of a different degree of saturation had almost an identical glycerol-to-FA ratio (PEL: 0.41 mol/mol vs. SEL: 0.40 mol/mol; PEH: 0.58 mol/mol vs. SEH: 0.56 mol/mol), their acylglycerol composition was different. Re-esterified palm oils showed a lower TAG content and a higher DAG content than did re-esterified soybean oils, which could be related to the differences observed in the acylglycerol and FFA composition of A oils, from which they originated. On the other hand, in all re-esterified oils, 1(3)-MAGs and 1,3-DAGs were the major isomers, which, in terms of fat absorption, are not expected to be as well absorbed as are 2-MAGs and 1(3), 2-DAGs, because pancreatic lipase specifically hydrolyzes the external *sn*-1,3 positions.

Digestibility Balance

The effects of dietary fat sources on the apparent absorption of individual FAs in both starter (from 8 to 12 d) and grower-finisher (from 34 to 36 d) periods are presented in Table 4. Two ages were employed because it is well known that young birds are less capable of utilizing fats than old birds (Krogdahl, 1985; Wiseman and Salvador, 1991). In general, when the interaction component of the model was not significant, the factor degree of saturation showed a greater effect on FA apparent absorption than did the factor molecular structure. However, when the interaction between both factors was significant, the magnitude of the difference observed among P treatments was greater than it was among S treatments.

Concerning the degree of saturation of fat effect, the dietary utilization (AME) of treatments containing S was much higher than for those containing P ($P < 0.05$) because it is well known that chicks can better use FAs from fat sources that are rich in UFAs than from fats that are rich in SFAs (Wiseman et al., 1991). However, the magnitude of the difference observed for AME between P and S sources in the grower-finisher period was only half that in the starter period, mainly owing to the improvement in the absorption of SFAs in P treatments.

For the fat molecular structure effect, treatments containing N (the positive controls) showed higher AME values than did those containing A (the negative controls) in young birds ($P = 0.035$), the difference being more pronounced in treatments containing P. Because FFAs are produced in the natural digestion process, it could be expected that a dietary supply of already hydrolyzed FFAs would be beneficial in terms of fat utilization. However, several authors (Young, 1961; Wiseman and Salvador, 1991) have seen a reduction in the AME of hydrolyzed fats when compared with the AME of the neutral oil from which they originated. In addition, these reports indicated that the reduction in dietary energy value following hydrolysis was more pronounced with saturated than with unsaturated fats.

Regarding re-esterified oils, EL and EH diets showed different responses for the starter than for the

Table 4. Apparent absorption coefficients (%) according to different fat sources in diet.[1]

