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The digestible energy, metabolizable energy, and net energy content of dietary fat sources in thirteen- and fifty-kilogram pigs

T. A. Kellner
Iowa State University

John F. Patience
Iowa State University, jfp@iastate.edu

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Abstract

The objective was to determine the energy concentration of a diverse array of dietary fat sources and from these data, develop regression equations that explain differences based on chemical composition. A total of 120 Genetiporc 6.0 × Genetiporc F25 (PIC, Inc., Hendersonville, TN) individually housed barrows were studied for 56 d. These barrows (initial BW of 9.9 ± 0.6 kg) were randomly allotted to 1 of 15 dietary treatments. Each experimental diet included 95% of a corn-soybean meal basal diet plus 5% either: corn starch or 1 of 14 dietary fat sources. The 14 dietary fat sources (animal-vegetable blend, canola oil, choice white grease source A, choice white grease source B, coconut oil, corn oil source A, corn oil source B, fish oil, flaxseed oil, palm oil, poultry fat, soybean oil source A, soybean oil source B, and tallow) were selected to provide a diverse and robust range of U:S (unsaturated fatty acid:SFA). Pigs were limit-fed experimental diets from d 0 to 10 and d 46 to 56 providing a 7 d adaption for fecal collection on d 7 to 10 (13 kg BW) and d 53 to 56 (50 kg BW). At 13 kg BW, the average energy content of the 14 sources was 8.42 Mcal of DE/kg, 8.26 Mcal of ME/kg, and 7.27 Mcal of NE/kg, respectively. At 50 kg BW, the average energy content was 8.45 Mcal of DE/kg, 8.28 Mcal of ME/kg, and 7.29 Mcal of NE/kg, respectively. At 13 kg BW, variation of dietary fat DE content was explained by: DE (Mcal/kg) = 9.363 + [0.097 × (FFA, %)] – [0.016 × Omega- 6:Omega-3] – [1.240 × (arachidic acid, %)] – [5.054 × (insoluble impurities, %)] + [0.014 × (palmitic acid, %)] (P = 0.008; R2 = 0.82). At 50 kg BW, variation of dietary fat DE content was explained by: DE (Mcal/kg) = 8.357 + [0.189 × U:S] – [0.195 × (FFA, %)] – [6.768 × (behenic acid, %)] + [0.024 × (PUFA, %)] (P = 0.002; R2 = 0.81). In summary, the chemical composition of dietary fat explained a large degree of the variation observed in the energy content of dietary fat sources at both 13 and 50 kg BW.

Keywords

fat composition, fat digestibility, energy, fatty acids, energy prediction, swine

Disciplines

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Comments

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The digestible energy, metabolizable energy, and net energy content of dietary fat sources in 13 and 50 kg pigs[1]

T. A. Kellner and J. F. Patience[2]

Department of Animal Science, Iowa State University, Ames, 50011, USA

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[2] Corresponding author: jfp@iastate.edu.

ABSTRACT: The objective was to determine the energy concentration of a diverse array of dietary fat sources and from these data, develop regression equations that explain differences based on chemical composition. A total of 120 Genetiporc 6.0 × Genetiporc F25 (PIC, Inc., Hendersonville, TN) individually housed barrows were studied for 56 d. These barrows (initial BW of 9.9 ± 0.6 kg) were randomly allotted to 1 of 15 dietary treatments. Each experimental diet included 95% of a corn-soybean meal basal diet plus 5% either: corn starch or 1 of 14 dietary fat sources. The 14 dietary fat sources (animal-vegetable blend, canola oil, choice white grease source A, choice white grease source B, coconut oil, corn oil source A, corn oil source B, fish oil, flaxseed oil, palm oil, poultry fat, soybean oil source A, soybean oil source B, and tallow) were selected to provide a diverse and robust range of U:S (unsaturated fatty acid:SFA). Pigs were limit-fed experimental diets from d 0 to 10 and d 46 to 56 providing a 7 d adaption for fecal collection on d 7 to 10 (13 kg BW) and d 53 to 56 (50 kg BW). At 13 kg BW, the average energy content of the 14 sources was 8.42 Mcal of DE/kg, 8.26 Mcal of ME/kg, and 7.27 Mcal of NE/kg, respectively. At 50 kg BW, the average energy content was 8.45 Mcal of DE/kg, 8.28 Mcal of ME/kg, and 7.29 Mcal of NE/kg, respectively. At 13 kg BW, variation of dietary fat DE content was explained by: DE (Mcal/kg) = 9.363 + [0.097 × (FFA, %)] – [0.016 × Omega-6:Omega-3] – [1.240 × (arachidic acid, %)] – [5.054 × (insoluble impurities, %)] + [0.014 × (palmitic acid, %)] (P = 0.008; R2 = 0.82). At 50 kg BW, variation of dietary fat DE content was explained by: DE (Mcal/kg) = 8.357 + [0.189 × U:S] – [0.195 × (FFA, %)] – [6.768 × (behenic acid, %)] + [0.024 × (PUFA, %)] (P = 0.002; R2 = 0.81). In summary, the chemical composition of dietary fat explained a large degree of the variation observed in the energy content of dietary fat sources at both 13 and 50 kg BW.

Key words: fat composition, fat digestibility, energy, fatty acids, energy prediction, swine

INTRODUCTION

Fat is included in swine diets as a source of energy when the cost is economically advantageous. However, DE, ME and NE content estimates of dietary fat have been variable and have not been fully validated (Kil et al., 2011; Boyd et al., 2015). A lack of precision in defining the energy value of dietary fat could lead to losses for pork producers due to incorrect costing in diet formulations and disappointing performance outcomes.

Prediction equations compiled by Powles et al. (1995) using data from Wiseman et al. (1990) and Powles et al. (1993, 1994) have been commonly used to estimate the energy content of fat sources by using the unsaturated fatty acid to SFA ratio (**U:S**) and FFA level. The ME and NE content is then often estimated from DE according to van Milgen et al. (2001) who suggested that ME is 98% of DE and NE is 88% of ME. The NRC (2012) points out that the equation accuracy across all compositions and characteristics of dietary fat sources is unknown. Boyd et al. (2015) recently utilized a growth assay to determine the NE content of choice white grease and reported a 14% difference compared to the NRC (2012) estimate. Clearly, validation and refinement of the energy values assigned to dietary fat sources in swine is needed. Including dietary fatty acid concentration and more detailed chemical composition along with FFA and U:S content across a diverse and robust range of dietary fat sources may generate a more accurate estimate of the DE, ME and NE of dietary fats.

Thus, the objective was to determine the energy concentration in a diverse array of dietary fat sources and from these data, develop regression equations that explain differences based on chemical composition. They could serve as prediction equations in the future. The hypothesis was that dietary fat DE variation among sources can be better explained using more detailed chemical composition than previous attempts.

MATERIALS AND METHODS

All experimental procedures adhered to guidelines for the ethical and humane use of animals for research, and were approved by the Iowa State University Institutional Animal Care and Use Committee (#2-16-8201-S).

Animals, Housing, and Experimental Design

A total of 120 Genetiporc 6.0 × Genetiporc F25 (PIC, Inc., Hendersonville, TN) barrows in 2 sequential replicate groups of 60 barrows each were studied. These barrows (initial BW of 9.9 ± 0.6 kg) were allotted at random to 1 of 15 dietary treatments: (control [**CNTR**], animal-vegetable blend [**AV**], canola oil [**CANO**], choice white grease source A [**CWGA**], choice white grease source B [**CWGB**], coconut oil [**COCO**], corn oil source A [**CORA**], corn oil source B [**CORB**], fish oil [**FISH**], flaxseed oil [**FLAX**], palm oil [**PALM**], poultry fat [**POUF**], soybean oil source A [**SOYA**], soybean oil source B [**SOYB**], and tallow [**TAL**]).

