Fat encapsulation enhances dietary nutrients utilization and growth performance of nursery pigs[1]

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ABSTRACT: Encapsulation of fat may facilitate digestion and absorption of fat in nursery pigs. Two experiments were conducted to evaluate 1) effects of encapsulation of palm oil (**PO**) and coconut oil (**CO**) on growth performance, feed intake, feed efficiency, and blood parameters, and 2) effects of encapsulation of PO and CO on apparent total tract digestibility (**ATTD**) of nutrients, and the activity of digestive enzymes in nursery pigs. In Exp. 1, 540 pigs (28 d of age, 8.23 ± 0.22 kg BW) were allotted to five treatments based on a randomized complete block design (as-fed basis). Pigs were fed basal diets with five different fat sources: 6.0% soybean oil (**SBO**), 6.0% PO, 6.0% PO from encapsulated fat (**EPO**), 6.0% CO, and 6.0% CO from encapsulated fat (**ECO**), respectively, with six pens per treatment and 18 pigs per pen for a 4-wk feeding trial. Dried casein and whey powder used for encapsulation were included at identical levels in all diets. Pigs fed EPO had increased ($P < 0.05$) ADG during days 0 to 14 and overall compared to pigs fed SBO and PO, whereas ADG of pigs fed ECO was not different from pigs fed EPO and CO. There were no differences in ADFI among treatments. Pigs fed EPO had increased G:F ($P < 0.05$) during days 0 to 14 compared to SBO, PO, and CO. Serum urea nitrogen concentrations in pigs fed EPO, CO, and ECO were lower ($P < 0.05$) than that of pigs fed SBO and PO. In Exp. 2, 30 pigs (28 d of age, 8.13 ± 0.10 kg BW) were housed individually ($n = 6$ per treatment) and allotted to five treatments as described in Exp.1. Pigs were fed ad libitum for 4 wk to measure ATTD of diets weekly and digestive enzyme activity at week 4. Pigs fed EPO, CO, and ECO had increased ($P < 0.05$) ATTD of DM and GE compared to pigs fed SBO and PO. Pigs fed SBO had reduced ($P < 0.05$) ATTD of CP compared to other treatments. Pigs fed PO had reduced ($P < 0.05$) ATTD of ether extracts (**EE**) compared to other treatments. Pigs fed PO had greater ($P < 0.05$) trypsin activity in the pancreas than pigs fed SBO and CO. Pigs fed PO tended to have lower ($P = 0.073$) pancreatic lipase activity compared to other treatments, whereas dietary treatments had no effect on pancreatic amylase activity. In conclusion, this study indicates that encapsulation of PO improved growth performance and ATTD of diets in nursery pigs, whereas the limited effects of encapsulated CO were likely due to the high digestibility of the medium-chain triglycerides abundant in CO.

Key words: blood parameters, digestive enzyme activity, fat encapsulation, growth performance, nursery pigs, nutrients digestibility

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INTRODUCTION

The abrupt change from a high-fat (50% of the total calories in the milk), liquid diet to a low-fat (4% fat), dry diet at weaning is one of the sources of nutritional stress in piglets (Klobasa

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et al., 1987; Oliver et al., 2005). Appropriate fat supplementation can improve ADG and feed efficiency of nursery pigs (Cera et al., 1989; Li et al., 1990; Mendoza and van Heugten, 2014), but the low digestibility of saturated fat in nursery diets may lead to negative effects on growth performance (Cera et al., 1988, 1989; Jung et al., 2003). Improving the digestibility of saturated fat in nursery diets is needed, because the activity of lipase in piglets is relatively low at weaning, and almost 300 times lower than at 8 wk of age (Corring et al., 1978). Palm oil (**PO**) and coconut oil (**CO**) are readily available and reasonably priced in Asia, and they both contain a high percentage of saturated fatty acids. Encapsulation of fat by milk proteins may have a positive effect on digestion and absorption of highly saturated fat sources for nursery pigs (Xing et al., 2004), because of decreased particle size and enhanced emulsification of fat. Consequently, one would expect that encapsulated PO and CO may increase digestibility of fat in nursery pigs. Therefore, this study investigated the effects of encapsulation of PO and CO on growth performance, nutrient use, blood parameters, and digestive enzyme activities in nursery pigs. It is hypothesized that encapsulation would improve the digestibility of PO and CO and in turn improve growth performance and nutrient use in nursery pigs. We also measured impacts of treatments on serum urea nitrogen (**SUN**), expecting improved nitrogen deposition in pigs fed encapsulated fat. The digestive enzyme activities were measured to evaluate the adaption of digestive enzymes to dietary changes related to different fat sources.

MATERIALS AND METHODS

All animal care and handling procedures were approved by the Institutional Animal Care and Use Committee of South China Agricultural University, and consistent with the *Guide for the Care and Use of Agricultural Animals in Research and Teaching* (FASS, 2010).

Fat Sources

Five different fat sources were used in this study. Soybean oil (**SBO**, grade 4, Cargill Grain & Oilseeds Ltd., Dongguan, China) was used as a control. Palm oil (Yihai Kerry Grain & Oil Ltd., Guangzhou, China) and **CO** (refined CO, Guangzhou Yide Biological Technology Co., Ltd., Guangzhou, China) were used as sources of fat with high proportions of saturated fatty acids. The same sources of PO and CO were encapsulated (**EPO** and **ECO**, respectively) using dried casein and whey powder to test effects of encapsulation of saturated fat on growth performance, feed intake, feed efficiency, blood parameters, apparent total tract digestibility (ATTD) of nutrients, and the activity of digestive enzymes in nursery pigs. The encapsulation process required an addition of 8.5% dried casein and 11.5% whey powder to PO and CO.