	Dietary treatments[2]								Degree of saturation[3]		Molecular structure[4]					*P*-values		
	P				S											Degree of	Molecular	
Item	N	A	EL	EH	N	A	EL	EH	P	S	N	A	EL	EH	RMSE	saturation	structure	Interaction
From 8 to 12 d																		
AME(kcal/kg)	3,102	3,018	3,126	3,099	3,228	3,188	3,217	3,177	3,086	3,202	3,165^{a}	3,103^{b}	3,172^{a}	3,138^{a,b}	53.3	<0.001	0.016	0.18
Total fatty acids	74.1	67.8	77.1	70.8	85.7	82.3	83.5	79.0	72.4	82.6	79.9^{a}	75.1^{b}	80.3^{a}	74.9^{b}	4.04	<0.001	<0.001	0.08
SFA	58.7^{b,c}	50.6^{c}	66.8^{a,b}	58.6^{b,c}	77.8^{a}	73.2^{a}	74.3^{a}	68.9^{a,b}	58.6	73.5	68.2	61.9	70.5	63.8	6.05	<0.001	0.004	0.012
MUFA	82.0	77.3	82.9	77.0	84.6	80.8	82.1	77.0	79.8	81.1	83.3^{a}	79.1^{a,b}	82.5^{a}	77.0^{b}	4.01	0.27	0.001	0.50
PUFA	79.7	75.8	80.3	74.4	87.8	85.0	86.1	82.1	77.5	85.2	83.8^{a}	80.4^{a,b}	83.2^{a}	78.3^{b}	3.21	<0.001	<0.001	0.63
C16:0	64.5^{c,d}	56.0^{d}	71.4^{b,c}	65.2^{c,d}	81.7^{a}	78.0^{a,b}	79.2^{a,b}	75.2^{a,b}	64.2	78.5	73.1	67.0	75.3	70.2	5.23	<0.001	0.003	0.007
C18:0	49.5^{e,f}	45.5^{f}	61.3^{c,d,e}	55.6^{d,e,f}	78.4^{a}	72.7^{a,b,c}	73.8^{a,b}	65.8^{b,c,d}	53.0	72.7	64.0	59.1	67.6	60.7	6.64	<0.001	0.017	0.001
C18:1 n-9	82.4	77.8	83.4	77.6	85.1	81.3	82.6	77.6	80.3	81.6	83.8^{a}	79.5^{a,b}	83.0^{a}	77.6^{b}	3.96	0.25	0.001	0.49
C18:2 n-6	79.3	75.9	80.3	74.6	87.6	84.7	85.7	81.8	77.5	85.0	83.4^{a}	80.3^{a,b}	83.0^{a}	78.2^{b}	3.18	<0.001	<0.001	0.57
C18:3 n-3	79.4	76.6	80.2	75.2	89.9	87.1	88.7	84.6	77.8	87.6	84.7^{a}	81.8^{a,b}	84.4^{a}	79.9^{b}	2.77	<0.001	<0.001	0.80
From 34 to 36 d																		
AME, kcal/kg	2,953	2,902	3,017	2,936	3,044	2,974	3,008	3,015	2,952	3,010	2,998	2,938	3,012	2,976	88.9	0.029	0.20	0.51
Total fatty acids	74.9^{c}	76.4^{c}	80.5^{b,c}	80.6^{a,b,c}	86.4^{a}	80.0^{b,c}	82.8^{a,b}	83.7^{a,b}	78.1	83.2	80.7	78.2	81.6	82.1	3.18	<0.001	0.019	0.003
SFA	64.7^{c}	70.3^{b,c}	75.8^{a,b}	76.3^{a,b}	80.5^{a}	73.9^{a,b}	76.4^{a,b}	78.5^{a}	71.8	77.3	72.6	72.1	76.1	77.4	4.42	<0.001	0.012	<0.001
MUFA	82.6^{a,b}	81.9^{a,b}	85.2^{a}	84.8^{a}	85.9^{a}	78.9^{b}	82.0^{a,b}	82.5^{a,b}	83.6	82.3	84.2	80.4	83.6	83.6	3.03	0.14	0.014	0.041
PUFA	80.6	79.9	82.4	82.5	88.4	82.4	85.0	85.8	81.4	85.4	84.5^{a}	81.1^{b}	83.7^{a,b}	84.1^{a}	2.65	<0.001	0.014	0.05
C16:0	65.4^{c}	70.4^{b,c}	76.3^{a,b}	76.8^{a,b}	81.7^{a}	75.2^{a,b}	78.2^{a}	79.9^{a}	72.2	78.7	73.6	72.8	77.3	78.3	4.15	<0.001	0.004	<0.001
C18:0	54.4^{c}	64.1^{b,c}	70.4^{a,b}	71.9^{a,b}	77.5^{a}	69.2^{a,b}	72.2^{a,b}	75.2^{a,b}	65.2	73.5	66.0	66.6	71.3	73.5	6.10	<0.001	0.010	<0.001
C18:1 n-9	83.0^{a,b}	82.2^{a,b}	85.5^{a}	85.0^{a}	86.1^{a}	79.3^{b}	82.3^{a,b}	82.9^{a,b}	83.9	82.6	84.5	80.7	83.9	84.0	3.01	0.15	0.015	0.05
C18:2 n-6	80.5	79.9	82.4	82.4	88.2	82.1	84.7	85.5	81.3	85.1	84.3^{a}	81.0^{b}	83.6^{a,b}	83.9^{a,b}	2.69	<0.001	0.018	0.05
C18:3 n-3	81.3	80.2	81.8	83.6	90.5	84.7	87.3	88.0	81.7	87.6	85.9^{a}	82.5^{b}	84.5^{a,b}	85.8^{a}	2.48	<0.001	0.006	0.08

[a–f]Values within the same row with no common superscripts are significantly different, $P < 0.05$.

