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Effects of changing omega-6 to omega-3 fatty acid ratios in corn–soybean meal-based diet on performance, serum lipid profile and colostrum and milk composition of sows and performance of piglets

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Abstract. This study aimed to test the effects of changing omega-6 to omega-3 fatty acid (FA) ratios in corn–soybean meal-based diet on performance, serum lipid profile and colostrum and milk nutrient contents of lactating sows as well as performance of suckling piglets. In total, 32 multiparous sows (Landrace × Yorkshire) were randomly allocated into one of four dietary treatments with eight replicates per treatment. The treatment diets were fed 7 days before farrowing until weaning. The omega-3 FA used in the experiment was from linseed oil and was coated using a spray-drying method. The dietary treatments consisted of control (CON, corn–soybean meal-based basal diet with omega-6 : omega-3 FA ratios of 25 : 1), and basal diets (CON) containing omega-6: omega-3 FA ratios at 20 : 1, 15 : 1 and 10 : 1 levels. Inclusion of omega-6 and omega-3 FA at different ratios in the feed did not affect ($P > 0.05$) the performance, nutrient digestibility and milk nutrient composition of sows. The concentrations of high-density lipid cholesterol (HDL-C) increased ($P < 0.05$) and the low-density lipid cholesterol (LDL-C) tended to be reduced ($P = 0.08$) at weaning for sows fed 10 : 1 omega 6 : omega-3 ratio diet. The bodyweights (BW) and average daily gains (ADG) of piglets born from sows fed 10 : 1 omega-6 : omega-3 FA diet were greater ($P < 0.05$) at Week 3 and overall respectively. The BW of piglets raised from sows fed all treatment diets were heavier ($P < 0.05$) at Week 4 (weaning) than those in the CON. Positive correlations between dietary omega-6 : omega-3 FA ratio and serum HDL-C concentrations and a negative correlations between dietary omega-6 : omega-3 FA ratio and serum LDL-C concentrations for sows at weaning were observed. In addition, a positive correlation between omega-6 : omega-3 FA in the diet and ADG in piglets was also observed. In conclusion, inclusion of omega-6 : omega-3 FA at different ratios in different proportions did not affect sow performance, while increasing HDL-C and tending to reduce LDL-C in serum lipids. However, the piglets born to sows fed 10 : 1 diets benefitted, with increased BW and ADG.

Additional keywords: lactating sow, linseed oil.

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Introduction

The polyunsaturated fatty acids (PUFA) such as omega-3 and omega-6 FA are considered nutritionally essential but cannot be synthesised by humans and animals. These fatty acids play a pivotal role in metabolism (Gurr *et al*. 2002). The efficiency of elongation and desaturation of the longer-chain derivatives varies among species, although the body has some capacity for synthesis (Martinez-Ramirez *et al*. 2008). The conversion of linoleic acid and α-linolenic acid (ALA) to higher-chain PUFA monologues in humans is also influenced by the consumption of omega-6 and omega-3 FA in the diet (Harnack *et al*. 2009). A study by Kim *et al*. (2007) reported that PUFA supplementation benefitted lactating sows under catabolic conditions by improving lactation performance, fetal growth and neonatal health. The supplementation of omega-3 FA in starter pigs improved the health status of weaned pigs that are faced with different stressors due to their effects on the immune system (Liu *et al*. 2003; Li *et al*. 2014). Despite the potential benefits of omega-3 FA, the commercial diets of pigs that are based on cereals and protein contain negligible amount of omega-3 PUFA (Rooke *et al*. 2001*a*). Therefore, the use of omega-3 FA has gained considerable attention in recent years due to potential health benefits for animals and consumers of pork products.

Previous studies indicated that providing fish oil-based omega-3 FA to rats, or plant-based omega-3 FA to pigs can improve performance and animal health (Joshi *et al*. 2003; Kim *et al*. 2007; Upadhaya *et al*. 2015, 2017). In swine, linseed and its by-products are often used as a source of omega-3 FA because ALA is readily available in linseed. In addition, ALA is less susceptible to oxidation than is fish oil. Therefore, omega-3 FA found in linseed and its by-products have fewer problems with quality or storage than do fish-oil FA. Inclusion of oils rich in PUFA (certain vegetable oils or fish oil) in sow diets modified fatty acid composition of colostrum and plasma as well as in the tissues of offspring (Fritsche *et al*. 1993; Lauridsen and Danielsen 2004; Sampels *et al*. 2011), ultimately exerting a positive influence on the health and growth of the piglet. Other studies have found that the presence of omega-3 FA in the diet did not affect embryonic survival percentage and the litter size at birth (Perez Rigau *et al*. 1995; Estienne *et al*. 2006). The failure of dietary omega-3 FA to affect reproductive performance of sows may be due to use of diets high in omega-6 FA, which might have interfered or masked the potential benefits of including omega-3 FA. The decrease in omega-6 : omega-3 FA ratios in the diet may lead to increased ability in animals to convert 18 carbon ALA into its longer-chain FA derivatives such as eicosapentaenoic acid and docosahexaenoic acids that are biologically active compounds. Thus, the balance of omega-6 : omega-3 FA ratio in the diet may be more important rather than the absolute amount of these FA in the diet (Eastwood *et al*. 2014). Previous studies in sows that used plant oil-based omega 6 : omega- 3 FA ratios ranging among 3 : 1, 9 : 1 and 13 : 1 (Yao *et al*. 2012) and 1 : 1, 5 : 1 and 9 : 1 (Eastwood *et al*. 2014) showed that altering the omega-6 : omega-3 FA ratio in the diet had some beneficial effects on sow feed intake, piglet growth or in the composition of milk and colostrum. Reducing the inclusion of omega-6 FA in relation to omega-3 FA in the diet may increase the cost of the feed in commercial swine production. A better method was sought to enhance the effective delivery of linseed oil as a source of omega-3 FA to appropriate sites in the body for absorption as well as to reduce the inclusion level of omega-3 FA for optimising feed costs. Therefore, we used encapsulated or coated omega-3 FA, unlike other studies, because coating helps the inner core component to pass safely through the stomach without being dissociated. We hypothesised that using a coated omega-3 FA may enhance the effective delivery of this FA to appropriate sites for absorption as well as compensate the higher inclusion of omega-3 FA in relation to omega-6 FA in the diets, thereby reducing feed costs. A study by Bosi *et al*. (1999) showed that when organic acids were protected, absorption of dietary acids in the stomach was effectively retarded, thereby allowing more effective delivery of the acids to the distal ileum, caecum and colon of piglets.