The encapsulated fat contained 80% PO or CO, 8.5% dried casein, and 11.5% whey powder. Ingredients were blended together in liquid form (60 °C for 30 min), pasteurized at 65 °C for 30 min, and homogenized (pressure 250kg/cm^2) before spray drying (EYELA Spray Drier SD-1000, Tokyo Rikakikai Co., LTD., Tokyo, Japan). The inlet temperature of the drier was 180 °C and the outlet temperature was 80 °C. The size of the dried fat powder particles was in the range of 30 to 50 μm. Fatty acid composition of the supplemental fat sources was analyzed by gas chromatograph (GC-2010 Pro, SHIMADZU Corporation, Kyoto, Japan) using a capillary column (100 m × 250 μm × 0.2 μm; DB-1, Agilent technologies, Santa Clara, CA). The fat samples of encapsulated PO and encapsulated CO were extracted with petroleum ether at 65 °C for 1 h using an automatic fat extractor (SZC-D, Shanghai Xianjian Instrument Co. Ltd., Shanghai, China). Samples were methylated according to the method of Ecker et al. (2012). The GC conditions were: injector, 270 °C; detector, 280 °C; injection volume was 0.5 μL, and N_2 as carrier gas; and temperature program, 100 °C for 5 min, followed by a programed increase of 4 °C/min to 240 °C and then it was held constant for 20 min. Peaks were identified by comparing the retention times with those of the corresponding standards (Lot No. XA22213V, Supelco, Bellefonte, PA). The fatty acids content of samples is given in Table 1.

Experiment 1: Growth Performance and Blood Parameters

Five hundred forty pigs (Landrace × Yorkshire × Duroc) were weaned at approximately 21 d of age and allotted to five treatments based on BW and sex at 28 d of age (8.23 ± 0.22 kg BW) in a randomized complete block design (six pens per treatment). Treatments were: 1) basal diet with 6.0% SBO, 2) basal diet with 6.0% PO, 3) basal diet with 6.0% PO from EPO, 4) basal diet with 6.0% CO, and 5) basal diet with 6.0% CO from ECO. The SBO diet was used as the control. All diets contained 17% CP formulated to meet the Lys requirements of 7

Table 1. Analyzed fatty acid composition of the fat sources used in Exp. 1 and 2 [% (wt/wt) of total fatty acids][1]

Fatty acid, %	Soybean oil	Palm oil	Encapsulated palm oil[2]	Coconut oil	Encapsulated coconut oil[2]
C6:0	0.05	0.09	0.11	0.58	0.49
C8:0	ND[3]	0.74	0.71	6.8	5.41
C10:0	0.1	0.74	0.72	5.67	4.60
C12:0	0.05	5.21	4.66	36.23	35.71
C14:0	0.11	3.23	3.01	14.06	14.75
C16:0	11.96	51.23	51.87	18.88	19.08
C16:1 (cis-9)	0.16	0.15	0.17	ND	ND
C17:0	0.11	0.15	0.14	ND	ND
C18:0	4.02	5.33	5.22	3.26	3.89
C18:1 (cis-9)	23.83	25.89	26.65	11.26	12.33
C18:2 (all-cis-9, 12)	52.71	5.83	5.41	2.34	3.36
C18:3 (all-cis-9,12,15)	4.81	ND	ND	ND	ND
C20:0	0.42	0.35	0.39	0.12	0.17
C20:1 (cis-11)	0.28	0.09	0.13	0.09	0.09
C22:0	0.41	0.49	0.48	ND	ND
Other[4]	0.98	0.48	0.33	0.71	0.12

[1]Means of two replicates.

[2]The tested fat samples of encapsulated palm oil (80% palm oil) and encapsulated coconut oil (80% coconut oil) were extracted with petroleum ether first at 65 °C for 1 h using an automatic fat extractor and analyzed accordingly.

[3]ND = not detected.

[4]Comprised of 0.5% or less of each of the following fatty acids including: C14:1 (cis-9), C15:0, C17:1 (cis-10), C18:3 (all-cis-6, 9, 12), C24:0.

to 11 kg pigs (NRC, 2012; Table 2). Concentrations of Met, Thr, Trp were kept constant at ratios suggested by Chung and Baker (1992). In the basal diet, feedstuffs with low fat content were used to reduce the effects of other fat sources on the results of this study. All diets were fed in a pellet form.

Pigs were housed 18 pigs per pen, using 30 pens, in an environmentally controlled nursery house with raised slatted flooring. Initial temperature in the nursery was 28 °C and was lowered by 1 °C each week. Pigs were allowed ad libitum access to feed and water throughout the experiment. Body weights and feed consumption were measured on days 14 and 28. The number of the pigs with symptoms of diarrhea (mild diarrhea, severe diarrhea, and watery diarrhea) was recorded by the attending veterinarian who was unaware of treatment assignment.

$$\text{Diarrhea incidence} = \frac{SN}{NP \times ND}$$

SN, total number of piglets with symptoms every day of experimental period. *NP*, numbers of piglets in each replicate. *ND*, numbers of days during the experimental period.