[1]Diets with 6% of native palm (PN), acid palm oil (PA), re-esterified palm oil low in MAG and DAG (PEL), re-esterified palm oil high in MAG and DAG (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in MAG and DAG (SEL), or re-esterified soybean oil high in MAG and DAG (SEH).

[2]Values are means of 6 cages with 3birds/cage.

[3]Values are means of 24 cages with 3birds/cagefed dietary treatments supplemented with 6% of palm (P) or soybean (S) oil sources.

[4]Values are means of 12 cages with 3birds/cagefed dietary treatments supplemented with 6% of native oil (N), acid oil (A), re-esterified oil low in MAG and DAG (EL), or re-esterified oil high in MAG and DAG (EH).

DAG = diacylglycerols; MAG = monoacylglycerols; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; RMSE = root mean square error; SFA = saturated fatty acids.

grower-finisher period. In the starter period, EL diets showed a higher nutritive value (AME) than did A ($P = 0.019$) and not different from N ($P = 0.99$), mainly owing to improved SFA apparent absorption. Nevertheless, the magnitude of the difference was much higher in P sources than it was in S ones, as indicated by the significance of the interaction for SFA apparent absorption ($P = 0.012$). Thus, although no differences were found among S sources ($P > 0.05$), PEL achieved higher SFA apparent absorption values than did PA ($P < 0.001$), which were no different from S treatments ($P > 0.05$). In the grower-finisher period, PEL treatment achieved even higher SFA apparent absorption values than did PN ($P = 0.002$), and these were also no different from S sources ($P > 0.05$). The high SFA apparent absorption obtained by PEL could be due to its lower FFA content and its higher *sn*-2 SFA content when compared with their corresponding native and acid oils. The chemical esterification reaction decreased the amount of FFAs (from 55.8% in PA oil and 4.79% in PN oil to 1.75% in PEL oil) and raised the fraction of SFAs at the *sn*-2 position (from 12.7 mol% in PA oil and 8.36 mol% in PN oil to 20.5 mol% in PEL oil). Thus, the greater absorption of SFAs in PEL would result from the greater content of 2-monopalmitin and the lower content of free palmitic acid in the intestine after hydrolysis. Consistent with our results, previous studies in rats (Tomarelli et al., 1968; Renaud et al., 1995; Lien et al., 1997), human newborn infants (Filer et al., 1969), and broiler chickens (Renner and Hill, 1961; Lin and Chiang, 2010) also found that SFAs present at the *sn*-2 position of dietary acylglycerols were more readily absorbed than were SFAs at the *sn*-1,3 positions.

In the starter period, EH treatments did not enhance the nutritive value (AME) of their corresponding A treatment from which they originated ($P = 1.00$), despite their markedly higher MAG and DAG contents. Assuming that the most limiting process in fat digestion is micelle formation, it could be expected that amphiphilic molecules (consisting of a hydrophilic and a hydrophobic part) could contribute to the fat digestibility of added feed fats, especially the poorly absorbed SFAs in young broiler chickens. However, our results suggest that high MAG and DAG contents do not improve the absorption of SFAs in young broiler chickens. Related to this, Taguchi et al. (2001) reported that the fecal excretion of FAs after feeding rats 5 weeks of age with a DAG-enriched diet was almost the same as with a TAG-enriched diet. The lack of improvement could be related to the high proportions of 1(3)-MAG and 1,3-DAG species present in EH oils. In young broiler chickens, the assimilation of dietary fats is limited because they have a reduced capacity to produce and secrete bile salts (Soede, 2005). Thus, dietary fats would remain longer in the intestinal lumen, which could lead to a complete hydrolysis of 1(3)-MAGs and 1,3-DAGs to glycerol and FFAs, impairing micelle formation and fat absorption. However, in older birds, PEH achieved higher SFA apparent absorption values than did PN ($P = 0.001$) and values that were no different from S treatments ($P > 0.05$), suggesting that MAGs and DAGs during the grower-finisher period are not completely hydrolyzed, and as a consequence, their emulsifying properties improve the rate of SFA incorporation into mixed micelles.