Thus, the objective of the current study was to evaluate the effects of changing the omega-6 to omega-3 FA ratios (25 : 1, 20 : 1, 15 : 1 and 10 : 1) in corn–soybean meal-based diets on the performance, serum lipid profile, colostrum and milk composition of lactating sows and performance of suckling piglets.

Materials and methods

The experimental protocol used in the present study was approved by the Animal Care and Use Committee of Dankook University.

Source of tested product

The tested product used in the present study was obtained from a commercial company (Morningbio Co. Ltd, Cheonan, Korea). Linseed oil, used as a source of omega-3 FA, was protected using a spray-drying method as described by Tonon *et al*. (2011). According to the information provided by the suppliers, the linolenic acid (omega 3) and linoleic acid (omega 6) contents in the linseed were 56.71% and 14.79% respectively.

Experimental design, animals, housing and diets

In total, 32 multiparous sows (Landrace × Yorkshire) were randomly allocated to one of four dietary treatments, with eight replicates per treatment. The dietary treatments were based on feeding a control corn–soybean-meal diet (CON) with an omega-6 : omega-3 FA ratio of 25 : 1, or diets in which tallow was replaced with protected linseed oil (LO) to reduce omega-6 : omega-3 FA ratios. The dietary treatments included the following: (1) CON (corn–soybean meal-based basal diet; omega-6 : omega-3 ratio of 25 : 1 (25 : 1); (2) CON + LO to provide omega-6 : omega-3 FA ratio of 20 : 1 (20 : 1); (3) CON + LO to provide omega-6 : omega-3 FA ratio of 15 : 1 (15:1); (4) CON + LO to provide omega-6 : omega-3 FA ratio of 10 : 1 (10 : 1). Diets were formulated to meet or exceed nutrient requirements for pigs (NRC 2012). The experimental feeding started 7 days before farrowing. Sows were fed 2.5 kg/day of their respective experimental gestation diets until farrowing. On the day of parturition, the sows were not offered feed. After farrowing, sows were fed their respective experimental lactation diets until weaning at Day 28 (Table 1). All diets were provided in mash form twice daily. The analysed values for the fatty acid profile of experimental diets are presented in Table 2. Water was provided on an *ad libitum* basis. All pregnant sows were housed in a temperature-controlled room in groups of eight in pens measuring 5.20 × 4.30 m, with a concrete floor and wood shavings, until Week 15 of gestation. On Day 105 of gestation, all sows were moved into farrowing crates (2.10 m × 1.80 m), where they stayed until weaning. The temperature in the farrowing house was maintained at a minimum of 20°C. Supplemental heat was provided for pigs by using heat lamps. Detection of return to oestrus was conducted twice per day from weaning onward, at 0800 hours and 1600 hours every day. A sow was considered to be in oestrus when exhibiting a standing response induced by a back-pressure test when in the presence of a boar.

Chemical analysis, sampling and measurements

All feed samples were analysed for dry matter (930.15), crude protein (990.03), crude fat (920.39), phosphorus (965.17) and calcium (984.01), using procedures from the AOAC International (2000). The gross energy was determined using bomb calorimeter (Mode 1241; Parr Instrument Co., Moline, IL, USA). The lysine content was analysed by Sykam Amino Acid Analyzer (Laserchrom HPLC Laboratories Ltd Inc., Rochester, UK) after acid hydrolysis for 24 h in 6 M HCl (AOAC International 2000). The FA content in the experimental diets was the mean of two replicates. The FA composition of the diets was determined according to the modified method of Kim *et al*. (2003). Lipid from the diets was extracted with hexane–isopropanol (3 : 2, v : v). The extracted lipids were mixed with 0.5 mL of toluene and 2 mL of 5% KOH–MeOH, and heated at 70°C for 8 min; then 2 mL of 14% BF3–MeOH

Table 1. Composition of sow gestation and lactation experimental diets (DM basis)
Dietary treatments are based on varying ratios of omega-6 : omega-3 fatty acids, using coated linseed oil including 25 : 1 (control) 20 : 1, 15 : 1 and 10 : 1

Item	Dietary treatment (omega-6 : omega-3 FA ratio)							
	Gestation diet				Lactation diet			
	25 : 1	20 : 1	15 : 1	10 : 1	25 : 1	20 : 1	15 : 1	10 : 1
	Ingredients (g/kg)							
Corn	633.8	623.1	603.7	547.6	541.2	541.2	535.3	505.5
Wheat bran	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3
Soybean meal	137.9	137.9	141.2	151.5	231.2	231.2	231.2	231.2
Rapeseed meal	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
Tallow	11.13	11.13	0	0	32.8	21.0	5.6	0.0
Molasses	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
Oat	17.8	17.8	17.8	17.8	–	–	–	–
Lysine	1.25	1.25	1.25	1.25	–	–	–	–
Limestone	9.35	9.35	9.35	9.35	6.68	6.68	6.68	6.68
Di-calcium phosphate	15.39	15.39	15.39	15.39	14.60	14.60	14.60	14.60
Choline	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Sodium chloride	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67
Vitamin premix[A]	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
Mineral premix[B]	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Coated linseed oil	–	10.68	37.83	83.66	–	11.84	33.20	68.53
	Calculated value							
ME (MJ/kg)	13.60	13.60	13.96	14.93	14.03	14.03	14.04	14.92
	Analysed value (g/kg)							
Crude fat	56.2	53.9	55.3	76.5	48.3	56.4	56.1	90.3
Crude protein	141	141	140	142	174	176	175	176
Lysine	7.6	7.6	7.6	7.6	9.0	9.2	9.1	9.2
Methionine	2.4	2.4	2.4	2.3	2.7	2.8	2.8	2.8
Met + Cys	6.3	6.3	6.2	6.1	7.0	7.0	7.0	7.0
Calcium	8.7	8.7	8.7	8.7	7.8	7.7	7.8	7.8
Phosphorus	6.4	6.4	6.3	6.3	6.5	6.5	6.5	6.4

[A]Provided per kilogram of complete diet: vitamin A, 12 100 IU; vitamin D_3, 2000 IU; vitamin E, 48 IU; vitamin K_3, 1.5 mg; riboflavin, 6 mg; niacin, 40 mg; d-pantothenic, 17 mg; biotin, 0.2 mg; folic acid, 2 mg; choline, 166 mg; vitamin B_6, 2 mg; and vitamin B_{12}, 28 µg.
[B]Provided per kilogram of complete diet: iron (as $FeSO_4 \cdot 7H_2O$), 90 mg; copper (as $CuSO_4 \cdot 5H_2O$), 15 mg; zinc (as $ZnSO_4$), 50 mg; manganese (as MnO_2), 54 mg; iodine (as KI), 0.99 mg; and selenium (as $Na_2SeO_3 \cdot 5H_2O$), 0.25 mg.