Blood samples were collected from one pig (representative of the average weight) of each pen via anterior vena cava puncture on days 14 and 28; blood samples were taken from the same pig at both times. The blood samples (10 mL) were held at room temperature for 1 h before being centrifuged at 3,000 g for 15 min to obtain the serum sample, and then stored at −80 °C until assay. The concentration of total cholesterol, total triglyceride (**TG**), high-density lipoprotein cholesterol (**HDL-C**), low-density lipoprotein cholesterol (**LDL-C**), and SUN in serum was analyzed in a spectrofluorometer (Multiskan GO 1510, Thermo Fisher Scientific, Osakeyhtiö, Finland) using commercially available kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, Jiangsu, P.R. China).

Experiment 2: Nutrient ATTD and Digestive Enzyme Activity

Thirty pigs (Yorkshire × Landrace × Duroc) were weaned at approximately 21 d of age and allotted to five treatments based on BW and sex at 28 d of age (8.13 ± 0.10 kg BW) in a randomized complete block design (six pigs per treatment, three males and three females). Five dietary treatments were the same as in Exp. 1 with additional 3.5 kg/T chromic oxide added as an inert marker. Pigs were housed individually for 4 wk in stainless steel cages (0.8 × 1.4 × 1.2 m, W × L × H) designed for digestion trials in a temperature-controlled room (initial temperature in the nursery was 28 °C and was lowered by 1 °C each week). Exp. 1 and 2 were carried out simultaneously. Pigs were allowed ad libitum access to feed and water throughout the experiment.

Table 2. Composition and nutrient content of experimental diets (as-fed basis)

	Treatments				
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]
Ingredient, %					
Corn	62.30	62.30	62.30	62.30	62.30
Soybean meal, 43% CP	4.20	4.20	4.20	4.20	4.20
Whey powder, 3.8% CP	5.86	5.86	5.00	5.86	5.00
Fish meal, 62% CP	3.50	3.50	3.50	3.50	3.50
Soybean oil	6.00				
Palm oil		6.00			
Encapsulated palm oil			7.50		
Coconut oil				6.00	
Encapsulated coconut oil					7.50
Fermented soybean meal	12.00	12.00	12.00	12.00	12.00
Dried casein	0.64	0.64		0.64	
Acidifier	0.60	0.60	0.60	0.60	0.60
Dicalcium phosphate	0.45	0.45	0.45	0.45	0.45
Calcium formate	1.34	1.34	1.34	1.34	1.34
Salt	0.30	0.30	0.30	0.30	0.30
L-lysine HCL (78.8%)	0.68	0.68	0.68	0.68	0.68
DL-methionine (99%)	0.37	0.37	0.37	0.37	0.37
L-threonine (99%)	0.31	0.31	0.31	0.31	0.31
L-tryptophan (98.5%)	0.08	0.08	0.08	0.08	0.08
Vitamin premix[2]	0.05	0.05	0.05	0.05	0.05
Trace element premix[3]	0.10	0.10	0.10	0.10	0.10
Choline chloride 50%	0.16	0.16	0.16	0.16	0.16
Chromic oxide[4]	0.35	0.35	0.35	0.35	0.35
Others[5]	0.71	0.71	0.71	0.71	0.71
Total	100.00	100.00	100.00	100.00	100.00
Calculated nutrient composition[6]					
DE, Mcal/kg	3.63	3.59	3.60	3.61	3.61
CP, %	17.01	17.01	17.01	17.01	17.01
Ether extract, %	8.43	8.43	8.43	8.43	8.43
Ash, %	3.52	3.52	3.52	3.52	3.52
Ca, %	0.70	0.70	0.70	0.70	0.70
P, %	0.48	0.48	0.48	0.48	0.48
AP, %	0.33	0.33	0.33	0.33	0.33
Total lysine, %	1.40	1.40	1.40	1.40	1.40
SID Lys, %	1.25	1.25	1.25	1.25	1.25
SID Met + Cys, %	0.76	0.76	0.76	0.76	0.76
SID Thr, %	0.81	0.81	0.81	0.81	0.81
SID Trp, %	0.23	0.23	0.23	0.23	0.23
Analyzed composition					
GE, Mcal/kg	4.40	4.58	4.50	4.47	4.52
DE,[7] Mcal/kg	3.75	3.64	3.97	3.97	4.04
CP, %	17.05	17.12	17.20	16.92	17.24
Ether extract, %	8.01	8.68	8.40	8.09	8.52

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil and encapsulated coconut oil (containing 80% ether extract) were produced by combing palm oil or coconut oil with dried casein and whey powder in a spray-drying process causing the milk proteins to encapsulate the fat particles as they dried. Dried casein and whey powder were obtained from the same source, other treatment diets without encapsulated fat contained identical amounts of casein and whey.

[2]Provided the following amounts of vitamins per kilogram of diet: vitamin A, 12,000 IU as retinyl acetate; vitamin D3, 3,600 IU as cholecalciferol; vitamin E, 150 IU as DL-α-tocopherol acetate; vitamin K3, 7.2 mg as menadione; thiamine, 3 mg; riboflavin, 10.8 mg; pyridoxine, 5.4 mg; vitamin B12, 0.06 mg; pantothenic acid, 36.0 mg; niacin, 60.0 mg; folic acid, 6 mg; biotin, 0.6 mg.

[3]Provided the following amounts of trace minerals per kilogram of diet: Cu, 10 mg as $CuSO_4.5H_2O$; Fe, 39 mg as $FeSO_4$. H_2O; Mn, 30 mg as $MnSO_4$; Zn, 39 mg as $ZnSO_4$; Se, 0.15 mg as Na_2SeO_3; I, 0.14 mg as $Ca(IO_3)_2$; Co, 0.1 mg as $CoCL_2$.