Excreta Acylglycerol and Free Fatty Acid Composition

The digestion products of fat in excreta were analyzed to better understand how the fat molecular structure affects digestion and absorption processes. The acylglycerol and FFA composition of excreta (g/100 g of fat intake) in both starter (from 8 to 12 d) and grower-finisher (from 34 to 36 d) periods is shown in Table 5. The amount of TAGs, DAGs, and MAGs was low in excreta of both periods. This means that TAGs and DAGs were almost completely hydrolyzed along the gastrointestinal tract, and MAGs were absorbed due to their hydrophilic character [2-MAGs and some 1(3)-MAGs] or completely hydrolyzed to glycerol and FFAs [mainly 1(3)-MAGs]. Thus, regardless of the treatment, fat lost in excreta was mainly composed of FFAs, which agrees with the results found by Sklan (1979). This suggests that in broiler chickens, especially at early ages, the main limiting factor of fat absorption is the emulsifying effect of bile salts, rather than the hydrolytic activity of pancreatic lipase, as was also indicated by Soede (2005).

The amount of TAG, DAG, and MAG molecules in excreta remained almost constant in both periods, while in the grower-finisher period FFA content decreased considerably, which explains the improved fat absorption observed in adult broiler chickens, possibly as a result of improved bile secretion. Thus, most TAG, DAG, and MAG molecules could come from endogenous losses or from dietary fat, if they have melting points above the chicken's body temperature.

The main differences among treatments were observed for FFAs. In this case, the interaction component of the model was significant ($P = 0.004$ and $P = 0.002$ for starter and grower-finisher periods, respectively), and the amount of FFAs excreted per 100 g of fat intake almost paralleled the results of SFA apparent absorption, suggesting that the emulsification of SFAs is the most critical step in fat absorption.

Regarding TAG, DAG, and MAG fractions, smaller differences were observed. For the degree of saturation of fat, higher excretion of MAGs (in the starter period, $P < 0.001$) and TAGs (in the grower-finisher period, $P = 0.002$) was observed in P sources, which probably corresponds to acylglycerol molecules rich in SFAs and, therefore, with melting points above the chicken's body temperature, hindering the digestion and absorption processes. For the fat molecular structure, only minor differences were observed for DAGs and MAGs in the starter period.

Table 5. Excreta acylglycerol and free fatty acid composition (g/100 g of fat intake) according to different fat sources in diet.[1]

	Dietary treatments[2]							Degree of saturation[3]		Molecular structure[4]				*P*-values		
	P			S												
Item	N	A	EL	EH	N	A	EL	EH	P	S	N	A	EL	EH	RMSE	Degree of saturation	Molecular structure	Interaction
From 8 to 12 d																		
TAG	2.21	3.05	2.47	3.12	2.59	2.69	2.41	2.84	2.71	2.63	2.40	2.87	2.44	2.98	0.616	0.66	0.05	0.47
DAG	2.30	3.06	2.31	3.16	2.21	2.60	2.32	2.78	2.70	2.48	2.26^{c}	$2.83^{a,b}$	$2.31^{b,c}$	2.97^{a}	0.472	0.10	<0.001	0.56
MAG	1.49	2.20	1.71	1.98	1.01	1.28	1.12	1.09	1.84	1.13	1.25^{b}	1.74^{a}	$1.41^{a,b}$	$1.54^{a,b}$	0.369	<0.001	0.02	0.38
FFA	20.5^{b}	28.9^{a}	$16.2^{b,c}$	19.9^{b}	10.6^{c}	$14.6^{b,c}$	12.5^{c}	$15.2^{b,c}$	21.4	13.2	15.6	21.7	14.3	17.5	3.73	<0.001	<0.001	0.004
From 34 to 36 d																		
TAG	2.69	2.58	2.34	2.39	1.85	1.99	2.29	2.29	2.50	2.11	2.27	2.29	2.32	2.34	0.400	0.002	0.97	0.05
DAG	3.33	3.59	2.90	3.25	2.46	3.12	3.07	3.08	3.27	2.93	2.89	3.36	2.99	3.17	0.603	0.06	0.26	0.20
MAG	1.98	1.95	1.71	1.72	1.38	1.83	1.61	1.72	1.84	1.64	1.68	1.89	1.66	1.72	0.390	0.08	0.47	0.24
FFA	18.1^{a}	$16.4^{a,b}$	$13.8^{a,b,c}$	$12.8^{b,c}$	9.10^{c}	$13.9^{a,b,c}$	$12.3^{b,c}$	$11.7^{b,c}$	15.3	11.7	13.6	15.1	13.0	12.3	2.62	<0.001	0.06	0.002