Pigs were housed individually throughout the 56 d experiment. From d 0 to 28 pigs were housed in a room in which each pen provided 0.50 m^2 of floor space per pig, a nipple drinker, and a stainless steel feeder and wire mesh flooring. From d 28 to 56 pigs were housed in a room in which each pen provided 1.83 m^2 of floor space per pig, a nipple drinker, and a composite feeder and had slatted concrete flooring.

Diets and Feeding

Each experimental diet (Table 1 and 2) included 95% of a corn-soybean meal basal diet plus 5% of either: corn starch (CNTR) or 1 of the previously listed 14 dietary fat sources. Pigs were fed their assigned diets from d 0 to 10 (Table 1) and d 46 to 56 (Table 2). These experimental periods provided a 7 d acclimation to the diet prior to fecal collection. Pigs were fed the same fat source in both experimental periods (from d 0 to 10 and d 46 to 56) and fed a common diet between experimental periods (d 10 to 46; Table 3). Feed allowance was limited from d 0 to 10 to provide a daily energy intake of 2.8 times maintenance (kcal of NE/d = $[(BW^{0.6}) \times 197] \times 2.8$; NRC, 2012). From d 10 to 46 feed was provided ad libitum. Feed allowance was limited from d 46 to 56 to provide a daily energy intake of 3.2 times maintenance (kcal of NE/d = $[(BW^{0.6}) \times 197] \times 3.2$; NRC, 2012). Feed allowances were selected for each phase to maximize intake without having variation of feed intake among pigs. Water was provided *ad libitum* at all times from d 0 to 56. Dietary fat sources were selected to provide a diverse range of degree of unsaturation. The chemical composition and the fatty acid profile of the sources of dietary fat are presented in Tables 4, 5 and 6, respectively.

Representative feed samples were collected at the time of mixing and stored at -20°C for later analysis. Representative dietary fat samples were collected by subsampling from a minimum of 5 different locations. The subsamples of dietary fat were taken from the top, middle, and bottom, as well as, the center and periphery of the container of fat. These samples were then homogenized and stored at -20°C to provide a representative sample for later analysis. Prior to the initiation of the experiment, pigs were fed a common post-weaning nursery diet.

Data and Sample Collection

Pigs were individually weighed on d 0, 7, 10, 22, 46, 53, and 56. Fecal grab samples were collected fresh from 0800 to 1000 h and 1600 to 1800 h on d 7 to 10 and d 53 to 56. Fecal samples were immediately stored at -20°C for later analysis.

Analytical Methods

Feed and fecal samples were homogenized, dried, and then finely ground through a 1 mm screen in a Retsch grinder (model ZMI; Retsch Inc., Newtown, PA). All feed analyses were performed in duplicate unless otherwise noted and repeated when the intraduplicate CV was greater than 1%. Acid hydrolyzed ether extract (method 2003.06; AOAC, 2007) was analyzed using a SoxCap SC 247 hydrolyzer and a Soxtec 255 semiautomatic extractor (FOSS North America, Eden Prairie, MN). Dry matter was determined by drying samples in an oven at 105°C to a constant weight. Gross energy was determined using an isoperibolic bomb calorimeter (model 6200; Parr Instrument Co., Moline, IL). Benzoic acid (6.318 Mcal/kg; Parr Instrument Co.) was used as the standard for calibration and determined to contain 6.319 ± 0.005 Mcal of GE/kg. Titanium dioxide was determined by spectrophotometer (synergy 4; BioTek Instruments Inc., Winooski, VT) according to the method of Leone (1973). Dietary fat sources were analyzed in duplicate by a commercial laboratory (Barrow-Agee Laboratories, Memphis, TN) to determine fatty acid content (method Ce 1-62; AOCS, 2009), FFA (Ca 5a-40; AOCS, 2009), moisture and volatile matter (**MOVM;** Ca 2c-25; AOCS, 2009), insoluble impurities (**INIM**; Ca 3a-46, AOCS, 2009), unsaponifiable matter (**UNS**; Cb-53, AOCS, 2009), and initial peroxide value (**PV**; Cd 8b-90; AOCS, 2009).

Calculations

Basal diet DE was determined using the following equation: $DE_{basal\ diet} = \{DE_{CNTR\ diet} - [DE_{corn\ starch}$ (4.000 Mcal/kg; NRC, 1998) × proportion of corn starch added to the basal diet (5%)]} × 1.05. Energy value for each dietary fat source was determined according to the following equations: $DE_{dietary\ fat}$ (Mcal/kg) = {$DE_{test\ diet}$ – [$DE_{basal\ diet}$ × (1 – proportion of dietary fat in the diet; 5%)]}/proportion of dietary fat in the diet; 5% (Villamide, 1996); $ME_{dietary\ fat}$ (Mcal/kg) = $DE_{deietary\ fat}$ × 98% (van Milgen et al., 2001); $NE_{dietary\ fat}$ (Mcal/kg) = $ME_{dietary\ fat}$ × 88% (van Milgen et al., 2001). Thus, DE values were determined directly, and ME and NE values were determined using constant conversion factors (NRC, 2012). All energy content values are reported on an as-fed basis. Iodine value was calculated from the fatty acid profile using the following equation: IV = [C16:1] × (0.95) + [C18:1] × (0.86) + [C18:2] × (1.732) + [C18:3] × (2.616) + [C20:1] × (0.795) + [C20:2] × (1.57) + [C20:3] × (2.38) + [C20:4] × (3.19) + [C20:5] × (4.01) + [C22:4] × (2.93) + [C22:5] × (3.68) + [C22:6] × (4.64); brackets indicate percentage concentration (Meadus et al., 2010).

Statistical Analysis

These data were analyzed using PROC MIXED (SAS 9.4; SAS Inst. Inc., Cary, NC) with dietary treatment (n = 15) as a fixed effect, replicate (n = 2; 60 barrows each) as a random effect, and pig (n = 120) as the experimental unit. Repeated measures analysis was not utilized, due to the extended period (28 d) of feeding a common diet. The comparison of the relationship between DE, ME, or NE content and the chemical composition of the 14 dietary fat sources were analyzed using PROC CORR and PROC REG. Correlation coefficients are reported as Pearson coefficients. Multivariate regression models were determined via stepwise selection with a significance stay level of 0.15. The dietary fat source multivariate factors included: fatty acid concentrations, SFA, MUFA, PUFA, Omega-3, Omega-6, IV, U:S, FFA, MOVA, INIM, UNS, MIU, and PV. The equation generated from each step of the regression analysis was reported sequentially. For each variable, normal distribution of residuals was tested using PROC UNIVARIATE.

To compare the observed dietary fat energy values herein to the previous equation reported by Powles et al. (1995), the standard error of prediction (prediction error [**PE**]) and prediction bias (**PBias**) were calculated using the following equations: PE = √ [(1/number of dietary fat treatments) × Σ (absolute differences between predicted and observed energy values)^2] and PBias = [(1/number of dietary fat treatments) × Σ (difference between predicted and observed energy values)] (smaller absolute value indicates greater accuracy of the equation; negative value indicates underestimation and positive value indicates overestimation; Lane et al., 2014).

Non-detectable fatty acid concentrations were treated in all statistical analyses as 0. All P-values < 0.05 were considered significant and P-values between 0.05 and 0.10 were considered trends.

RESULTS

Determination of DE, ME and NE content of dietary fat sources

Dietary DE (Table 7) at 13 kg BW (d 7 to 10) was greater when dietary fat was added regardless of source in comparison to barrows fed CNTR (P < 0.001). The least dietary DE and fat DE and estimated dietary ME and NE were observed in pigs fed the CORA-based diet (a moderately unsaturated but high FFA source) and the second least dietary DE and fat DE and estimated dietary ME and NE content were observed in pigs fed the COCO-based diet (the most saturated dietary fat source; P < 0.001). Across all the dietary fat sources tested at 13 kg BW, the average determined dietary fat DE was 8.42 Mcal/kg, ME was 8.26 Mcal/kg, and NE was 7.27 Mcal/kg; the range in DE among the 14 dietary fat sources was 2.14 Mcal/kg (as-fed basis).