[4]The diets of Exp. 2 are the same as in Exp. 1 with additional 3.5kg/T chromic oxide as an inert marker.

[5]Others contains antibiotics, enzymes, mycotoxin removal agent, sweetening agents, zeolite (carrier).

[6]Based on nutrient composition of feed ingredients according to NRC (2012).

[7]The mean of the 4 wk digestibility of DE in Exp. 2.

Fecal samples were collected from each pig on the last 3 d of each week to determine the weekly nutrient ATTD. All samples were collected three times per day. Fecal samples obtained over the 3-d collection period were thawed, mixed within animal, and oven dried (at 65 °C for 3 d), finely ground, and stored at −20 °C until they were analyzed. A sample of each diet was collected as well. Samples were analyzed for nutrients according to procedures from AOAC International (2007). All the feces and diets were analyzed for DM (method 930.15), ether extract (**EE**, method 920.39). Gross energy was determined by adiabatic oxygen bomb calorimetry (Model C200, Ika-Werke Gmbh & Co., Staufen, Germany) with benzoic acid as the reference material. Crude protein was determined in a Foss Kjell 2300 auto Kjeldahl nitrogen analyzer (Foss Analytical A/S, Hilleroed, Denmark). Chromium contents of diets and feces were determined by wet digestion flame atomic absorption spectrophotometry (Spectra AA 220FS/220Z, Varian Medical Systems Inc., Palo Alto, CA).

Pigs were euthanized after 28 d of feeding, ending the experiment. Pancreas samples were removed by dissection, flash frozen in liquid N, and stored at −80 °C until analysis. The pH of the digesta was measured immediately. For the homogenization of the pancreas samples, an Ultra Turrax T 10 (Ika-Werke GmbH & Co.) equipped with a S 10 N-10G-ST probe was used. The pancreas was thawed and a 1 g sample was homogenized in 9 mL of ultrapure water at around 0 °C. The homogenate was then centrifuged (10,000 × *g*, 4 °C) for 15 min (Centrifuge 5804 R, Eppendorf AG, Hamburg, Germany). The supernatant was divided into five sample tubes and stored at −80 °C until the determination of specific activities of digestive enzymes. The activities of amylase, lipase, trypsin, and total protein were measured using commercial assay kits (Suzhou Comin Biotechnology Co., Ltd, Jiangsu, China). Amylase was used to hydrolyze starch at 40 °C for 5 min to generate reducing sugars, and the reducing sugars were treated with 3, 5-dinitrosalicylic acid to generate a brown-red reactant which had the greatest absorbency at 540 nm. The activity of amylase was calculated by measuring the absorption difference with or without amylase at 540 nm. One unit of amylase was defined as the amount of enzyme that release 1 mg of reducing sugar per minute under the assay conditions. Lipase activity was determined by measuring the amount of fatty acid released during incubation with emulsified olive oil. After incubation at 37 °C for 10 min, the fatty acid was reacted with copper acetate (5%, m/m) to produce copper complex which had maximum absorption at 710 nm. One unit of lipase was defined as the amount of enzyme that release 1 μmol of fatty acid per minute at 37 °C. Trypsin was used to hydrolyze N-benzoyl-L-arginine-ethyl ester (**BAEE**) at 37 °C for 1 min to produce N-benzoyl-L-arginine (**BA**) which had maximum absorption at 253 nm. The activity of trypsin was calculated by measuring the absorption difference of sample tube and blank tube (distilled water) in 1 min. One unit of trypsin was defined as the amount of enzyme that increase the absorbance value by 1 per minute at 253 nm. Analysis was done using a spectrophotometer (Multiskan GO 1510, Thermo Fisher Scientific). The specific enzyme activity was calculated as the activity of enzyme divided by total protein.

Statistical Analyses

Data for both experiments were analyzed by ANOVA as a randomized complete block design using the PROC MIXED procedure of SAS (SAS Inst., Inc., Cary, NC). Data were averaged across pigs in a pen where pen was the experimental unit in Exp. 1. Pig was the experimental unit in Exp. 2. The linear model used included block (BW), treatment, and block × treatment (random error) to evaluate the difference among five treatments. The effects of fat source (PO vs. CO) and encapsulation were analyzed via a 2 × 2 factorial design with a linear model that included block (BW), fat source, encapsulation, fat source × encapsulation, and block × fat source × encapsulation. Results were reported as least square means and SE, and differences were considered statistically significant at $P \leq 0.05$ and were considered tendencies when $0.05 < P \leq 0.10$.

RESULTS

Experiment 1: Growth Performance and Blood Parameters

Pigs fed encapsulated fats had increased ($P < 0.05$) BW on days 14 and 28 compared to pigs fed unencapsulated fats (Table 3). Significant interaction was observed between fat source and encapsulation for ADG ($P = 0.05$) and G:F ($P = 0.04$) during days 0 to 14. There was a tendency for fat source × encapsulation interaction ($P = 0.09$) for ADG during the overall period. Pigs fed encapsulated fats had increased ($P < 0.05$) ADG from days 0 to 14, days 15 to 28, and overall compared