[a–c]Values within the same row with no common superscripts are significantly different, $P < 0.05$.

[1]Diets with 6% of native palm (PN), acid palm oil (PA), re-esterified palm oil low in MAG and DAG (PEL), re-esterified palm oil high in MAG and DAG (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in MAG and DAG (SEL), or re-esterified soybean oil high in MAG and DAG (SEH).

[2]Values are means of 6 cages with 3birds/cage.

[3]Values are means of 24 cages with 3birds/cagefed dietary treatments supplemented with 6% of palm (P) or soybean (S) oil sources.

[4]Values are means of 12 cages with 3birds/cagefed dietary treatments supplemented with 6% of native oil (N), acid oil (A), re-esterified oil low in MAG and DAG (EL), or re-esterified oil high in MAG and DAG (EH).

DAG = diacylglyerols; FFA = free fatty acids; MAG = monoacylglycerols; RMSE = root mean square error; TAG = triacylglycerols.

Growth Performance and Carcass Fat Depots

The effects of dietary fat sources on growth performance in both starter (from 0 to 20 d) and grower-finisher (from 20 to 40 d) periods are presented in Table 6. No significant interactions were observed in any feeding period ($P > 0.05$), but several differences were detected for the degree of saturation of fat. Regardless of the period, the FCRs were lower for birds fed S than for those fed P ($P < 0.05$), probably owing to their greater ability to absorb fat, as was also seen in other studies (Pinchasov and Nir, 1992; Zollitsch et al., 1997; Crespo and Esteve-Garcia, 2001). During the starter period, the improved FCR in chicks fed S was due to the greater ADG ($P = 0.043$). However, in the grower-finisher period and the overall experiment, birds fed P consumed a greater amount of feed ($P = 0.017$) to gain the same weight ($P = 0.39$) than did those fed S. Boilers try to consume the amount of feed that covers their energy requirements (NRC, 1994). Therefore, differences in feed intake compensated differences in dietary AME, leading to an overall similar AME intake in both P and S groups.

For the fat molecular structure, no differences among birds fed N and A diets were detected ($P > 0.05$), which agrees with the results of Young (1961) and Vilà and Esteve-Garcia (1996a). Birds fed re-esterified oil-enriched diets showed no differences among other treatments ($P > 0.05$). Concerning the effect of the FA positional distribution, Smink et al. (2008) and Lin and Chiang (2010) showed no differences in performance between broiler chickens fed high palmitic acid content at the TAG *sn*-2 position and those fed low palmitic acid content at the TAG *sn*-2 position. In contrast, Innis et al. (1997) reported a higher weight gain per liter of formula intake in piglets fed randomized oils than in those fed native oils. Regarding the fat acylglycerol and FFA composition, Murata et al. (1997), Taguchi et al. (2001), and Murase et al. (2005) found no differences in performance of rats fed DAG or TAG oil-enriched diets. In contrast, Meng et al. (2004) reported that weight gain was lower in rats fed a DAG oil-rich diet, and Kamphuis et al. (2003) observed a diminished feeling of hunger and appetite in women fed a DAG oil-rich diet.