Adding dietary fat regardless of source increased the dietary DE (Table 8) at 50 kg BW (d 53 to 56) in comparison to pigs fed CNTR ($P < 0.001$). Dietary DE and fat DE and the estimated dietary ME and NE were the greatest in the highly unsaturated dietary fat sources CANO and FLAX and the lowest DE, ME and NE were observed in AV- and CORA- (two sources with ≥ 7% FFA) based diets ($P < 0.001$). Across the 14 dietary fat sources tested at 50 kg BW, the average determined DE was 8.45 Mcal/kg, ME was 8.28, and NE was 7.29 Mcal/kg; the range in DE among the 14 dietary fat sources was 2.09 Mcal/kg (as-fed basis).

Relationship between dietary fat DE and chemical composition of dietary fat sources

At 13 kg BW, the DE content of dietary fat sources tended to be negatively correlated with Omega-6:Omega-3, FFA, and MOVM content ($P \leq 0.090$; Table 9). At 50 kg BW, the DE content of dietary fat sources was positively correlated with U:S ($P = 0.042$; Table 9). In addition, dietary fat DE tended to be positively correlated with linolenic acid and MUFA:SFA (**C18:3**; $P \leq 0.080$; Table 9).

The DE, ME and NE variation among dietary fat sources at 13 kg BW was largely explained ($R^2 = 0.82$) by a stepwise regression model with intercepts of 9.36, 9.18, and 8.08 Mcal/kg for DE, ME and NE respectively (Table 10). The models suggest that the energy value of dietary fat declines with increased FFA, Omega-6:Omega-3, INIM, and C20:0 content and rises with increasing C16:0 concentration ($P = 0.008$).

The variation in DE, ME and NE in 50 kg pigs was largely explained ($R^2 = 0.81$) by a stepwise regression model with intercepts of 8.35, 8.19, and 7.21 Mcal/kg for DE, ME and NE, respectively; Table 10). The model further suggested that the energy value of dietary fat was increased by increased dietary fat U:S and PUFA content and declined with increased FFA level and behenic acid (**C22:0**) concentration ($P = 0.002$).

DISCUSSION

Impact of U:S on the DE content of dietary fat

Assigning accurate energy values to dietary fat sources not only allows pork producers to appropriately value dietary fat relative to other sources of energy, but also supports differentiation of available fat sources. Previous prediction equations used dietary fat U:S and FFA level as prediction variables (Powles et al., 1995; Rosero et al., 2015). In those equations, dietary fat DE content rose with increased U:S (Powles et al., 1995; NRC, 2012). Unsaturated fatty acids are more soluble when exposed to bile salts, which may increase their incorporation into mixed micelles and facilitate subsequent absorption (Stahly, 1984; Wiseman et al., 1986). In the data reported herein, increased U:S resulted in increased fat DE content at 50 kg BW, but not at 13 kg BW. The difference between the two stages of growth may possibly be due to bile secretion. Increased bile secretion was first proposed by Lloyd et al. (1957) to be the reason that fat digestion increased with pig age. Walker (1959) reported that the bile volume in the gall bladder is minimal in the young pig and is slow to increase over the early stages of growth. A gradual increase of bile salt secretion due to increased age in growing pigs was also reported by Harada et al. (1987). Thus, if bile salt exposure to fatty acids in the small intestine is greater with increased age, then the solubility of unsaturated fatty acids would similarly increase with age. However, the data reported in Powles et al. (1995) does not support this explanation, as they observed that the impact of U:S was greater in 12 kg pigs than in 30 to 90 kg pigs.

Impact of FFA on the DE content of dietary fat

The 14 fat sources evaluated in this experiment provided a wide range of U:S. They did not, however, vary much in FFA levels (≤ 13.4%). Despite this, FFA level was still a significant variable that decreased the energy value of dietary fat sources. For the younger pig, the negative effects of FFA were reduced if the dietary fat source was also highly unsaturated. Powles et al. (1995), using growing pigs, and Rosero et al. (2015) using lactating sows, also reported that saturated FFA lowered DE more than unsaturated FFA. Wiseman (1991) suggested that FFA, compared with esterified fatty acids could suppress bile salt secretion, resulting in a subsequent decrease of fatty acid incorporation into mixed micelles and thus absorption. Unsaturated FFA are more effectively digested than their saturated FFA counterparts due to their being less hydrophobic (Liu et al., 2015) which in turn makes them less reliant on bile salts for emulsification and micelle incorporation (Liu et al., 2015).

The data reported herein agree with Powles et al. (1995) who also concluded that the negative effects of increased FFA is more pronounced in younger than older pigs. However, the magnitude of the impact was greater than that reported by Powles et al. (1995). They suggested that a 10% increase in FFA would reduce the predicted DE by 0.05 Mcal/kg; the data reported herein suggested that the impact was 0.97 Mcal/kg (at 13 kg BW) and 1.95 Mcal/kg (at 50 kg BW). The difference may be due to Powles et al. (1995) testing sources with a greater range of FFA level.

Estimation of the DE, ME and NE content of dietary fat

The NRC (2012) estimate of the DE content of various fat sources is based on Powles et al. (1995). This series of experiments (Wiseman et al., 1990; Powles et al., 1993, 1994) used blends of dietary fat sources that ranged from 0.66 to 15.67 U:S and 0.8 to 81.8% FFA level. However, these experiments included dietary fat sources with primarily 16 or 18 carbon fatty acids. Therefore, the utility of the Powles et al. (1995) equation is unknown for shorter-chain fatty acid sources (i.e. COCO) or longer-chain fatty acid sources (i.e. FISH; NRC, 2012). Powles et al. (1995) related the DE content to chemical composition as follows: DE, kcal/kg = $\{36.898 - [(0.005 \times \text{FFA, g/kg}) - (7.330 \times \exp^{(-0.906 \times \text{U:S})}]\} / 4.184$. Input of the analyzed composition of the 14 dietary fat sources into the Powles et al. (1995) equation generated an average predicted DE of 8.43 Mcal/kg (Table 11 and 12). The average observed DE content of the 14 dietary fat sources herein was 8.42 Mcal/kg at 13 kg BW and 8.45 Mcal/kg at 50 kg BW, respectively. Thus, the PBais of Powles et al. (1995) equation to the observed DE content of dietary fat was minimal. However, at both 13 kg and 50 kg BW, the Powles et al. (1995) equation underestimated the DE content of saturated fat sources COCO and PALM and overestimated the CORA DE content to a large degree. Comparison of the equations generated herein to the Powles et al. (1995) equation is unfair as these equations were fitted to the same dataset to which they are being compared. Thus, validation of these equations in additional experiments is needed to determine if they are more precise than the Powles et al. (1995) equation across the wide range of dietary fat sources used by the swine industry.

The approach herein for estimating dietary fat ME and NE content was modeled after the approach used by NRC (2012). Calculations of ME and NE from DE were based on diets containing 7% vegetable oil using indirect calorimetry (van Milgen et al., 2001). They estimated the conversion of DE to ME to be 98% and ME to NE to be 88%. The ME and NE estimates reported herein assume that the conversion of DE to NE is the same across all fat sources. The NRC (2012) ME and NE estimates are, of course, subject to the same assumption. More studies are required to determine if these relationships are correct, and can be broadly applied to many different fat sources.

A calibration of the NRC (2012) NE estimate of dietary fat was recently completed using a commercial scale growth-assay as reported by Boyd et al. (2015). Employing a diluent (bentonite, fine washed sand), Boyd et al. (2015) determined that the NE for choice white grease was 8.06 Mcal/kg at 38 to 67 kg BW and 8.50 Mcal/kg at 79 to 107 kg BW. These estimates are 10% and 14%, respectively, greater than those reported by the NRC (2012). The Boyd et al. (2015) calibration concluded that the energetic efficiency from DE to NE is greater than currently thought. Clearly, more work is needed to refine the estimation and prediction of dietary fat energy content in both the ME and NE systems.