Table 3. Effect of fat encapsulation on growth performance of nursery pigs

	Treatments						*P* value		
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]	SEM[2]	Fat source[3]	Encapsulation[4]	Fat source × encapsulation
BW, kg									
Day 0	8.28	8.10	8.19	8.27	8.32	0.17	0.71	0.86	0.96
Day 14	11.88	11.07	12.36	11.75	12.23	0.20	0.51	0.04	0.32
Day 28	16.28	15.35	17.09	16.42	17.21	0.25	0.20	0.01	0.30
ADG, g									
Days 0 to 14	221^{b}	177^{c}	263^{a}	213^{bc}	243^{ab}	8	0.53	<0.001	0.05
Days 15 to 28	314	305	337	333	356	7	0.06	0.03	0.67
Days 0 to 28	268^{bc}	241^{c}	300^{a}	273^{ab}	300^{a}	6	0.10	<0.001	0.09
ADFI, g									
Days 0 to 14	322	285	315	316	337	9	0.21	0.22	0.82
Days 15 to 28	533	549	558	525	532	11	0.36	0.76	0.97
Days 0 to 28	427	417	437	420	435	7	0.96	0.30	0.86
G:F, kg/kg									
Day 0 to 14	0.68^{bc}	0.62^{c}	0.79^{a}	0.68^{bc}	0.72^{ab}	0.01	0.85	0.001	0.04
Days 15 to 28	0.59^{bc}	0.56^{c}	0.60^{abc}	0.63^{ab}	0.67^{a}	0.01	0.01	0.15	0.67
Days 0 to 28	0.63^{b}	0.57^{c}	0.67^{ab}	0.65^{ab}	0.69^{a}	0.01	0.03	0.007	0.16
Diarrhea incidence, %									
Day 0 to 28	10.68^{b}	14.44^{a}	7.46^{bc}	10.49^{b}	6.61^{c}	0.71	0.06	<0.001	0.22

$^{a-c}$Within a row, means with differing superscripts differ ($P < 0.05$). The linear model used included block (BW), treatment, and block × treatment to evaluate the difference among five treatments, *P* value is not shown.

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil (granular, containing 80% palm oil), encapsulated coconut oil (granular, containing 80% coconut oil).

[2]SEM is for treatment within the same row.

[3]Palm oil vs. coconut oil.

[4]Encapsulation vs. not.

to pigs fed unencapsulated fats. However, encapsulation had limited effect on ADG of pigs fed CO compared to pigs fed encapsulated PO (9.89% vs. 24.48%, days 0 to 28). Pigs fed EPO had increased ($P < 0.05$) ADG during days 0 to 14 and overall compared to SBO and PO, pigs fed ECO had increased ($P < 0.05$) ADG during days 0 to 28 compared to SBO and PO. The ADFI was similar among treatments. Pigs fed encapsulated fats had increased ($P < 0.05$) G:F during days 0 to 14 and overall compared to pigs fed unencapsulated fats. Pigs fed EPO had increased G:F ($P < 0.05$) during days 0 to 14 compared to SBO, PO, and CO, whereas G:F of pigs fed ECO was not different from SBO, EPO, and CO. During days 0 to 28, pigs fed EPO had increased G:F ($P < 0.05$) compared to PO, whereas G:F of pigs fed ECO was not different from EPO and CO. Pigs fed EPO had the lowest DI ($P < 0.05$) and PO had the greatest ($P < 0.05$) during overall, whereas DI of pigs fed ECO was not different from EPO.

Pigs fed encapsulated fats had lower ($P < 0.05$) SUN on days 14 and 28 compared to unprocessed ones, whereas SUN of pigs fed EPO was not different from SBO, CO, and ECO (Table 4). The concentration of TG of pigs fed PO was greater ($P < 0.05$) on day 14 compared to SBO and EPO. Encapsulation of fats resulted in lower LDL-C ($P < 0.05$) on day 14 and tended to increase HDL-C ($P = 0.06$) compared to unencapsulated fats.

Experiment 2: Nutrient ATTD and Digestive Enzyme Activity

Pigs fed EPO had increased ($P < 0.05$) ATTD of DM compared to pigs fed PO and SBO, whereas pigs fed ECO only had increased ($P < 0.05$) ATTD of DM in the first week compared to pigs fed CO (Table 5). Pigs fed EPO had increased ($P < 0.05$) ATTD of GE compared to pigs fed SBO and PO, whereas ATTD of GE of pigs fed ECO was not different from CO. Pigs fed SBO had reduced ($P < 0.05$) ATTD of CP compared to other treatments. Pigs fed EPO had increased ATTD of EE ($P < 0.05$) compared to pigs fed PO, whereas ATTD of EE of pigs fed EPO was not different from SBO. Pigs fed ECO had the greatest ATTD of EE ($P < 0.05$) and were not different from CO. Pigs fed PO, EPO, CO, and ECO had reduced ATTD of EE ($P < 0.05$) in the first week compared to the third and fourth week.