Table 2. Analysed fatty acid (FA) profile for experimental diets (g/kg of diet)
Means represent the average FA profile of duplicate samples of each diet. MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids

Item	Dietary treatment (omega-6 : omega-3 FA ratio)							
	Gestation diet				Lactation diet			
	25 : 1	20 : 1	15 : 1	10 : 1	25 : 1	20 : 1	15 : 1	10 : 1
C 16 : 0 (palmitic)	7.98	8.12	8.44	9.23	8.82	9.08	9.56	10.56
C 16 : 1 (palmitoleic)	0.20	0.21	0.26	0.42	0.12	0.17	0.27	0.51
C 18 : 0 (stearic)	1.56	1.61	1.81	2.47	1.31	1.54	1.93	2.91
C 18 : 1 (oleic)	17.14	16.82	16.29	15.60	19.35	19.16	18.48	17.40
C 18 : 2 (linoleic)	26.30	26.34	26.17	25.06	30.95	30.55	29.83	27.65
C 18 : 3 (linolenic)	0.98	1.24	1.72	2.47	1.13	1.36	1.94	2.91
C 20 : 0 (arachidic)	–	–	0.01	0.03	–	–	0.01	0.03
SFA	9.54	9.73	10.26	11.73	10.13	10.62	11.50	13.50
Total MUFA	17.34	17.03	16.55	16.02	19.47	19.33	18.75	17.91
Total PUFA	27.28	27.58	27.89	27.53	32.08	31.91	31.77	30.56
Omega-3 PUFA	0.98	1.24	1.72	2.47	1.13	1.36	1.94	2.91
Omega-6 PUFA	26.30	26.34	26.17	25.06	30.95	30.55	29.83	27.65
Omega-6 : omega-3 ratio	26.84	21.24	15.22	10.15	27.39	22.46	15.38	9.50

were added to the mixture, and heated at 70°C for 2 min. The FA methyl esters were extracted with 3 mL of 5% NaCl and 1 mL of hexane. Samples were analysed for total FA, using a gas chromatograph (GC-2010 Plus, Shimadzu, Kyoto, Japan) associated with a flame ionisation detector. The FA methyl esters were separated using Omegawax-320 fused silica capillary column (30 m × 0.32 mm × 0.25 μm; Supelco Inc., Bellefonte, PA, USA), with 1.2 mL/min of helium flow. The oven temperature was increased from 180°C to 204°C, at the rate of 1.5°C/min. Temperatures of the injector and detector were 260°C and 280°C respectively. The peaks for FA were identified by comparing with the retention time and peak area with each respective FA standard. The content of each FA was expressed as a percentage of the sum of all of the FA analysed.

Sow bodyweight and backfat thickness were measured on Day 2 and Day 28 postpartum. Feed intake was recorded daily for the 4 weeks of lactation and bodyweight was measured after farrowing and at weaning. Piglets were weighed at 1, 2, 3 and 4 weeks of age and were weaned at 4 weeks of age. The backfat of sows was measured 6 cm off the midline at the 10th rib, using a real-time ultrasound instrument (Piglot 105, SFK Technology, Herlev, Denmark). After farrowing, numbers of piglets born alive, numbers of weaned pigs, bodyweights (BW) of piglets at birth and weaning were recorded. Heat lamps provided additional heat to newborn piglets for 72 h after farrowing. Piglets were not offered creep feed. Sow milk was the only feed available to the piglets during lactation. At weaning, the sows were relocated to a mating room, with the piglets remaining in the pen for 1 week (weaning pigs).

Chromium oxide (Cr_2O_3, 2 g/kg) was added to the sow diets as an indigestible marker for a period of 7 days before faecal collection to determine apparent nutrient digestibility. Fresh faecal samples from all sows (n = 8) per treatment were collected by rectal massage after farrowing and at weaning, to determine the apparent digestibility of dry matter (DM), nitrogen (N) and energy. All faecal samples were stored immediately at −20°C until analysis. Faecal samples were dried at 70°C for 72 h and finely ground to pass through a 1-mm screen. The procedures utilised for the determination of DM and N digestibility were conducted in accordance with the methods established by the AOAC International (2000). Chromium concentrations were determined via UV absorption spectrophotometry (UV-1201; Shimadzu, Kyoto, Japan) and the apparent total-tract digestibility of DM and N were calculated using indirect methods described by Williams *et al*. (1962). The gross energy was determined by measuring the heat of combustion in the samples using a Parr 6100 oxygen bomb calorimeter (Parr instrument Co., Moline, IL, USA).

Five sows per treatment were randomly chosen to evaluate colostrum and milk nutrient composition. Colostrum was sampled at Day 1 of farrowing, and milk was sampled on Day 20 by hand-milking. The collected samples were stored in opaque plastic bottles at −20°C until analysed for lactose, fat, protein and solids not fat (SNF) using Micro Scan (FOSS Electric A/s, Hillerod, Denmark).

Blood samples were collected from the jugular vein of sows (n = 8 per treatment) into vacuum tubes with no additive to obtain serum. The serum samples were centrifuged (2000*g*) for 30 min at 4°C. The total cholesterol, high-density lipoprotein (HDL) cholesterol, low-density lipoprotein (LDL) cholesterol, and triglyceride concentrations in serum samples were determined with an auto analyzer (Automatic Biochemical Analyzer, RA-1000; Bayer Corporation, Tarrytown, NY, USA), using colourimetric methods.