Conclusion

The chemical composition of dietary fat explained a large degree of the variation observed in the energy content of dietary fat sources. However, the relationship between the energy content of dietary fat and the chemical composition of dietary fat was not the same at 13 kg and 50 kg BW, respectively. The Powles et al. (1995) equation accurately predicted the average DE content of the 14 sources. However, these data have identified 2 potential weaknesses of the equation. The Powles et al. (1995) equation incorrectly predicted the DE content of saturated sources of dietary fat that are composed of fatty acid chain lengths < 16 carbons and underestimated the negative impact of FFA. Further research is needed to validate the equations generated herein when predicting the DE content of diverse fat sources.

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Table 1. Ingredient and nutrient composition (as-fed basis) of experimental diets d 0 to 10

	Dietary treatments[1]														
Item	CNTR	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL
Ingredient, %															
Corn	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90	59.90
Soybean meal (46.5% CP)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Corn Starch	5.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Experimental dietary fat	-	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Whey, permeate	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20	6.20
Plasma (spray-dried)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Limestone	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Monocalcium phosphate (21%)	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Salt	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-lysine HCL	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
DL-methionine	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
L-threonine	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
L-isoleucine	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
L-valine	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Trace mineral premix[2]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Vitamin premix[3]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Santoquin[4]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Analyzed composition															
DM, %	88.12	88.69	88.29	88.76	89.00	88.74	88.60	88.94	88.95	88.85	88.91	88.54	89.52	88.79	88.52
GE, Mcal/kg	3.94	4.21	4.15	4.12	4.17	4.13	4.10	4.18	4.15	4.17	4.20	4.17	4.18	4.21	4.17
Acid hydrolyzed ether extract, %	2.63	8.79	8.62	7.69	8.20	8.01	7.73	8.00	8.46	8.30	8.28	8.18	8.22	8.69	8.47

[1]CNTR = control, AV = animal-vegetable blend (sourced via Darling Pro Ingredients [Wahoo, NE]), CANO = canola oil (sourced via Bulk Apothecary [Aurora, OH]), CWGA = choice white grease source A (sourced via JBS [Marshalltown, IA]), CWGB = choice white grease source B (sourced via JBS [Worthington, MN]), COCO = coconut oil (sourced via Bulk Apothecary), CORA = corn oil source A (sourced via Feed Energy Co. [Des Moines, IA]), CORB = corn oil source B (sourced via Double S Liquid Feed Services [Danville, IL]), FISH = fish oil (sourced via Double S Liquid Feed Services), FLAX = flaxseed oil (sourced via Double S Liquid Feed Services), PALM = palm oil (sourced via Bulk Apothecary), POUF = poultry fat (sourced via Boyer Valley Co. [Denison, IA]), SOYA = soybean oil source A (sourced via Status Foods [Memphis, TN]), SOYB = soybean oil source B (sourced via Bulk Apothecary), TAL = tallow (sourced via Darling Pro Ingredients [Omaha, NE]).

[2]Provided 165 mg Zn (zinc sulfate), 165 mg Fe (iron sulfate), 39 mg Mn (manganese sulfate), 17 mg Cu (copper sulfate), 0.3 mg I (calcium iodate), and 0.3 mg Se (sodium selenite) per kilogram of diet.

[3]Provided 6,614 IU vitamin A, 827 IU vitamin D, 26 IU vitamin E, 2.6 mg vitamin K, 29.8 mg niacin, 16.5 mg pantothenic acid, 5.0 mg riboflavin, and 0.023 mg vitamin B12 per kilogram of diet.

[4]Santoquin Mixture 6 (feed and forage antioxidant; Novus International, St. Charles, MO).

Table 2. Ingredient and nutrient composition (as-fed basis) of experimental diets d 46 to 56

Item	Dietary treatment[1]														
	CNTR	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL
Ingredient, %															
Corn	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41	68.41
Soybean meal (46.5% CP)	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50
Corn Starch	5.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Experimental dietary fat	-	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Limestone	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Monocalcium phosphate (21%)	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L-lysine HCL	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
DL-methionine	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
L-threonine	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Trace mineral premix[2]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Vitamin premix[3]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Santoquin[4]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Analyzed composition															
DM, %	86.66	87.35	87.43	87.68	87.64	87.77	86.79	87.41	87.61	87.83	87.36	88.02	87.07	87.27	87.45
GE, Mcal/kg	3.92	4.07	4.11	4.13	4.09	4.06	4.05	4.10	4.06	4.13	4.10	4.08	4.11	4.09	4.09
Acid hydrolyzed ether extract, %	2.97	9.32	9.56	9.32	9.07	8.94	8.55	8.92	9.14	9.51	9.02	9.20	9.59	9.56	9.21

[1]CNTR = control, AV = animal-vegetable blend (sourced via Darling Pro Ingredients [Wahoo, NE]), CANO = canola oil (sourced via Bulk Apothecary [Aurora, OH]), CWGA = choice white grease source A (sourced via JBS [Marshalltown, IA]), CWGB = choice white grease source B (sourced via JBS [Worthington, MN]), COCO = coconut oil (sourced via Bulk Apothecary), CORA = corn oil source A (sourced via Feed Energy Co. [Des Moines, IA]), CORB = corn oil source B (sourced via Double S Liquid Feed Services [Danville, IL]), FISH = fish oil (sourced via Double S Liquid Feed Services), FLAX = flaxseed oil (sourced via Double S Liquid Feed Services), PALM = palm oil (sourced via Bulk Apothecary), POUF = poultry fat (sourced via Boyer Valley Co. [Denison, IA]), SOYA = soybean oil source A (sourced via Status Foods [Memphis, TN]), SOYB = soybean oil source B (sourced via Bulk Apothecary), TAL = tallow (sourced via Darling Pro Ingredients [Omaha, NE]).

[2]Provided 165 mg Zn (zinc sulfate), 165 mg Fe (iron sulfate), 39 mg Mn (manganese sulfate), 17 mg Cu (copper sulfate), 0.3 mg I (calcium iodate), and 0.3 mg Se (sodium selenite) per kilogram of diet.

[3]Provided 6,614 IU vitamin A, 827 IU vitamin D, 26 IU vitamin E, 2.6 mg vitamin K, 29.8 mg niacin, 16.5 mg pantothenic acid, 5.0 mg riboflavin, and 0.023 mg vitamin B12 per kilogram of diet.

[4]Santoquin Mixture 6 (feed and forage antioxidant; Novus International, St. Charles, MO).

Table 3. Ingredient and nutrient composition (as-fed basis) of experimental diets d 10 to 46[1]

Item	Common diet
Ingredient, %	
Corn	62.34
Soybean meal (46.5% CP)	31.20
Soybean oil	2.50
Limestone	0.98
Monocalcium phosphate (21%)	1.25
Salt	0.60
L-lysine HCL	0.37
DL-methionine	0.16
L-threonine	0.15
Trace mineral premix[2]	0.20
Vitamin premix[3]	0.20
Santoquin[4]	0.06
Analyzed composition	
DM, %	87.14
GE, Mcal/kg	4.02
Acid hydrolyzed ether extract, %	5.60

[1]Feed to all pigs from d 10 to 46 regardless of experiment or treatment assigned.

[2]Provided 165 mg Zn (zinc sulfate), 165 mg Fe (iron sulfate), 39 mg Mn (manganese sulfate), 17 mg Cu (copper sulfate), 0.3 mg I (calcium iodate), and 0.3 mg Se (sodium selenite) per kilogram of diet.