Table 4. Effect of fat encapsulation on blood parameters of nursery pigs

	Treatments						*P* value		
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]	SEM[2]	Fat source[3]	Encapsulation[4]	Fat source × encapsulation
TC,[5] mg/dL									
Day 14	118.9	98.7	99.0	114.7	106.1	2.5	0.03	0.41	0.37
Day 28	140.4	121.6	124.5	150.5	149.8	4.7	0.004	0.89	0.82
TG,[5] mmol/L									
Day 14	23.53^{c}	40.33^{a}	28.70^{bc}	31.67^{abc}	37.62^{ab}	1.93	0.97	0.46	0.04
Day 28	29.99	34.39	35.37	33.96	31.65	2.29	0.48	0.67	0.18
HDL-C,[5] mmol/L									
Day 14	204.0	191.7	220.4	213.1	241.2	6.4	0.16	0.06	0.98
Day 28	105.5	114.9	121.5	127.6	119.7	2.8	0.27	0.89	0.15
LDL-C,[5] mmol/L									
Day 14	105.4	100.1	89.1	118.3	97.1	3.9	0.25	0.03	0.30
Day 28	53.36	44.03	46.39	57.40	52.97	7.91	0.02	0.78	0.37
SUN,[5] mmol/L									
Day 14	6.57^{ab}	7.43^{a}	5.71^{bc}	6.06^{ab}	4.49^{c}	0.31	0.02	0.004	0.88
Day 28	7.84^{ab}	9.30^{a}	7.35^{b}	6.73^{b}	6.62^{b}	0.27	0.01	0.06	0.09

[a–c]Within a row, means with differing superscripts differ ($P < 0.05$). The linear model used included block (BW), treatment, and block × treatment to evaluate the difference among five treatments, *P* value is not shown.

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil (granular, containing 80% palm oil), encapsulated coconut oil (granular, containing 80% coconut oil).

[2]SEM is for treatment within the same row.

[3]Palm oil vs. coconut oil.

[4]Encapsulation vs. not.

[5]TC = serum total cholesterol, TG = total triglyceride, HDL-C = high-density lipoprotein cholesterol, LDL-C = low-density lipoprotein cholesterol, SUN = serum urea nitrogen.

There were no treatment effects on pH values of the digesta (Table 6). The activity of amylase in the pancreas was likewise not affected by the dietary treatments (Table 7). PO supplementation tended to decrease ($P = 0.073$) the activity of lipase in the pancreas. Pigs fed encapsulated fats had increased activity of lipase ($P < 0.05$) and trypsin ($P = 0.05$) in the pancreas compared to unprocessed ones, whereas the activity of trypsin in the pancreas of pigs fed EPO was not different from PO and ECO.

DISCUSSION

Improving Postweaning Growth Performance and Nutrients Use

Encapsulation of fat with a high ratio of long-chain saturated fatty acids may have positive effects on growth performance in nursery pigs. Xing et al. (2004) observed a small increase in ADG and G:F in piglets during 36 to 49 d of age when they were fed with encapsulated, spray-dried lard, compared with unencapsulated lard. The results from the current experiment were similar to those of Xing et al. (2004). Pigs fed EPO (encapsulated PO with a high ratio of long-chain saturated fatty acids) had increased ADG and G:F during 28 to 42 d of age and overall compared with PO. De Passillé et al. (1989) indicated that feeding adaption and weaning weight was positively correlated with pancreas enzyme contents, and the adaption period of feeding may enhance the pancreatic secretion of nursery pigs, benefitting digestion, and absorption of the diets. Therefore, the larger initial BW (8.2 kg) and an adaption period to feed (21 to 28 d of age) in this study may contribute to the earlier response to added fat in diets compared to other research (Cera et al., 1990; Li et al., 1990; Adeola et al., 2013).

The limited effect of encapsulated CO is likely due to the high digestibility of the medium-chain triglycerides (**MCT**) abundant in CO. The CO that contains about 60% MCT has greater digestibility compared with other fat sources (Cera et al., 1990; Li et al., 1990; Jung et al., 2003; Adeola et al., 2013). With a low esterification of medium-chain fatty acids (**MCFA**), most MCFA can be absorbed directly (without lipase hydrolysis) into the portal vein for transport (Odle, 1997), then enter the liver directly to oxidize. The high hydrophilic and low esterification of MCFA in CO may be sufficient to enhance nursery pig growth and fat digestibility

Table 5. Effect of fat encapsulation on nutrient digestibility in nursery pigs (DM basis)