The effects of dietary fat sources on abdominal fat pad and liver weights are presented in Table 6. Despite there being no differences in final BW, differences in carcass fat depots were observed with respect to the degree of saturation of fat. Broiler chickens fed P deposited a greater amount of abdominal fat than did those fed S ($P < 0.001$), which, in absolute value, represented an increase of approximately 17%. The higher AME of S diets could be expected to cause a higher fat deposition. However, several studies (Sanz et al., 1999; Crespo and Esteve-Garcia, 2001, 2002; Ferrini et al., 2008) have shown that dietary PUFAs, compared to SFAs, result in a lower abdominal fat depot

Table 6. Growth performance and carcass fat depots of broiler chickens according to different fat sources in diet.[1]

Item		Degree of saturation[2]		Molecular structure[3]				RMSE	*P*-values		
		P	S	N	A	EL	EH		Degree of saturation	Molecular structure	Interaction
From 0 to 20 d											
ADFI(g/d/bird)		49.9	50.3	51.0	48.9	49.5	50.9	2.87	0.70	0.32	0.15
ADG(g/d/bird		36.2	37.8	37.4	36.0	36.9	37.7	2.15	0.043	0.35	0.64
FCR(g/g)		1.38	1.33	1.37	1.36	1.35	1.35	0.045	0.007	0.75	0.07
BW at 20 d(g)		767	798	790	762	780	797	42.9	0.042	0.34	0.63
From 20 to 40 d											
ADFI(g/d/bird)		173	166	170	170	165	174	8.19	0.017	0.23	0.22
ADG(g/d/bird)		89.0	90.4	89.9	89.0	88.0	91.9	4.34	0.39	0.32	0.43
FCR(g/g)		1.95	1.84	1.89	1.91	1.88	1.90	0.061	<0.001	0.70	0.30
BW at 40 d(g)		2,548	2,605	2,588	2,542	2,541	2,635	114.8	0.16	0.28	0.49
From 0 to 40 d											
ADFI(g/d/bird)		112	108	111	109	107	112	4.74	0.048	0.21	0.11
ADG(g/d/bird)		62.6	64.1	63.6	62.5	62.5	64.8	2.87	0.16	0.29	0.49
FCR(g/g)		1.78	1.69	1.74	1.76	1.72	1.74	0.043	<0.001	0.45	0.22
Carcass fat depots											
Abdominal fat	g	65.2	55.8	59.2	60.3	61.3	61.3	8.28	<0.001	0.91	0.61
	%	2.82	2.44	2.57	2.63	2.59	2.73	0.387	0.002	0.76	0.33
Liver	g	51.9	49.1	54.0	48.4	49.3	50.4	5.25	0.08	0.06	0.92
	%	2.26	2.14	2.35	2.11	2.13	2.21	0.221	0.08	0.05	0.87

[a–b]Values within the same row with no common superscripts are significantly different, $P < 0.05$.

[1]Diets with 6% of native palm (PN), acid palm oil (PA), re-esterified palm oil low in MAG and DAG (PEL), re-esterified palm oil high in MAG and DAG (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in MAG and DAG (SEL), or re-esterified soybean oil high in MAG and DAG (SEH).

[2]Values are means of 24 cages with 3 birds/cage fed dietary treatments supplemented with 6% of palm (P) or soybean (S) oil sources.

[3]Values are means of 12 cages with 3 birds/cage fed dietary treatments supplemented with 6% of native oil (N), acid oil (A), re-esterified oil low in MAG and DAG (EL), or re-esterified oil high in MAG and DAG (EH).

DAG = diacylglycerols; FCR = feed conversion ratio; MAG = monoacylglycerols; RMSE = root mean square error.

in broiler chickens, which seems to be related to an increased rate of lipid catabolism and lower rate of FA synthesis. The same trend was observed for liver weight ($P = 0.08$). Crespo and Esteve-Garcia (2002) and Ferrini et al. (2010) found no differences in liver weight (both in absolute and relative terms) among animals fed saturated and unsaturated fat sources, but they did find differences in the liver lipid content. Regarding the fat molecular structure, no differences were found for carcass fat depots, although birds fed N tended to show higher liver weights (both in absolute and in relative terms) than did those fed A ($P = 0.06$). Regarding the FA positional distribution effect, Ponnampalam et al. (2011) found that animals fed lard-enriched diets (high *sn*-2 SFAs) showed a greater external adipose tissue thickness than did those fed native palm oil (low *sn*-2 SFAs). In relation to the fat acylglycerol composition, Murase et al. (2002) and Meng et al. (2004) reported a reduced accumulation of fat in visceral adipose and subcutaneous tissue and a reduced fat content in the liver of rodents fed 1,3-DAG-enriched diets, as compared to those fed TAGs of the same FA composition. The presence of dietary 1,3-DAGs has been shown to increase the β-oxidation of FAs in the liver (Murata et al., 1997) and in the small intestine (Murase et al., 2002). We might not have encountered significant differences in fat depots of animals fed re-esterified palm oils because the effect of MAGs and DAGs might have counteracted the effect of *sn*-2 SFAs.