[3]Provided 6,614 IU vitamin A, 827 IU vitamin D, 26 IU vitamin E, 2.6 mg vitamin K, 29.8 mg niacin, 16.5 mg pantothenic acid, 5.0 mg riboflavin, and 0.023 mg vitamin B12 per kilogram of diet.

[4]Santoquin Mixture 6 (feed and forage antioxidant; Novus International, St. Charles, MO).

Table 4. Analyzed chemical composition[1] of dietary fat sources[2]

Item	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL
Free fatty acid, %	7.00	0.03	2.00	2.00	0.08	12.80	0.28	2.80	13.40	0.08	9.20	0.02	0.02	3.60
Moisture and volatile matter, %	0.06	0.02	0.16	0.12	0.02	0.42	0.02	0.34	0.30	0.02	0.32	0.02	0.02	0.06
Insoluble impurities, %	0.02	0.02	0.04	0.02	0.02	0.02	0.14	0.06	0.02	0.02	0.02	0.02	0.02	0.06
Unsaponifiable matter, %	0.41	0.67	0.51	0.39	0.23	0.47	0.39	0.69	0.76	0.17	0.82	0.43	0.35	0.31
MIU,[3] %	0.49	0.71	0.71	0.53	0.27	0.91	0.55	1.09	1.08	0.21	1.16	0.47	0.39	0.43
Initial peroxide value, mEq/kg	0.30	0.80	7.10	9.90	0.20	0.60	0.20	13.80	4.20	1.20	1.00	2.00	0.40	1.30

[1]Analysis via Barrow Agee Laboratories (Memphis, TN).

[2]AV = animal-vegetable blend (sourced via Darling Pro Ingredients [Wahoo, NE]), CANO = canola oil (sourced via Bulk Apothecary [Aurora, OH]), CWGA = choice white grease source A (sourced via JBS [Marshalltown, IA]), CWGB = choice white grease source B (sourced via JBS [Worthington, MN]), COCO = coconut oil (sourced via Bulk Apothecary), CORA = corn oil source A (sourced via Feed Energy Co. [Des Moines, IA]), CORB = corn oil source B (sourced via Double S Liquid Feed Services [Danville, IL]), FISH = fish oil (sourced via Double S Liquid Feed Services), FLAX = flaxseed oil (sourced via Double S Liquid Feed Services), PALM = palm oil (sourced via Bulk Apothecary), POUF = poultry fat (sourced via Boyer Valley Co. [Denison, IA]), SOYA = soybean oil source A (sourced via Status Foods [Memphis, TN]), SOYB = soybean oil source B (sourced via Bulk Apothecary), TAL = tallow (sourced via Darling Pro Ingredients [Omaha, NE]).

[3]MIU = moisture, impurities, and unsaponifiables.

Table 5. Analyzed fatty acid concentrations[1] of dietary fat sources[2]

Item	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL
Fatty acid,[3] %														
C5:0	ND[4]	ND	ND	ND	0.46	ND	ND	ND	ND	ND	ND	ND	ND	ND
C8:0	ND	ND	ND	ND	6.17	ND	ND	ND	ND	ND	ND	ND	ND	ND
C10:0	ND	ND	ND	ND	5.39	ND	ND	ND	ND	ND	ND	ND	ND	ND
C12:0	ND	ND	ND	ND	48.46	ND	ND	0.11	ND	0.19	ND	ND	ND	ND
C14:0	1.63	ND	1.31	1.33	19.75	ND	0.07	9.88	ND	1.03	0.74	0.07	0.07	2.78
C14:1	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.14	ND	ND	0.54
C15:0	0.14	ND	ND	ND	ND	ND	ND	0.73	ND	ND	ND	ND	ND	0.43
C16:0	22.39	4.16	22.47	22.35	9.44	11.92	10.60	20.33	5.20	44.19	18.89	10.79	10.55	24.08
C16:1	2.92	0.20	2.49	2.52	ND	0.09	0.08	11.66	ND	0.15	3.99	0.08	0.08	2.48
C16:2	ND	ND	ND	ND	ND	ND	ND	1.43	ND	ND	ND	ND	ND	ND
C17:0	0.46	ND	0.33	0.33	ND	ND	0.11	0.82	ND	0.10	0.24	0.10	0.10	1.22
C17:1	0.41	0.15	ND	ND	ND	ND	ND	0.25	ND	ND	ND	ND	ND	ND
C18:0	10.45	1.80	11.21	10.97	9.08	1.71	4.30	3.49	3.20	4.47	6.31	3.78	3.78	20.29
C18:1	45.25	63.36	42.15	42.34	1.07	27.20	22.94	9.28	17.00	39.42	34.53	22.00	23.50	41.59
C18:2	13.41	19.28	16.54	16.72	0.06	56.84	53.37	1.15	14.90	9.52	31.78	54.19	52.27	2.81
C18:3	0.62	8.41	0.60	0.60	ND	1.35	7.61	1.34	59.60	0.19	2.06	7.84	8.14	0.31
C18:4	ND	ND	ND	ND	ND	ND	ND	2.01	ND	ND	ND	ND	ND	ND
C19:0	ND	ND	ND	ND	ND	ND	0.11	ND	0.20	ND	ND	ND	ND	ND
C19:1	ND	0.36	ND	ND	ND	ND	ND	0.42	ND	ND	ND	ND	ND	0.11
C20:0	0.15	0.58	0.16	0.16	0.12	0.36	0.31	0.24	ND	0.36	ND	0.28	0.27	0.12
C20:1	0.67	1.10	0.82	0.83	ND	0.26	0.18	0.86	ND	0.13	0.25	0.17	0.17	0.23
C20:2	0.57	ND	0.83	0.84	ND	ND	ND	0.20	ND	ND	0.23	ND	ND	ND
C20:3	ND	ND	0.13	0.13	ND	ND	ND	1.36	ND	ND	0.62	ND	ND	ND
C20:4	0.24	ND	0.36	0.36	ND	ND	ND	1.36	ND	ND	0.62	ND	ND	ND
C20:5	ND	ND	ND	ND	ND	ND	ND	14.32	ND	ND	ND	ND	ND	ND
C22:0	ND	0.31	ND	ND	ND	0.13	0.34	0.16	ND	ND	ND	0.33	0.32	ND
C22:1	ND	ND	ND	ND	ND	ND	ND	0.10	ND	ND	ND	ND	ND	ND
C22:3	ND	ND	ND	ND	ND	ND	ND	0.40	ND	ND	ND	ND	ND	ND
C22:4	ND	ND	0.17	0.16	ND	ND	ND	0.23	ND	ND	ND	ND	ND	ND
C22:5	ND	0.15	ND	ND	ND	0.16	ND	2.81	ND	ND	ND	ND	ND	ND
C22:6	ND	ND	ND	ND	ND	ND	ND	8.22	ND	ND	ND	ND	ND	ND
C24:1	ND	0.13	ND	ND	ND	ND	ND	0.25	ND	ND	ND	ND	ND	ND
Other	0.46	ND	0.36	0.35	ND	ND	ND	7.56	ND	0.23	0.23	0.13	0.14	3.01

[1]Analysis via Barrow Agee Laboratories (Memphis, TN).

[2]AV = animal-vegetable blend (sourced via Darling Pro Ingredients [Wahoo, NE]), CANO = canola oil (sourced via Bulk Apothecary [Aurora, OH]), CWGA = choice white grease source A (sourced via JBS [Marshalltown, IA]), CWGB = choice white grease source B (sourced via JBS [Worthington, MN]), COCO = coconut oil (sourced via Bulk Apothecary), CORA = corn oil source A (sourced via Feed Energy Co. [Des Moines, IA]), CORB = corn oil source B (sourced via Double S Liquid Feed Services [Danville, IL]), FISH = fish oil (sourced via Double S Liquid Feed Services), FLAX = flaxseed oil (sourced via Double S Liquid Feed Services), PALM = palm oil (sourced via Bulk Apothecary), POUF = poultry fat

(sourced via Boyer Valley Co. [Denison, IA]), SOYA = soybean oil source A (sourced via Status Foods [Memphis, TN]), SOYB = soybean oil source B (sourced via Bulk Apothecary), TAL = tallow (sourced via Darling Pro Ingredients [Omaha, NE]).