Statistical analyses

All data in this experiment were analysed in accordance with a completely randomised design, using the general linear modelling procedure (SAS Institute Inc., Cary, NC, USA). The individual sow or litter of piglets was used as the experimental unit. Differences among the treatment means were determined by using the Tukey's multiple-comparison test, with $P < 0.05$ indicating significance and $P < 0.10$ indicating trends. Pearson's correlation coefficients and probabilities were generated using the correlation procedures of SAS, (SAS Institute, Inc. Cary, NC, USA).

Results

The nutrient composition of diets differing in omega-6 : omega-3 FA ratio is shown in Table 1. The tallow was replaced by coated LO in the 20 : 1 diet. For 15 : 1 and 10 : 1 diets, tallow and corn were replaced mainly by coated LO. The calculated metabolisable energy (ME) values for 10 : 1 diets were greater at 14.92 MJ/kg than they were for corresponding diets for other omega-6 : omega-3 FA ratios ranging from 13.6 to 14 MJ/kg for gestation diets and ~14 MJ/kg for lactation diets. The 10 : 1 diet had higher concentrations of crude fat (Table 1) as well as stearic acid (Table 2) than did the other diets.

Performance of sows and piglets

Altering the dietary omega-6 : omega-3 FA ratio did not affect BW, loss in BW or changes in backfat thickness for sows from farrowing to weaning. The weights of piglets born from sows fed the CON diet were lighter ($P < 0.05$) at Week 3 than were piglet weights from sows fed the 10 : 1 diet. Lowering the ratios of omega-6 : omega-3 FA fed to sows generally increased piglet weights at weaning (Week 4) and average daily gain (ADG) at Weeks 1–3 compared with weights and gains for piglets from sows fed the CON diet. Piglet weights and ADG at Week 4 were significantly ($P < 0.05$) greater from sows fed the 10 : 1 diet than weights and gains for piglets from sows fed the CON diet. Likewise, the overall gains were significantly ($P = 0.01$) greater for piglets from sows fed 10 : 1 diet than were gains for piglets from sows fed the CON diet (Table 3).

Apparent total-tract digestibility of nutrients

The apparent total-tract digestibility of nutrients in sows fed diets with different omega-6 : omega- 3 ratios were not significantly ($P > 0.05$) different from that in sows fed the CON diet, after farrowing and at weaning (Table 4).

Nutrient composition in colostrum and milk from lactating sows

Altering the omega-6 : omega-3 FA content of sow diets did not significantly ($P > 0.05$) affect concentrations of lactose, protein, fat and SNF in colostrum and milk compared with sows fed the CON diet (Table 5).

Table 3. Effects of varying dietary ratios of omega-6 : omega-3 fatty acids (FA) on performance of sows and their piglets
CON, basal diet (25 : 1, omega-6 : omega-3 FA ratio). Bodyweight loss was measured for the period from after farrowing to weaning. Backfat thickness loss was measured from after farrowing to weaning

Item	Dietary treatment (omega-6 : omega-3 FA ratio)				s.e.m.	*P*-value
	CON	20 : 1	15 : 1	10 : 1		
Parity	2.5	2.4	2.5	2.6	0.17	0.776
Litter						
Number of live pigs (head)	10	10	10	10	0.4	0.974
Weaned pigs (head)	9.4	9.6	9.6	9.5	0.5	0.983
Bodyweight (kg)						
After farrowing	190.0	188.7	190.3	189.9	1.90	0.930
Weaning	177.1	174.8	176.7	175.6	2.13	0.873
Bodyweight loss	12.95	13.87	13.68	14.28	0.81	0.704
Average daily feed intake (kg)						
Lactation	6.89	6.91	6.94	6.95	0.035	0.614
Backfat thickness (mm)						
After farrowing	19.0	19.9	19.1	20.4	0.62	0.374
Weaning	16.5	17.4	16.8	18.3	0.59	0.186
Backfat thickness loss	2.5	2.5	2.4	2.1	0.19	0.452
Oestrus interval (days)	4.5	4.3	4.3	4.3	0.18	0.708
Piglets						
Piglet survival (%)	94.1	98.9	98.4	97.6	1.87	0.287
Bodyweight (kg)						
Birthweight	1.42	1.41	1.41	1.43	0.08	0.997
1 week of age	2.48	2.57	2.57	2.6	0.09	0.798
2 weeks of age	3.94	4.14	4.13	4.21	0.084	0.148
3 weeks of age	5.50b	5.83ab	5.83ab	5.94a	0.087	0.010
4 weeks of age	7.26b	7.62a	7.65a	7.81a	0.085	0.001
Average daily gain (g)						
1 week of age	150.4b	164.8ab	166.0ab	167.3a	4.25	0.035
2 weeks of age	206.1b	225.4a	223.0a	229.8a	2.17	<0.001
3 weeks of age	224.0b	241.6a	242.9a	247.1a	3.92	0.002
4 weeks of age	250.1b	254.5b	259.1ab	267.5a	3.27	0.008
Overall	225.5b	235.5ab	236.8ab	242.1a	2.97	0.006

Table 4. Effects of varying dietary ratios of omega-6 : omega-3 fatty acids (FA) on apparent total-tract nutrient digestibility of sows
CON, basal diet (25 : 1, omega-6 : omega-3 FA ratio)

Item	Dietary treatment (omega-6 : omega-3 FA ratio)				s.e.m.	*P*-value
	CON	20 : 1	15 : 1	10 : 1		
After farrowing						
Dry matter (%)	73.77	74.36	74.56	75.04	0.86	0.78
Nitrogen (%)	70.64	71.34	71.66	72.02	0.57	0.39
Energy (%)	73.06	73.17	73.63	73.85	0.56	0.72
Weaning						
Dry matter (%)	72.82	72.91	73.47	73.95	0.82	0.74
Nitrogen (%)	73.99	74.70	74.69	74.93	0.58	0.69
Energy (%)	73.57	73.59	73.84	74.03	0.65	0.95

Serum lipid profiles in lactating sows

In general, concentrations of cholesterol, HDL-C, LDL-C and triglycerides were not affected ($P \geq 0.19$) by dietary treatment. However, the feeding of 10 : 1 diet to sows significantly ($P < 0.05$) increased HDL-C concentrations at weaning and tended to decrease ($P = 0.08$) LDL-C concentrations at weaning as compared with corresponding serum lipid concentrations for sows fed the CON diet (Table 5).