Fatty Acid Composition of Abdominal Adipose Tissue

The effect of dietary fat sources on the FA composition of abdominal adipose tissue is presented in Table 7. The FA composition of abdominal adipose tissue was a clear reflection of the dietary FA profile, which is consistent with the findings of other researchers (Pinchasov and Nir, 1992; Ferrini et al., 2008). Thus, as expected, animals fed P showed a higher SFA and MUFA content and a lower PUFA content ($P < 0.001$) than did those fed S. However, the magnitude of the difference for the UFA-to-SFA ratio was markedly lower for the fat deposited (P: 2.00 ± 0.031 wt/wt and S: 2.90 ± 0.046 wt/wt) than for the fat absorbed (P: 1.59 ± 0.039 wt/wt and S: 4.82 ± 0.038 wt/wt) owing to the importance of maintaining the UFA-to-SFA ratio within a narrow range to maintain the fluidity of the cell membranes, as suggested by Villaverde et al. (2006).

Concerning the fat molecular structure effect, a slightly but significantly lower MUFA content was observed in abdominal adipose tissue of broilers fed N and EL when compared with those fed A and EH ($P < 0.05$). PUFA levels were almost inversely related to those of MUFA. For the SFA content of abdominal adipose tissue, the interaction between the degree of saturation of fat and the fat molecular structure was found to be significant ($P = 0.019$). Whereas the SFA content of abdominal adipose tissue was lower and not different

Table 7. Fatty acid composition (%) of abdominal adipose tissue according to different fat sources in diet.[1]