[3]Valeric acid (C5:0), caproic acid (C8:0), capric acid (C10:0), lauric acid (C12:0), myristic acid (C14:0), myristoleic acid (C14:1), pentadecanoic acid (C15:0), palmitic acid (C16:0), palmitoleic acid (C16:1), hexadecadienoic acid (C16:2), margaric acid (C17:0), margaroleic acid (C17:1), stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), linolenic acid (C18:3), octadecatetraenoic acid (C18:4), nonadecenoic acid (C19:1), arachidic acid (C20:0), gadoleic acid (C20:1), eicosadienoic acid (C20:2), homo-γ linolenic acid (20:3), arachidonic acid (C20:4), eicosapentaenoic acid (C20:5), behenic acid (C22:0), erucic acid (C22:1), docosatrienoic acid (C22:3), docosatetraenoic acid (C22:4), docosapentaenoic acid (C22:5), docosahexaenoic acid (C22:6), nervonic acid (C24:1).

[4]ND = non-detectable.

Table 6. Analyzed fatty acid composition and characteristics[1] of dietary fat sources[2]

Item	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL
Omega-3, %	0.62	8.56	0.73	0.73	0.00	1.51	7.61	29.08	59.60	0.19	2.06	7.84	8.14	0.31
Omega-6, %	14.22	19.28	17.90	18.08	0.06	56.84	53.37	2.94	14.90	9.52	32.63	54.19	52.57	2.81
Omega-6:Omega-3	22.94	2.25	24.52	24.77	NC	37.64	7.10	0.10	0.25	50.11	15.84	6.91	6.46	9.06
MUFA, %	49.46	65.30	45.46	45.69	1.07	27.55	23.20	22.82	17.00	39.70	38.91	22.25	23.75	44.95
PUFA, %	14.84	27.84	18.63	18.81	0.06	58.35	60.98	33.85	74.40	9.71	34.69	62.03	60.71	3.12
SFA, %	35.22	6.85	35.36	35.14	98.87	14.12	15.84	35.76	8.60	50.34	26.18	15.59	15.39	48.92
MUFA:PUFA	3.33	2.35	2.44	2.43	17.83	0.47	0.38	0.67	0.23	4.09	1.12	0.36	0.39	14.41
MUFA:SFA	1.40	9.53	1.28	1.30	0.01	1.95	1.46	0.64	1.97	0.79	1.49	1.43	1.54	0.92
PUFA:SFA	0.42	4.06	0.52	0.54	0.00	4.13	3.85	0.95	8.66	0.19	1.33	3.98	3.94	0.06
IV, (Meadus, 2010)[3] g/ 100 g	68.7	111.5	72.7	73.2	1.0	126.3	132.3	137.4	196.2	51.1	96.5	133.5	132.8	44.0
U:S[4]	1.83	13.60	1.80	1.84	0.01	6.08	5.31	1.58	10.63	0.98	2.81	5.41	5.49	0.98

[1]Analysis via Barrow Agee Laboratories (Memphis, TN).

[2]AV = animal-vegetable blend (sourced via Darling Pro Ingredients [Wahoo, NE]), CANO = canola oil (sourced via Bulk Apothecary [Aurora, OH]), CWGA = choice white grease source A (sourced via JBS [Marshalltown, IA]), CWGB = choice white grease source B (sourced via JBS [Worthington, MN]), COCO = coconut oil (sourced via Bulk Apothecary), CORA = corn oil source A (sourced via Feed Energy Co. [Des Moines, IA]), CORB = corn oil source B (sourced via Double S Liquid Feed Services [Danville, IL]), FISH = fish oil (sourced via Double S Liquid Feed Services), FLAX = flaxseed oil (sourced via Double S Liquid Feed Services), PALM = palm oil (sourced via Bulk Apothecary), POUF = poultry fat (sourced via Boyer Valley Co. [Denison, IA]), SOYA = soybean oil source A (sourced via Status Foods [Memphis, TN]), SOYB = soybean oil source B (sourced via Bulk Apothecary), TAL = tallow (sourced via Darling Pro Ingredients [Omaha, NE]).

[3]Iodine value calculated from fatty acid composition: (IV) = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.795 + [C20:2] × 1.57 + [C20:3] × 2.38 + [C20:4] × 3.19 + [C20:5] × 4.01 + [C22:4] × 2.93 + [C22:5] × 3.68 + [C22:6] × 4.64; brackets indicate percentage concentration (Meadus et al., 2010).

[4]U:S = unsaturated fatty acid concentration to SFA concentration.

Table 7. Determination of DE, ME and NE content of dietary fat sources (Mcal/kg; as-fed basis) based on the apparent total tract digestion of GE at 13 kg BW[1]

	Dietary treatment[2]																
Item	CNTR	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL	SEM	*P*-value
Diet (Mcal/kg)																	
GE	3.94	4.21	4.15	4.12	4.17	4.13	4.10	4.18	4.15	4.17	4.20	4.17	4.18	4.21	4.17	-	-
DE	3.701[f]	3.936[ab]	3.925[abc]	3.912[bcd]	3.929[abc]	3.878[d]	3.841[e]	3.922[abc]	3.930[abc]	3.898[cd]	3.936[ab]	3.929[abc]	3.947[a]	3.946[ab]	3.912[bcd]	0.012	<0.001
Dietary fat (Mcal/kg)																	
DE[3]	-	8.805[abc]	8.587[abc]	8.317[bcd]	8.667[abc]	7.645[d]	6.897[e]	8.522[abc]	8.692[abc]	8.058[cd]	8.807[ab]	8.666[abc]	9.038[a]	8.993[ab]	8.325[bcd]	0.245	<0.001
ME[4]	-	8.629[abc]	8.415[abc]	8.151[bcd]	8.493[abc]	7.493[d]	6.579[e]	8.352[abc]	8.516[abc]	7.896[cd]	8.631[ab]	8.493[abc]	8.856[a]	8.813[ab]	8.160[bcd]	0.240	<0.001
NE[5]	-	7.594[abc]	7.406[abc]	7.173[bcd]	7.474[abc]	6.594[d]	5.948[e]	7.350[abc]	7.496[abc]	6.949[cd]	7.595[ab]	7.474[abc]	7.795[a]	7.756[ab]	7.180[bcd]	0.212	<0.001

[1]Determined via 120 pigs (8 pigs/treatment) with a d 7 BW of 12.3 ± 0.2 kg and a d 10 BW of 13.8 ± 0.4 kg.

[2]Each experimental diet included 95% of a corn-soybean meal basal diet and then 5% of either: corn starch (CNTR), animal-vegetable blend (AV), canola oil (CANO), choice white grease source A (CWGA), choice white grease source B (CWGB), coconut oil (COCO), corn oil source A (CORA), corn oil source B (CORB), fish oil (FISH), flaxseed oil (FLAX), palm oil (PALM), poultry fat (POUF), soybean oil source A (SOYA), soybean oil source B (SOYB), or tallow (TAL).

[3]$DE_{\text{dietary fat}}$ (Mcal/kg) = {$DE_{\text{test diet}}$ – [$DE_{\text{basal diet}}$ (3.68 Mcal/kg) × (1 – proportion of dietary fat in the diet; 5%)]}/proportion of dietary fat in the diet; 5% (Villamide, 1996).

[4]$ME_{\text{dietary fat}}$ (Mcal/kg) = DE × 98% (van Milgen et al., 2001; NRC, 2012).

[5]$NE_{\text{dietary fat}}$ (Mcal/kg) = ME × 88% (van Milgen et al., 2001; NRC, 2012).