Correlation coefficients

A positive correlation between omega-6 : omega-3 FA ratio in the diet and ADG in piglets was observed (Table 6). In addition, a positive correlation between omega-6 : omega-3 FA ratio in the diet and serum HDL-C concentration was observed and a negative correlation between omega-6 : omega-3 FA ratio in the diet and serum LDL-C concentration was observed in sows at weaning (Table 7). The association between the stearic acid concentrations as a result of altering the omega-6 : omega-3 FA ratio in the diet and HDL-C concentrations for sows at weaning was assumed.

Discussion

In pigs, supplementing the maternal diet with omega-3 fatty acids improves pre- and post-natal survival (Rooke *et al*. 2001*b*;

Table 5. Composition of colostrum, milk and serum lipid profiles in lactating sows fed diets differing in omega-6 : omega-3 fatty acid (FA) ratios

CON, basal diet (25 : 1, omega-6 : omega-3 FA ratio); HDL-C, high-density lipid cholesterol; LDL-C, low-density lipid cholesterol

Item	Dietary treatment (omega-6 : omega-3 FA ratio)				s.e.m.	*P*-value
	CON	20 : 1	15 : 1	10 : 1		
Colostrum (%)						
Lactose (%)	3.19	3.23	3.21	3.22	0.03	0.825
Protein (%)	14.23	14.33	14.25	14.44	0.23	0.916
Fat (%)	5.69	5.72	5.81	5.84	0.05	0.167
Solids not fat (%)	24.02	24.16	24.14	24.57	0.37	0.736
Milk (%)						
Lactose (%)	4.91	4.89	4.96	4.92	0.08	0.944
Protein (%)	5.35	5.25	5.43	5.55	0.12	0.387
Fat (%)	7.02	7.10	7.26	7.26	0.15	0.573
Solids not fat (%)	18.51	18.74	18.81	19.01	0.28	0.636
After farrowing (serum lipid profile, mg/dL)						
Cholesterol	88.38	85.75	84.38	81.5	2.78	0.358
HDL-C	38.75	41.13	42.25	43.75	1.60	0.19
LDL-C	44.0	41.63	41.38	40.5	1.29	0.287
Triglycerides	46.75	46.13	44.13	44.75	2.46	0.867
Weaning (serum lipid profile, mg/dL)						
Cholesterol	82.8	78.1	79.5	77.4	3.14	0.638
HDL-C	37.9^{b}	40.0^{ab}	41.6^{ab}	44.0^{a}	1.36	0.029
LDL-C	42.5	42.0	39.6	38.8	1.13	0.079
Triglycerides	43.9	43.9	43.5	42.5	2.50	0.976

Table 6. Pearson correlation coefficients between omega-6 : omega-3 fatty acid (FA) ratio in the diet and average daily gain (ADG) of piglets at 1, 2, 3 and 4 weeks of age

*, $P < 0.05$. **, $P < 0.01$

Variable	Omega-6 : omega-3 FA ratio	ADG1	ADG2	ADG3	ADG4
ADG1	0.370*	1			
ADG2	0.598**	0.358*	1		
ADG3	0.562**	0.295	0.135	1	
ADG4	0.571**	0.367*	0.216	0.339	1

Table 7. Pearson correlation coefficients between omega-6 : omega-3 fatty acid (FA) ratio in the diet and serum lipid profile of sows at weaning

HDL-C, high-density lipid cholesterol; LDL-C, low-density lipid cholesterol. **, $P < 0.01$. ***, $P < 0.001$

Variable	Omega-6 : omega-3 FA ratio	Cholesterol	Triglyceride	HDL-C	LDL-C
Cholesterol	–0.207	1			
Triglycerides	–0.069	–0.039	1		
HDL-C	0.449**	0.219	0.070	1	
LDL-C	–0.464**	–0.087	0.349	–0.700***	1

Spencer *et al.* 2004). At farrowing, sows undergo many metabolic changes associated with milk production, which can put them into a negative energy balance. The lipolytic activity and the ability of the animal to mobilise body fat can be affected by altering FA composition in adipose tissue. The addition of omega-3 FA to sow diets may alter lipid metabolism, and may also affect feed intake. However, feed intake was not affected by omega-3 FA in the present study. Moreover, the body-fat mobilisation may possibly be affected by the ratio of omega-3 FA in relation to omega-6 FA in the diet, as high amounts of omega-6 FA in the diet may interfere with the potential benefits of omega-3 FA (Eastwood *et al.* 2016).

In the present study, we aimed to evaluate the effects of omega-3 FA supplementation to produce different omega-6 : omega-3 FA ratios in corn–soybean meal-based diets, on the performance of sows and their suckling piglets. The omega 6 : omega-3 FA ratio in the CON diet was reduced by replacing the tallow as well as some corn in the diet with coated LO to formulate the treatment diets. There is a concern in the present study that possible treatment effects for sows fed the 10 : 1 omega-6 : omega-3 FA ratio may be due to greater amounts of ME and a greater fat content than in all other diets (Table 1). However, 20 : 1 diets having the amount of ME and total fats similar to those of the CON diets (25 : 1) also showed an increased BW at 4 weeks of age and an increased ADG at 1, 2 and 3 weeks of age, indicating that altering omega-6 : omega-3 FA ratio might have led to a positive response, especially in piglets.