	Treatments						*P* value		
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]	SEM[2]	Fat source[3]	Encapsulation[4]	Fat source × encapsulation
DM, %									
Week 1	78.6^{c}	80.2^{b}	83.4^{ab}	83.3^{ab}	85.0^{a}	0.7	0.03	0.02	0.43
Week 2	79.9^{b}	79.9^{b}	84.1^{a}	85.8^{a}	85.0^{a}	0.6	<0.001	0.02	0.001
Week 3	80.2^{b}	79.1^{b}	84.1^{a}	84.6^{a}	84.6^{a}	0.6	<0.001	0.001	0.001
Week 4	79.5^{b}	78.7^{b}	84.5^{a}	84.4^{a}	85.1^{a}	0.6	0.001	<0.001	0.003
SEM[5]	0.6	0.5	0.3	0.4	0.2				
P value[6]	0.83	0.71	0.66	0.25	0.82				
GE, %									
Week 1	83.4^{ab}	80.3^{b}	87.1^{a}	85.9^{ay}	87.2^{a}	0.8	0.04	0.007	0.05
Week 2	85.7^{b}	79.7^{c}	88.3^{a}	90.0^{ax}	89.7^{a}	0.9	<0.001	<0.001	<0.001
Week 3	86.0^{b}	79.5^{c}	88.9^{a}	89.4^{ax}	89.8^{a}	0.9	<0.001	<0.001	<0.001
Week 4	85.9^{b}	79.2^{c}	88.8^{a}	89.4^{ax}	89.9^{a}	0.8	<0.001	<0.001	<0.001
SEM[5]	0.6	0.5	0.4	0.6	0.5				
P value[6]	0.37	0.93	0.32	0.02	0.17				
DE, Mcal/kg									
Week 1	3.67^{b}	3.63^{b}	3.92^{a}	3.85^{aby}	3.95^{a}	0.04	0.11	0.01	0.25
Week 2	3.77^{b}	3.65^{c}	3.97^{a}	4.03^{ax}	4.06^{a}	0.04	<0.001	<0.001	<0.001
Week 3	3.79^{b}	3.64^{c}	4.00^{a}	4.00^{ax}	4.06^{a}	0.04	<0.001	<0.001	<0.001
Week 4	3.78^{b}	3.67^{c}	3.99^{a}	4.00^{ax}	4.07^{a}	0.04	<0.001	<0.001	<0.001
SEM[5]	0.03	0.01	0.02	0.02	0.02				
P value[6]	0.37	0.93	0.33	0.02	0.16				
CP, %									
Week 1	71.6^{b}	83.1^{a}	81.6^{a}	79.8^{a}	83.2^{a}	1.06	0.63	0.60	0.20
Week 2	76.8^{b}	82.6^{a}	83.0^{a}	83.9^{a}	84.5^{a}	0.82	0.38	0.78	0.94
Week 3	78.0^{b}	82.3^{a}	83.7^{a}	82.2^{a}	84.0^{a}	0.64	0.94	0.18	0.88
Week 4	77.0^{b}	80.8^{ab}	83.3^{a}	82.4^{a}	84.0^{a}	0.80	0.47	0.22	0.78
SEM[5]	0.8	0.9	0.6	0.9	0.5				
P value[6]	0.08	0.88	0.70	0.48	0.83				
Ether extract, %									
Week 1	83.1^{ab}	33.3^{cy}	79.4^{by}	83.8^{aby}	88.0^{ay}	3.6	<0.001	<0.001	<0.001
Week 2	85.9^{bc}	39.0^{dxy}	83.7^{cxy}	89.0^{abx}	89.8^{axy}	4.0	<0.001	<0.001	<0.001
Week 3	87.7^{ab}	41.0^{cx}	85.2^{bx}	89.1^{ax}	90.8^{ax}	4.0	<0.001	<0.001	<0.001
Week 4	87.5^{bc}	41.7^{dx}	86.4^{cx}	89.8^{abx}	91.4^{ax}	4.2	<0.001	<0.001	<0.001
SEM[5]	0.7	1.1	1.0	0.7	0.4				
P value[6]	0.13	0.04	0.049	0.004	0.03				

$^{a-d}$Within a row, means with differing superscripts differ ($P < 0.05$). The linear model used included block (BW), treatment, and block × treatment to evaluate the difference among five treatments, *P* value is not shown.

^{x,y}Within a column, means with differing superscripts differ ($P < 0.05$).

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil (granular, containing 80% palm oil), encapsulated coconut oil (granular, containing 80% coconut oil).

[2]SEM is for treatment within the same row.

[3]Palm oil vs. coconut oil.

[4]Encapsulation vs. not.

[5]SEM is for different weeks within a treatment in the same column.

[6]*P* value is for among weeks within a treatment in the same column.

without encapsulation. In this experiment, the EE digestibility of pigs fed ECO was similar to CO with other nutrients showing a similar response.

The fatty acid composition was directly related to the digestibility of supplemented fat in nursery pigs (Li et al., 1990; Wiseman et al., 1990; Powles et al., 1993). It was reported that CO with a high percentage of medium-chain saturated fatty acids (60%, C8:0, C10:0, and C12:0) has the greatest apparent fat digestibility in nursery diets, the digestibility of SBO with a high percentage of unsaturated fatty acids (80%, C18:1 and C18:2) is lower than CO, but greater than tallow and lard with a high percentage of long-chain saturated fatty acids

Table 6. Effect of fat encapsulation on digesta pH values of nursery pigs

	Treatments						*P* value		
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]	SEM[2]	Fat source[3]	Encapsulation[4]	Fat source × encapsulation
Stomach	4.10	3.92	3.16	4.23	3.80	0.18	0.27	0.17	0.70
Duodenum	5.63	6.05	5.76	5.67	5.84	0.07	0.38	0.74	0.19
Jejunum	5.74	6.27	6.05	5.97	5.93	0.07	0.17	0.38	0.55
Ileum	6.84	6.80	6.92	6.86	6.96	0.04	0.52	0.18	0.89
Cecum	5.84	5.86	6.15	5.85	5.95	0.06	0.40	0.15	0.48
Colon	6.57	6.08	6.44	6.34	6.43	0.05	0.29	0.06	0.26

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil (granular, containing 80% palm oil), encapsulated coconut oil (granular, containing 80% coconut oil).

[2]SEM is for treatment within the same row, the *P* value is not shown.

[3]Palm oil vs. coconut oil.

[4]Encapsulation vs. not.

Table 7. Effect of fat encapsulation on the activity of pancreatic enzymes in nursery pigs

	Treatments						*P* value		
Item	Control[1]	Palm oil	Encapsulated palm oil[1]	Coconut oil	Encapsulated coconut oil[1]	SEM[2]	Fat source[3]	Encapsulation[4]	Fat source × encapsulation
Amylase, U/g protein	19.0	18.1	18.4	19.5	20.1	0.3	0.08	0.56	0.82
Lipase, U/g protein	743	526[5]	774	724	868	37	0.06	0.02	0.44
Trypsin, U/g protein	203[c]	488[ab]	605[a]	376[bc]	630[a]	48.6	0.61	0.05	0.43

[a–d]Within a row, means with differing superscript differ ($P < 0.05$). The linear model used included block (BW), treatment, and block × treatment to evaluate the difference among five treatments, *P* value is not shown.