Table 8. Determination of DE, ME and NE content of dietary fat sources (Mcal/kg; as-fed basis) based on the apparent total tract digestion of GE at 50 kg BW[1]

	Dietary treatment[2]																*P*-
Item	CNTR	AV	CANO	CWGA	CWGB	COCO	CORA	CORB	FISH	FLAX	PALM	POUF	SOYA	SOYB	TAL	SEM	value
Diet (Mcal/kg)																	
GE	3.89	4.07	4.11	4.13	4.09	4.06	4.05	4.10	4.06	4.13	4.10	4.08	4.11	4.09	4.09	-	-
DE	3.649^{i}	3.814^{h}	3.915^{a}	3.905^{ab}	3.875^{cd}	3.837^{fgh}	3.810^{h}	3.867^{cde}	3.827^{gh}	3.910^{ab}	3.864^{cdef}	3.846^{efg}	3.891^{abc}	3.848^{defg}	3.849^{defg}	0.015	<0.001
Dietary fat (Mcal/kg)																	
DE[3]	-	7.508^{g}	9.526^{a}	9.310^{a}	8.721^{bc}	7.966^{efg}	7.429^{g}	8.553^{bcd}	7.769^{fg}	9.429^{a}	8.500^{bcde}	8.136^{def}	9.049^{ab}	8.181^{cdef}	8.217^{cdef}	0.313	<0.001
ME[4]	-	7.358^{g}	9.336^{a}	9.124^{a}	8.547^{bc}	7.807^{efg}	7.280^{g}	8.382^{bcd}	7.614^{fg}	9.240^{a}	8.330^{bcde}	7.973^{def}	8.868^{ab}	8.017^{cdef}	8.052^{cdef}	0.307	<0.001
NE[5]	-	6.475^{g}	8.215^{a}	8.029^{a}	7.521^{bc}	6.870^{efg}	6.407^{g}	7.376^{bcd}	6.700^{fg}	8.132^{a}	7.330^{bcde}	7.017^{def}	7.804^{ab}	7.055^{cdef}	7.086^{cdef}	0.270	<0.001

[1]Determined via 120 pigs (8 pigs/treatment) with a d 53 BW of 49.1 ± 2.2 kg and a d 56 BW of 51.7 ± 1.7 kg.

[2]Each experimental diet included 95% of a corn-soybean meal basal diet and then 5% of either: corn starch (CNTR), animal-vegetable blend (AV), canola oil (CANO), choice white grease source A (CWGA), choice white grease source B (CWGB), coconut oil (COCO), corn oil source A (CORA), corn oil source B (CORB), fish oil (FISH), flaxseed oil (FLAX), palm oil (PALM), poultry fat (POUF), soybean oil source A (SOYA), soybean oil source B (SOYB), or tallow (TAL).

[3]$DE_{dietary\ fat}$ (Mcal/kg) = {$DE_{test\ diet}$ – [$DE_{basal\ diet}$ (3.62 Mcal/kg) × (1 – proportion of dietary fat in the diet; 5%)]}/proportion of dietary fat in the diet; 5% (Villamide, 1996).

[4]$ME_{dietary\ fat}$ (Mcal/kg) = DE × 98% (van Milgen et al., 2001; NRC, 2012).

[5]$NE_{dietary\ fat}$ (Mcal/kg) = ME × 88% (van Milgen et al., 2001; NRC, 2012).

Table 9. Correlation coefficients (*r*) between dietary fatty acid composition and estimated dietary fat DE content (Mcal/kg)

	Dietary fat DE (Mcal/kg)	
Item	13 kg[1]	50 kg[2]
Fatty acid[3], %		
Linoleic acid (C18:3)	NS[7]	0.489*
Omega-3, %	NS	NS
Omega-6, %	NS	NS
Omega-6:Omega-3	-0.468*	NS
MUFA, %	NS	NS
PUFA, %	NS	NS
SFA, %	NS	NS
MUFA:PUFA	NS	NS
MUFA:SFA	NS	0.483*
PUFA:SFA	NS	NS
IV, (Meadus, 2010)[4] g/ 100 g	NS	NS
U:S[5]	NS	0.549**
Free fatty acid, %	-0.530*	NS
Moisture and volatile matter, %	-0.498*	NS
Insoluble impurities, %	NS	NS
Unsaponifiable matter, %	NS	NS
MIU,[6] %	NS	NS
Initial peroxide value, mEq/kg	NS	NS

*Probability value of obtaining the observed coefficient ($P \leq 0.100 \geq 0.050$).

**Probability value of obtaining the observed coefficient ($P \leq 0.050$).

[1]Determined via 120 pigs (8 pigs/treatment) with a d 7 BW of 12.3 ± 0.2 kg and a d 10 BW of 13.8 ± 0.4 kg.

[2]Determined via 120 pigs (8 pigs/treatment) with a d 53 BW of 49.1 ± 2.2 kg and a d 56 BW of 51.7 ± 1.7 kg.

[3]Other than linoleic acid (C18:3, %), no other dietary fatty acid concentrations were correlated with the DE content of dietary fat ($P \geq 0.101$).

[4]Iodine value calculated from fatty acid composition: (IV) = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.795 + [C20:2] × 1.57 + [C20:3] × 2.38 + [C20:4] × 3.19 + [C20:5] × 4.01 + [C22:4] × 2.93 + [C22:5] × 3.68 + [C22:6] × 4.64; brackets indicate percentage concentration (Meadus et al., 2010).

[5]Unsaturated fatty acid concentration to SFA concentration.

[6]MIU = moisture, impurities, and unsaponifiables.

[7]NS = non-significant ($P > 0.100$).

Table 10. Relationship between dietary fat DE, ME and NE (Mcal/kg; as-fed basis) content and chemical composition[1] of dietary fat source as determined via stepwise regression analysis

Item	Equation	Mean square error	R^2	*P*-value
13 kg[2]				
DE	= 8.671 – [0.063 × (FFA)]	0.258	0.282	0.051
	= 8.967 – [0.073 × (FFA)] – [0.012 × Omega-6:Omega-3]	0.164	0.581	0.008
	= 9.353 – [0.092 × (FFA)] – [0.013 × Omega-6:Omega-3] – [1.290 × (C20:0)]	0.140	0.675	0.008
	= 9.656 – [0.104 × (FFA)] – [0.015 × Omega-6:Omega-3] – [1.389 × (C20:0)] – [5.294 × (INIM)]	0.118	0.755	0.008
	= 9.363 – [0.097 × (FFA)] – [0.016 × Omega-6:Omega-3] – [1.240 × (C20:0)] – [5.054 × (INIM)] + [0.014 × (C16:0)]	0.099	0.815	0.008
ME	= 8.498 – [0.062 × (FFA)]	0.248	0.282	0.051
	= 8.787 – [0.071 × (FFA)] – [0.012 × Omega-6:Omega-3]	0.157	0.581	0.008
	= 9.353 – [0.090 × (FFA)] – [0.013 × Omega-6:Omega-3] – [1.265 × (C20:0)]	0.135	0.675	0.008
	= 9.463 – [0.102 × (FFA)] – [0.015 × Omega-6:Omega-3] – [1.361 × (C20:0)] – [5.188 × (INIM)]	0.113	0.755	0.008
	= 9.176 – [0.095 × (FFA)] – [0.016 × Omega-6:Omega-3] – [1.215 × (C20:0)] – [4.953 × (INIM)] + [0.014 × (C16:0)]	0.096	0.815	0.008
NE	= 7.478 – [0.055 × (FFA)]	0.192	0.282	0.051
	= 7.732 – [0.063 × (FFA)] – [0.010 × Omega-6:Omega-3]	0.122	0.581	0.008
	= 8.066 – [0.079 × (FFA)] – [0.011 × Omega-6:Omega-3] – [1.113 × (C20:0)]	0.104	0.675	0.008
	= 8.327 – [0.089 × (FFA)] – [0.013 × Omega-6:Omega-3] – [1.198 × (C20:0)] – [4.566 × (INIM)]	0.087	0.755	0.008
	= 8.075 – [0.093 × (FFA)] – [0.014 × Omega-6:Omega-3] – [1.070 × (C20:0)] – [4.359 × (INIM)] + [0.013 × (C16:0)]	0.074	0.815	0.008
50 kg[3]				
DE	= 8.050 + [0.096 × U:S]	0.358	0.302	0.042
	= 8.190 + [0.110 × U:S] – [0.052 × (FFA)]	0.319	0.429	0.046
	= 8.439 + [0.189 × U:S] – [0.107 × (FFA)] – [3.232 × (C22:0)]	0.222	0.639	0.014
	= 8.357 + [0.189 × U:S] – [0.195 × (FFA)] – [6.768 × (C22:0)] + [0.024 × (PUFA)]	0.128	0.813	0.003
ME	= 7.889 + [0.094 × U:S]	0.344	0.302	0.042
	= 8.026 + [0.108 × U:S] – [0.052 × (FFA)]	0.307	0.429	0.046
	= 8.270 + [0.185 × U:S] – [0.105 × (FFA)] – [3.168 × (C22:0)]	0.217	0.639	0.014
	= 8.190 + [0.185 × U:S] – [0.191 × (FFA)] – [6.633 × (C22:0)] + [0.023 × (PUFA)]	0.123	0.813	0.003
NE	= 6.942 + [0.083 × U:S]	0.266	0.302	0.042
	= 7.063 + [0.095 × U:S] – [0.045 × (FFA)]	0.237	0.429	0.046
	= 7.277 + [0.163 × U:S] – [0.092 × (FFA)] – [2.787 × (C22:0)]	0.165	0.639	0.014
	= 7.207 + [0.163 × U:S] – [0.168 × (FFA)] – [5.836 × (C22:0)] + [0.021 × (PUFA)]	0.095	0.813	0.003