The present study found that altering the omega-6 : omega-3 FA ratios for sows did not affect BW loss or changes in backfat thickness from farrowing to weaning, indicating that reducing omega-6 : omega-3 FA ratios from 25 : 1 to 10 : 1 did not affect performance. The daily feed intake and apparent total-tract digestibility of nutrients in the current study also remained unaffected by the dietary omega-6 : omega-3 FA ratio. Previous work by Yao *et al.* (2012) also found that feed intake, BW loss and backfat thickness were not affected in sows fed plant-oil diets where omega-6 : omega-3 FA ratio ranged from 3 : 1 to 13 : 1. Eastwood *et al.* (2014, 2016) indicated that BW and backfat thickness were unaffected by dietary omega-6 : omega-3 FA ratios at the onset of their feeding trials. However, values for these traits were greater at Day 110 or 1 week after farrowing and at weaning for sows fed plant oil-based diets with 1 : 1 and 5 : 1 omega-6 : omega-3 FA ratios than they were for sows fed control (8 : 1) and 9 : 1 omega-6 : omega-3 FA ratio diets. The increase is backfat thickness over time, as explained by these authors, is probably due to long-term dietary PUFA manipulation, leading to changes in leptin expression and, in turn, to changes in FA esterification. Whereas dietary omega-6 : omega-3 FA ratio did not affect feed intake in the present study, Eastwood *et al.* (2016) reported greater intakes in sows fed the control or 5 : 1 omega-6 : omega-3 FA ratio diets, with intermediate and lowest intakes found in sows fed 1 : 1 and 9 : 1 omega-6 : omega-3 FA ratio diets respectively. The differences in feed intake were assumed by Eastwood *et al.* (2016) to be due to metabolic signals that trigger satiety receptors or due to palatability differences among diets. These reported inconsistent results may be due to the variation in the composition of diets, dietary omega-6 : omega-3 FA ratios, length of time of feeding, or physiological status of sows.

The apparent total-tract digestibility of nutrients was unaffected in sows by changing the omega-6 : omega-3 FA ratios in the diet. Previous studies have indicated that omega-3 FA content has no effect on nutrient digestibility in finishing pigs (Cho and Kim 2013; Upadhaya *et al*. 2017). Martin *et al*. (2008) reported the negative effects of omega-3 FA derived from LO on nutrient digestibility in dairy cows, which were most likely due to an imbalance in the omega-6 : omega-3 FA ratio. The specific and relative role of dietary PUFA ratio on nutrient digestibility in sows is unclear because there has been very limited research in the past regarding the effects of dietary omega-6 : omega-3 FA ratios on nutrient digestion in gestating and lactating sows.

Milk nutrient composition can undergo variations as a result of modifications in the diet of the sow. The composition of milk FA is strongly associated with the types of fat added into the feed (Gulati *et al*. 2002; Cattaneo *et al*. 2006). The fatty acid composition of maternal fat reserves has been reported to influence milk composition, which, in turn, may have a consequence for piglet growth and survival (Rooke *et al*. 2001*c*). Milk and colostrum nutrient composition for lactose, protein, fat and SNF in colostrum and milk in the present study were not affected by altering the omega-6 : omega-3 FA ratios in the diet. The effects of varied omega-6 : omega-3 FA ratios on milk nutrient composition such as protein, lactose and SNF have not been reported; thus, comparisons could not be made with other studies. However, a significant increase in omega-3 FA has been observed in the colostrum and milk of sows fed 9 : 1 and 13 : 1 omega-6 : omega-3 FA ratio diets (Yao *et al*. 2012). We did not assess the FA profile of colostrum and milk in the current experiment, which is a limitation of the present study.

Dietary fat saturation plays an influential role in the modulation of plasma cholesterol concentrations and determination of risks associated with coronary heart diseases (Temme *et al*. 1996). Omega-3 FA-enriched diets are known for their efficacy to reduce blood cholesterol concentrations, thereby reducing the risk of arthritis, cardiovascular and neurodegenerative diseases (Lands 2012). In the present study, the total cholesterol, HDL-C, LDL-C or triglyceride concentrations were not affected by dietary treatments during farrowing. However, at weaning, the HDL-C concentrations significantly increased and the LDL-C concentrations tended to decrease in sows fed the 10 : 1 diet, indicating that altering the FA ratio by lowering omega-6 FA in sow diets can positively affect serum lipid profiles. Other studies have also reported that replacement of dietary carbohydrate with PUFA from LO in humans is associated with a greater increase in HDL-C (the health-promoting cholesterol) and reduced concentrations of LDL-C (Pan *et al*. 2009; Siri-Tarino 2011; Avelino *et al*. 2015). Altering the omega-6 : omega-3 FA ratios in the diet from 25 : 1 to 10 : 1 showed a positive correlation between the treatment diet and serum HDL-C concentrations and a negative correlation between the treatment diet and serum LDL-C concentrations for sows at weaning. The reduction in dietary omega-6 : omega-3 FA ratio led to an increase in stearic acid, as can been seen in analysed FA profile of treatment diets. We assumed that there may be an association between stearic acid and serum HDL-C concentrations in sows. The greater HDL-C and lower LDL-C concentrations indicate that feeding the 10 : 1 diet may positively affect the sow health. The HDL-C concentrations in the serum of sows at weaning increased despite the increase in stearic acid in the 10 : 1 diet versus the 25 : 1 diets.

In the present study, piglet weights from birth to Week 2 were unaffected by dietary treatment; however, at Week 3, the weight of piglets was significantly higher in those born to sows consuming 10 : 1 diet and, in Week 4, the weights were improved in all treatments compared with the CON. The ADG of piglets was higher from Week 1 through to Week 4 and, overall, in piglets born to sows consuming the 10 : 1 diet. Previous studies on fish oil-based omega-3 FA supplementation also showed that the BW and ADG of suckling piglets at 21 days postnatal were increased when 7% fish oil was fed to late-gestation and lactation sows (Rooke *et al*. 2000; Xiao *et al*. 2008). In another study, supplementing sows with a 5 : 1 omega-6 : omega-3 FA ratio diets significantly increased piglet ADG during lactation compared with sows fed 8 : 1 omega-6 : omega-3 FA ratio control diets low in PUFA (Eastwood *et al*. 2014). Although supplementation of the coated omega-3 FA in the present study did not have an impact on sow performance, it positively affected piglet performance, despite the high omega-6 : omega-3 FA ratio (10 : 1) as compared with the low omega-6 : omega-3 FA ratio (5 : l) in the previous study by Eastwood *et al*. (2014). The possible reason for improved BW and ADG in piglets born to sows fed the 10 : 1 diet may be due to altering the dietary omega-6 : omega-3 FA ratio as well as a higher fat content than in other diets. Previous studies have also demonstrated that piglets consuming dam's milk with a high fat content was beneficial for their growth. For instance, Rooke *et al*. (2001*a*) reported that piglets born to sows fed tuna oil as a source of omega-3 FA had an active suckling behaviour immediately after birth, which contributed to enhanced growth during lactation. Mc Pherson *et al*. (2004) reported that maternal dietary nutrients during the last days of gestation can positively affect piglet weight, which may be due to increase in transfer of energy and nutrients to the piglets *in utero* (Gabler *et al*. 2009). In addition, Farmer and Petit (2009) indicated that sows transfer the omega FA to their offspring via milk.