	Dietary treatments[2]								Degree of saturation[3]		Molecular structure[4]					*P*-values		
	P				S													
Item	N	A	EL	EH	N	A	EL	EH	P	S	N	A	EL	EH	RMSE	Degree of saturation	Molecular structure	Interaction
C14:0	0.79^{b}	0.81^{a,b}	0.87^{a}	0.82^{a,b}	0.36^{c}	0.42^{c}	0.37^{c}	0.41^{c}	0.82	0.39	0.58	0.62	0.62	0.61	0.038	<0.001	0.028	0.013
C16:0	26.4^{a}	26.7^{a}	28.0^{a}	27.0^{a}	18.8^{c}	20.0^{b,c}	19.3^{b,c}	20.7^{b}	27.0	19.7	22.6	23.3	23.6	23.8	1.01	<0.001	0.022	0.030
C16:1 n-9	5.31	6.22	5.00	6.20	3.08	3.63	3.27	4.08	5.68	3.51	4.20^{b}	4.92^{a}	4.13^{b}	5.14^{a}	0.624	<0.001	<0.001	0.42
C18:0	4.93^{a,b}	4.79^{b}	5.76^{a}	5.07^{a,b}	5.30^{a,b}	5.48^{a,b}	5.32^{a,b}	5.27^{a,b}	5.14	5.34	5.11	5.14	5.54	5.17	0.491	0.16	0.13	0.05
C18:1 n-9	44.1	45.5	44.2	45.3	32.4	34.5	32.3	34.3	44.8	33.4	38.3^{b}	40.0^{a}	38.2^{b}	39.8^{a}	1.30	<0.001	0.001	0.75
C18:1 n-7	2.07	2.34	2.20	2.28	1.87	1.91	1.86	2.01	2.22	1.91	1.97^{b}	2.13^{a,b}	2.03^{a,b}	2.14^{a}	0.159	<0.001	0.028	0.32
C18:2 n-6	13.7	11.5	11.8	11.1	32.6	29.1	31.9	28.5	12.0	30.5	23.1^{a}	20.3^{b}	21.8^{a}	19.8^{b}	1.40	<0.001	<0.001	0.08
C18:3 n-3	0.96^{c}	0.75^{c}	0.76^{c}	0.74^{c}	4.02^{a}	3.46^{b}	4.14^{a}	3.38^{b}	0.80	3.75	2.49	2.11	2.45	2.06	0.146	<0.001	<0.001	<0.001
C20:1 n-9	0.43^{a}	0.38^{b}	0.35^{b,c}	0.36^{b,c}	0.32^{c}	0.32^{c}	0.31^{c}	0.31^{c}	0.38	0.31	0.37	0.35	0.33	0.33	0.026	<0.001	<0.001	0.022
Minor fatty acids	1.36	1.12	1.11	1.07	1.27	1.17	1.36	1.16	1.16	1.24	1.31^{a}	1.14^{a,b}	1.23^{a,b}	1.11^{b}	0.160	0.09	0.015	0.09
SFA	32.5^{b}	32.8^{a,b}	35.2^{a}	33.4^{a,b}	24.8^{c}	26.2^{c}	25.3^{c}	26.6^{c}	33.5	25.7	28.6	29.5	30.2	30.0	1.38	<0.001	0.031	0.019
MUFA	52.1	54.6	51.9	54.4	37.8	40.5	37.8	40.8	53.2	39.2	44.9^{b}	47.5^{a}	44.8^{b}	47.6^{a}	1.64	<0.001	<0.001	0.96
PUFA	15.5^{c}	12.6^{c,d}	12.9^{c,d}	12.2^{d}	37.5^{a}	33.3^{b}	36.9^{a}	32.6^{b}	13.3	35.1	26.5	23.0	24.9	22.4	1.60	<0.001	<0.001	0.033
UFA:SFA	2.09^{b}	2.06^{b}	1.85^{b}	2.00^{b}	3.05^{a}	2.81^{a}	2.97^{a}	2.77^{a}	2.00	2.90	2.57	2.44	2.41	2.38	0.173	<0.001	0.06	0.036

[a–d]Values within the same row with no common superscripts are significantly different, $P < 0.05$.

[1]Diets with 6% of native palm (PN), acid palm oil (PA), re-esterified palm oil low in MAG and DAG (PEL), re-esterified palm oil high in MAG and DAG (PEH), native soybean oil (SN), acid soybean oil (SA), re-esterified soybean oil low in MAG and DAG (SEL), or re-esterified soybean oil high in MAG and DAG (SEH).

[2]Values are means of 6 determinations.

[3]Values are means of 24 determinations from birds fed dietary treatments supplemented with 6% of palm (P) or soybean (S) oil sources.

[4]Values are means of 12 determinations from birds fed dietary treatments supplemented with 6% of native oil (N), acid oil (A), re-esterified oil low in MAG and DAG (EL), or re-esterified oil high in MAG and DAG (EH).

DAG = diacylglycerols; MAG = monoacylglycerols; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; RMSE = root mean square error; SFA = saturated fatty acids; UFA = unsaturated fatty acids.

among animals fed S sources, animals fed PEL showed a higher SFA content than did those fed PN ($P = 0.029$). This difference seems to be attributable to the higher dietary SFA content (3%) and the higher SFA apparent absorption (11%) of PEL when compared with PN. The study by Smink et al. (2008) also demonstrated that the increased absorption of SFA in randomized palm oils, especially of palmitic acid, caused higher SFA deposition in broiler chickens.

Taken together, results of this experiment suggest that, in general, the degree of saturation of fat exerts a greater impact on FA apparent absorption, growth performance, carcass fat depots, and FA composition of abdominal adipose tissue than does the fat molecular structure. However, the increased fat *sn*-2 SFA content, in the starter period, and the increased MAG and DAG contents of re-esterified palm oils, in the grower-finisher period, exerted a favorable effect on the SFA apparent absorption. Thus, re-esterified oils, mainly from P sources, can be used in broiler chicken diets as alternative fat sources, showing similar or even higher total FA apparent absorption than their corresponding native and acid oils, with small changes in abdominal adipose tissue FA composition.

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