[1]C16:0 = palmitic acid (%); C20:0 =arachidic acid (%); C22:0 = behenic acid (%); FFA = free fatty acid (%); INIM = insoluble impurities (%); U:S = unsaturated to saturated fatty acid ratio; parenthesis indicate concentration (%).

[2]Determined via 120 pigs (8 pigs/treatment) with a d 7 BW of 12.3 ± 0.2 kg and a d 10 BW of 13.8 ± 0.4 kg.

[3]Determined via 120 pigs (8 pigs/treatment) with a d 53 BW of 49.1 ± 2.2 kg and a d 56 BW of 51.7 ± 1.7 kg.

Table 11. Comparison of predicted versus observed DE (Mcal/kg) values at 13 kg

Item	Observed DE[1]	Powles et al. (1995) predicted DE[2]	Δ DE[3]	Predicted DE[4]	Δ DE
Source					
Animal-vegetable blend	8.81	8.40	-0.41	8.34	-0.46
Canola oil	8.59	8.82	0.23	8.56	-0.02
Choice white grease source A	8.32	8.45	0.13	8.69	0.37
Choice white grease source B	8.67	8.46	-0.21	8.79	0.12
Coconut oil	7.65	7.08	-0.56	7.64	-0.01
Corn oil source A	6.90	8.66	1.76	7.14	0.24
Corn oil source B	8.52	8.80	0.28	8.28	-0.24
Fish oil	8.69	8.37	-0.32	8.78	0.08
Flax oil	8.06	8.66	0.60	8.03	-0.03
Palm oil	8.81	8.10	-0.71	8.62	-0.18
Poultry fat	8.67	8.57	-0.10	8.38	-0.28
Soybean oil source A	9.04	8.81	-0.23	8.95	-0.08
Soybean oil source B	8.99	8.81	-0.18	8.97	-0.02
Tallow	8.33	8.06	-0.27	8.76	0.43
Predication error[5]	-	1.60	-	0.68	-
Prediction bias[6]	-	0.01	-	-0.01	-

[1]Determined via 120 pigs (8 pigs/treatment) with a d 7 BW of 12.3 ± 0.2 kg and a d 10 BW of 13.8 ± 0.4 kg.

[2]DE (kcal/kg) = $[36.898 - (0.005 \times \text{free fatty acid, \%}) - 7.330 \times e^{-0.906 \times \text{unsaturated fatty acid to SFA ratio}})]/0.004184$ (Powles et al., 1995); refer to table 5 and 6 for dietary fatty acid and chemical composition.

[3]Delta DE (Mcal/kg) = predicted DE (Mcal/kg) – observed DE (Mcal/kg).

[4]DE (Mcal/kg) = 9.363 – [0.097 × FFA, %] – [0.016 × Omega-6:Omega-3] – [1.240 × arachidic acid, %] – [5.054 × insoluble impurities, %] + [0.014 × palmitic acid, %]; refer to table 10.

[5]Prediction error = $\sqrt{}$ [(1/number of dietary fat treatments) × Σ (absolute differences between predicted and observed energy values)^2] (Lane et al., 2014).

[6]Prediciton bias = [(1/number of dietary fat treatments) × Σ (difference between predicted and observed energy values)] (smaller absolute value indicates greater accuracy of the equation; negative value indicates underestimation and positive value indicates overestimation; Lane et al., 2014).

Table 12. Comparison of predicted versus observed DE (Mcal/kg) values at 50 kg

Item	Observed DE[1]	Powles et al. (1995) predicted DE[2]	Δ DE[3]	Predicted DE[4]	Δ DE
Source					
Animal-vegetable blend	7.51	8.40	0.89	7.69	0.19
Canola oil	9.53	8.82	-0.71	9.52	-0.01
Choice white grease source A	9.31	8.45	-0.86	8.75	-0.56
Choice white grease source B	8.72	8.46	-0.26	8.77	0.04
Coconut oil	7.97	7.08	-0.89	8.34	0.38
Corn oil source A	7.43	8.66	1.23	7.54	0.11
Corn oil source B	8.55	8.80	0.25	8.50	-0.05
Fish oil	7.77	8.37	0.60	7.85	0.09
Flax oil	9.43	8.66	-0.77	9.54	0.11
Palm oil	8.50	8.10	-0.40	8.76	0.26
Poultry fat	8.14	8.57	0.43	7.93	-0.21
Soybean oil source A	9.05	8.81	-0.24	8.66	-0.39
Soybean oil source B	8.18	8.81	0.63	8.71	0.53
Tallow	8.22	8.06	-0.16	7.92	-0.30
Predication error[5]	-	2.22	-	0.86	-
Prediction bias[6]	-	-0.02	-	0.01	-

[1]Determined via 120 pigs (8 pigs/treatment) with a d 53 BW of 49.1 ± 2.2 kg and a d 56 BW of 51.7 ± 1.7 kg.

[2]DE (kcal/kg) = [36.898 – (0.005 × free fatty acid, %) – 7.330 × $^{e-0.906 \times \text{unsaturated fatty acid to SFA ratio}}$)]/0.004184 (Powles et al., 1995); refer to table 5 and 6 for dietary fatty acid and chemical composition.

[3]Delta DE (Mcal/kg) = predicted DE (Mcal/kg) – observed DE (Mcal/kg).

[4]DE (Mcal/kg) = 8.357 + [0.189 × unsaturated fatty acid:SFA] – [0.195 × FFA, %] – [6.768 × behenic acid, %] + [0.024 × PUFA, %]; refer to table 10.

[5]Prediction error = √ [(1/number of dietary fat treatments) × Σ (absolute differences between predicted and observed energy values)^2] (Lane et al., 2014).

[6]Predicton bias = [(1/number of dietary fat treatments) × Σ (difference between predicted and observed energy values)] (smaller absolute value indicates greater accuracy of the equation; negative value indicates underestimation and positive value indicates overestimation; Lane et al., 2014).