[1]Control diet contains 6.0% soybean oil; encapsulated palm oil (granular, containing 80% palm oil), encapsulated coconut oil (granular, containing 80% coconut oil).

[2]SEM is for treatment within the same row.

[3]Palm oil vs. coconut oil.

[4]Encapsulation vs. not.

[5]Decreased tendency among five treatments, $P = 0.073$.

(Cera et al., 1989; Jørgensen and Fernández, 2000; Jung et al., 2003; Straarup et al., 2006; Adeola et al., 2013). As shown in this experiment, pigs fed CO and ECO had the greatest ATTD of EE, and pigs fed PO (51%, C16:0) had reduced ATTD of EE compared to other treatments. The digestibility of EE in week 1 was lower than that of the last 2 wk, which may be due to the markedly increased lipase activity from the age of 3 to 4 wk of nursery pigs. The activity of lipase increased 18-fold between birth to 3 wk of age, but 300-fold from 3 to 6 wk of age in weanling pigs (Corring et al. 1978).

Increased fat digestibility is associated with an increased utilization of DM and GE (Cera et al., 1988, 1989; Jones et al., 1992; Jung et al., 2003; Xing et al., 2004). Pigs fed EPO, CO, and ECO had increased ATTD of DM and GE compared to pigs fed SBO and PO in this experiment. There was little difference on GE of the treatment diets, but DE of diets containing EPO, CO, and ECO was quite different from the calculated values. Based on these results, it would be appropriate to reevaluate the DE of EPO, CO, and ECO. When the energy supply is insufficient, the body will accelerate the degradation of the protein to replenish the energy requirement (van Milgen et al., 2001). The unexpected elevation of CP digestibility in PO may due to the extremely low digestibility of PO.

Blood Parameters

Serum urea nitrogen concentration inversely reflects the efficiency of nitrogen deposition in the body (Webel et al., 1997; Cho et al., 2007; Whitney and Lupton, 2010). Dietary protein is preferentially used for deposition when the energy supply is sufficient, because protein has lower energetic efficiency compared to starch and lipid (van Milgen et al., 2001). With increased digestibility of nutrients and energy supply in pigs fed encapsulated fat, the protein in the encapsulated fat diets was likely used for protein deposition rather than oxidized to provide energy. Pigs fed unsaturated fat had lower serum TG compared to saturated fat (Cera et al., 1989;

Jones et al., 1992). Compensation for lower DE of saturated fat in the diets might be accomplished by increasing the degradation of body fat (Jones et al., 1992), resulting in a greater concentration of serum TG in pigs fed PO compared to SBO. Faster rates of absorption and metabolism of ingested fat results in less serum TG in pigs (Jones et al., 1992). Pigs fed EPO had increased ATTD of EE compared to PO, thus the serum TG of pigs fed EPO was less than PO.

Digestive Enzymes Activity

Pancreatic digestive enzymes adapt to dietary changes in given substrates through parallel changes in synthesis. Pancreatic lipase activity is primarily a function of the amount of dietary fat (Yago et al., 2000) and is not stimulated at or below levels where 47% of dietary kcal is provided as fat (Sabb et al., 1986). The energy provided as fat in this experiment (approximately 20%) was below the threshold level of dietary fat, therefore, there was no difference in the activity of pancreatic lipase between the treatment diets in this experiment. The relationship between fat digestibility and pancreatic lipase secretion has not been entirely established, but Deschodt-Lanckman et al., (1971) and Sabb et al. (1986) reported better stimulation of lipase by unsaturated fats than by saturated fats when the amount of fat was fed at a moderate level in the diet. According to previous research, unsaturated fats were more digestible than saturated fats (Cera et al., 1989; Li et al., 1990). We hypothesized that the increased fat digestibility of encapsulated fat may have stimulated the secretion of pancreatic lipase compared with unencapsulated fats, while the extremely low digestibility of PO may have tended to decrease the lipase activity in this experiment.

Normally, increased fat digestibility is associated with an increased utilization of CP (Cera et al., 1988, 1989; Jones et al., 1992; Jung et al., 2003; Xing et al., 2004). The increased digestibility of encapsulated fats may be associated with the increased digestibility of CP and greater activity of trypsin in the pancreas in pigs fed EPO and ECO compared with PO and CO in this experiment. Due to the consistency of source and amount of starch among the treatment diets, and the stability of amylase activity by the 4th week after weaning (Corring et al., 1978; Kelly et al., 1991), the activity of amylase in the pancreas was similar among the dietary treatments in this experiment. The pH of the digesta remained unchanged among the dietary treatments which was consistent with a normal physiological status of satiety (Ma et al., 2002; Merchant et al., 2011), providing a relatively stable environment for the activity of digestive enzymes.

In conclusion, encapsulation improved the digestibility of PO and in turn improved growth performance and nutrient use in nursery pigs. The digestibility of DM in EPO increased by 5.8% and EE digestibility increased by 116% compared to PO, improving ADG by 24.5% and G:F by 13.8%. The lower SUN of pigs fed EPO suggested more nitrogen deposition than in PO, and the lower digestibility of PO led to decreased activity of lipase and increased activity of trypsin in the pancreas. Encapsulation is a feasible process to improve the utilization of PO which contains a high percentage of long-chain saturated fat but not CO, the high hydrophilic and low esterification of MCFA in CO may be sufficient to enhance nursery pig growth and fat digestibility without encapsulation.

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