Conclusions

In conclusion, altering omega-6 : omega-3 FA ratios (20 : 1, 15 : 1 and 10 : 1) in sow diets using plant-based LO did not affect reproductive performance or nutrient composition in colostrum and milk nutrients. However, HDL-C concentrations were significantly increased in sows fed 10 : 1 omega-6 : omega-3 FA ratio diet, relative to sows fed the control diet. A positive correlation between HDL-C concentration in sow at weaning and dietary omega-6 : omega-3 FA ratio was observed. The concentrations of LDL-C tended to decrease in sows fed 10 : 1 omega-6 : omega-3 FA ratio diets at weaning. The reason for no effect from altering dietary omega-6 : omega-3 FA ratios on sow performance is not clear. Thus, further investigation on the assessment of systemic FA in the tissue and blood is suggested. The BW and ADG were higher in piglets born to sows fed 10 : 1 omega-6 : omega-3 FA diets than control diets. A positive correlation was seen between omega-6 : omega-3 FA ratios in the diet and ADG of piglets at 1, 2, 3 and 4 weeks of age.

Conflicts of interest

The authors declare no conflicts of interest.

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References

AOAC International (2000) 'Official methods of analysis of AOAC International.' 16th edn. (AOAC International: Gaithersburg, MD)

Avelino AP, Oliveira GM, Ferreira CC, Luiz RR, Rosa G (2015) Additive effect of linseed oil supplementation on the lipid profiles of older adults. *Journal of Clinical Intervention in Aging* **10**, 1679–1685.

Bosi P, Jung HJ, Han IK, Perini S, Cacciavillani JA, Casini L, Creston D, Gremokolini C, Mattuzzi S (1999) Effects of dietary buffering characteristics and protected and unprotected acids on piglet growth, digestibility and characteristics of gut content. *Asian-Australasian Journal of Animal Sciences* **12**, 1104–1110. doi:10.5713/ajas.1999.1104

Cattaneo D, Dell'Orto V, Varisco G, Agazzi A, Savoini G (2006) Enrichment in n-3 fatty acids of goats' colostrum and milk by maternal fish oil supplementation. *Small Ruminant Research* **64**, 22–29. doi:10.1016/j.smallrumres.2005.03.013

Cho JH, Kim IH (2013) Effects of dietary microencapsulated n-3 fatty acid supplementation on growth performance, nutrient digestibility, blood profiles, carcass characteristics and fatty acid compositions in finishing pigs. *Asian Journal of Animal and Veterinary Advances* **8**, 703–712. doi:10.3923/ajava.2013.703.712

Eastwood L, Leterme P, Beaulieu AD (2014) Changing the omega-6 to omega-3 fatty acid ratio in sow diets alters serum, colostrum, and milk fatty acid profiles, but has minimal impact on reproductive performance. *Journal of Animal Science* **92**, 5567–5582. doi:10.2527/jas.2014-7836

Eastwood L, Leterme P, Beaulieu AD (2016) Body fat mobilization during lactation in high producing sows fed varied omega-6 to omega-3 fatty acid ratios. *Canadian Journal of Animal Science* **96**, 69–78. doi:10.1139/cjas-2015-0082

Estienne MJ, Harper AF, Estienne CE (2006) Effects of dietary supplementation with omega-3 polyunsaturated fatty acids on some reproductive characteristics in gilts. *Reproductive Biology* **6**, 231–241.

Farmer C, Petit HV (2009) Effects of dietary supplementation with different forms of flax in late-gestation and lactation on fatty acid profiles in sows and their piglets. *Journal of Animal Science* **87**, 2600–2613. doi:10.2527/jas.2008-1588

Fritsche KL, Huang SC, Cassity NA (1993) Enrichment of omega-3 fatty acids in suckling pigs by maternal dietary fish oil supplementation. *Journal of Animal Science* **71**, 1841–1847. doi:10.2527/1993.7171841x

Gabler NK, Radcliffe JS, Spencer JD, Webel DM, Spurlock ME (2009) Feeding long-chain n-3 polyunsaturated fatty acids during gestation increases intestinal glucose absorption potentially via the acute activation of AMPK. *The Journal of Nutritional Biochemistry* **20**, 17–25. doi:10.1016/j.jnutbio.2007.11.009

Gulati SK, May C, Wynn PC, Scott TW (2002) Milk fat enriched in n-3 fatty acids. *Animal Feed Science and Technology* **98**, 143–152. doi:10.1016/S0377-8401(02)00021-4

Gurr MI, Harwood JL, Frayn KN (2002) 'Lipid biochemistry: an introduction.' 5th edn. (Wiley-Blackwell: Oxford, UK)

Harnack K, Andersen G, Somoza V (2009) Quantitation of alpha-linolenic acid elongation to eicosapentaenoic and docosahexaenoic acid as affected by the ratio of n6/n3 fatty acids. *Nutrition & Metabolism* **6**, 8. doi:10.1186/1743-7075-6-8

Joshi S, Rao S, Golwilkar A, Patwardhan M, Bhonde R (2003) Fish oil supplementation of rats during pregnancy reduces adult disease risks in their offspring. *The Journal of Nutrition* **133**, 3170–3174. doi:10.1093/jn/133.10.3170

Kim YJ, Lee KW, Lee S, Kim H, Lee HJ (2003) The production of high-purity conjugated linoleic acid (CLA) using two-step urea-inclusion crystallization and hydrophilic arginine-CLA complex. *Journal of Food Science* **68**, 1948–1951. doi:10.1111/j.1365-2621.2003.tb06999.x

Kim SW, Mateo RD, Yin YL, Wu G (2007) Functional amino acids and fatty acids for enhancing production performance of sows and piglets. *Asian-Australasian Journal of Animal Sciences* **20**, 295–306. doi:10.5713/ajas.2007.295

Lands B (2012) Consequences of essential fatty acids. *Nutrients* **4**, 1338–1357. doi:10.3390/nu4091338

Lauridsen C, Danielsen V (2004) Lactational dietary fat levels and sources influence milk composition and performance of sows and their progeny. *Livestock Production Science* **91**, 95–105. doi:10.1016/j.livprodsci.2004.07.014

Li Q, Brendemuhl JH, Jeong KC, Badinga L (2014) Effects of dietary omega-3 fatty acid on growth and immune response of weanling pigs. *Journal of Animal Science and Technology* **56**, 7. doi:10.1186/2055-0391-56-7

Liu YL, Li DF, Gong LM, Yi GF, Gaines AM, Carroll JA (2003) Effects of fish oil supplementation on the performance and immunological, adrenal, and somatotropic responses of weaned pigs after an *Escherichia coli* lipopolysaccharide challenge. *Journal of Animal Science* **81**, 2758–2765. doi:10.2527/2003.81112758x

Martin C, Rouel J, Jouany JP, Doreau M, Chilliard Y (2008) Methane output and diet digestibility in response to feeding dairy cows crude linseed, extruded linseed, or linseed oil. *Journal of Animal Science* **86**, 2642–2650. doi:10.2527/jas.2007-0774

Martinez-Ramirez HR, Holub BJ, de Lange CFM (2008) The efficiency of retention and conversion of a-linolenic acid to other omega-3 fatty acids in the whole body of growing gilts is reduced over time. *Journal of Animal Science* **86**(E-Suppl 2), 238.

McPherson RL, Ji F, Wu G, Blanton JR, Kim SW (2004) Growth and compositional changes of fetal tissues in pigs. *Journal of Animal Science* **82**, 2534–2540. doi:10.2527/2004.8292534x

National Research Council (2012) 'Nutrient requirements of swine.' 11th edn. (National Academic Press: Washington, DC)

Pan A, Yu D, Demark-Wahnefried W, Franco OH, Lin X (2009) Meta-analysis of the effects of flaxseed interventions on blood lipids. *The American Journal of Clinical Nutrition* **90**, 288–297. doi:10.3945/ajcn.2009.27469

Perez Rigau A, Lindemann MD, Kornegay ET, Harper AF, Watkins BA (1995) Role of dietary lipids on fetal tissue fatty acid composition and fetal survival in swine at 42 days of gestation. *Journal of Animal Science* **73**, 1372–1380. doi:10.2527/1995.7351372x

Rooke JA, Shanks M, Edwards SA (2000) Effect of offering maize, linseed or tuna oils throughout pregnancy and lactation on sow and piglet tissue composition and piglet performance. *Animal Science* **71**, 289–299. doi:10.1017/S1357729800055132

Rooke JA, Sinclair AG, Edwards SA (2001*a*) Feeding tuna oil to the sow at different times during pregnancy has different effects on piglet long-chain polyunsaturated fatty acid composition at birth and subsequent growth. *British Journal of Nutrition* **86**, 21–30. doi:10.1079/BJN2001363

Rooke JA, Sinclair AG, Ewen M (2001*b*) Changes in piglet tissue composition at birth in response to increasing maternal intake of long-chain n-3 polyunsaturated fatty acids are non-linear. *British Journal of Nutrition* **86**, 461–470. doi:10.1079/BJN2001422

Rooke JA, Sinclair AG, Edwards SA, Cordoba R, Pkiyach S, Penny PC, Penny P, Finch AM, Horgan GW (2001*c*) The effect of feeding salmon oil to sows throughout pregnancy on pre-weaning mortality of piglets. *Animal Science* **73**, 489–500. doi:10.1017/S135772980005846X

Sampels S, Pickova J, Högberg A, Neil M (2011) Fatty acid transfer from sow to piglet differs for different polyunsaturated fatty acids (PUFA). *Physiological Research* **60**, 113–124.

Siri-Tarino PW (2011) Effects of diet on high-density lipoprotein cholesterol. *Current Atherosclerosis Reports* **13**, 453–460. doi:10.1007/s11883-011-0207-y

Spencer JD, Wilson L, Webel SK, Moser RC, Webel DM (2004) Effect of feeding protected n-3 polyunsaturated fatty acids (Fertilium®329) on litter size in gilts. *Journal of Animal Science* **82**, 81. [Abstr.]

Temme HM, Mensink RP, Hornstra G (1996) Comparison of the effects of diets enriched in lauric, palmitic, or oleic acids on serum lipids and lipoproteins in healthy women and men. *The American Journal of Clinical Nutrition* **63**, 897–903. doi:10.1093/ajcn/63.6.897

Tonon RV, Grosso CRF, Hubinger D (2011) Influence of emulsion composition and inlet air temperature on the microencapsulation of flaxseed oil by spray drying. *Food Research International* **44**, 282–289. doi:10.1016/j.foodres.2010.10.018

Upadhaya SD, Kim JC, Mullan BP, Pluske JR, Kim IH (2015) Vitamin E and omega-3 fatty acids independently attenuate plasma concentrations of pro-inflammatory cytokines and prostaglandin E3 in *Escherichia coli* lipopolysaccharide-challenged growing–finishing pigs. *Journal of Animal Science* **93**, 2926–2934. doi:10.2527/jas.2014-8330

Upadhaya SD, Li TS, Kim IH (2017) Effects of protected omega-3 fatty acid derived from linseed oil and vitamin E on growth performance, apparent digestibility, blood characteristics and meat quality of finishing pigs. *Animal Production Science* **57**, 1085–1090. doi:10.1071/AN15641

Williams CH, David DJ, Lismaa O (1962) The determination of chromic oxide in faeces samples by atomic absorption spectrophotometry. *The Journal of Agricultural Science* **59**, 381–385. doi:10.1017/S002185960001546X

Xiao CL, Tian CZ, Huang FR, Luo J, Peng J (2008) Effects of feeding sows fish oil on fatty acids in milk and growth performance of piglets. *Chinese Journal of Animal Nutrition* **20**, 8–15.

Yao W, Li J, Wang JJ, Zhou W, Wang Q, Zhu R, Wang F, Thacker P (2012) Effects of dietary ratios of n-6 to n-3 polyunsaturated fatty acids on immunoglobulins, cytokines, fatty acid composition, and performance of lactating sows and suckling piglets. *Journal of Animal Science and Biotechnology* **3**, 43–50. doi:10.1186/2049-1891-3-43