Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on performance, digestibility of nutrients, composition, and fat globule size in milk¹

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ABSTRACT: The objective of this study was to determine the effects of feeding sodium stearoyl-2-lactylate (SSL) as a new feeding emulsifier diet with and without soybean oil (SO) on the milk fat globule (MFG) size, milk composition, digestibility of nutrients, and performance in lactating sows. Sixty sows (Large White × Landrace) were randomly assigned to 1 of 4 treatments according to a 2 × 2 factorial arrangement of treatments. Each treatment had 15 replicates composed of 1 sow. The factors included 1) the fat level (0% vs. 3% SO) and 2) the emulsifier content (0% vs. 0.1% SSL). Treatments included 1) Control (without SO and SSL), 2) SO (3% SO without SSL), 3) SSL (0.1% SSL without SO), and 4) SO + SSL (3% SO and 0.1% SSL). During the suckling period, sows in the SO + SSL group lost less back fat thickness ($P < 0.05$) compared to other groups; sows fed 3% SO diets consumed less feed ($P < 0.05$) compared to sows fed diets without SO, but there were no significant effects ($P > 0.05$) of dietary fat and its interaction with a dietary emulsifier on energy intake

and the weaning-estrus interval. The digestibility of ether extract in the SO + SSL group was greater than in the SO group ($P < 0.05$). Moreover, greater digestibility of CP, Ca, and P in the SO+SSL group was observed compared to that of other groups ($P < 0.05$). Feeding the SO + SSL diet improved the concentrations of milk fat, protein, and total solids on d 11 of lactation compared to other diets ($P < 0.05$). Also, an interaction between supplemental SSL and SO was observed for the milk fat and total solids concentrations. The average diameter of MFG on d 11 of lactation was significantly decreased by the addition of 0.1% SSL compared to a diet with no SSL supplementation ($P < 0.05$). No significant differences among the dietary treatments were observed in cholesterol, triglyceride, high-density lipoprotein cholesterol, or low-density lipoprotein cholesterol in sows' plasma ($P > 0.05$). In conclusion, feeding a 0.1% SSL diet to lactating sows may decrease the average diameter of MFG and improve the digestibility of nutrients and composition of milk.

Key words: digestibility of nutrients, lactating sows, milk fat globule size, sodium stearoyl-2-lactylate, soybean oil

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INTRODUCTION

Sows lose weight and back fat by mobilizing body stores to support milk production (Tilton et al., 1999) and supply essential fatty acids through milk for infants (Lauridsen and Jensen, 2007) during lactation. Supplemental high-level fat in diets has become an at-

tractive method to augment energy intake. Sows must absorb fat through the gastrointestinal tract because of the features of fat, which is difficult to dissolve in a water medium, so an emulsive process is required. Reports showed that an emulsifier can decrease the size of the fat globule and increase total available surface for enzymatic digestion (Jones et al., 1992; Al-Marzooqi and Leeson, 1999; Soares and Lopezbote, 2002; Gu and Li, 2003). Sodium stearoyl-2-lactylate (SSL) is a reactive product of 2 naturally occurring food components, stearic acid and lactic acid, which are neutralized to sodium salt (Verger et al., 1998). As an emulsifier, SSL has been applied to promote growth performance and nutrient digestibility in broilers' diets (Gheisar et al., 2015). The macrostructure of milk lipids includes

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globules made up of triglycerides with different melting points enveloped by a biological membrane from mammary epithelial cells (Lopez et al., 2011). The size of the milk fat globule (MFG) and surface exposed to the digestive system affect fat digestion in different ways (Martini et al., 2016). The ultrastructure of MFG might play an important role in digestion and absorption of milk fat (Gallier et al., 2013). Using SSL as an additive in the feed industry is still in its infancy; especially, application of SSL in lactating sows has not been well studied. It is also not known whether supplementation with SSL and soybean oil (SO) in lactating diets has an interactive effect on the availability of dietary fat and performance of sows and litters. Therefore, the aim of this study was to examine the effects of SSL and/or SO in diets of lactating sows on performance, nutrient digestibility, composition, and fat globule size in milk.

MATERIALS AND METHODS

The protocols used in this experiment were approved by the Northeast Agricultural University Institutional Animal Care and Use Committee of China.

Sodium stearoyl-2-lactylate was purchased from Guangzhou Quanao Chemical Products Co. Ltd. (Guangzhou, China). This emulsifier had a purity of 99% and a hydrophilic lipophilic balance value of 8.3.

Animals, Diets, and Procedures

On d 107 of gestation, a total of 60 multiparous sows (Large White × Landrace, parity: 3 to 6) from a commercial farm the Dawan Pig Breeding Farm located in Mudanjiang, China, were housed in individual farrowing stalls (2.10 × 1.50 m) in an enclosed building until weaning. The farrowing stalls had a piglet creep area provided with a heat lamp and nipple waterer. Sows were randomly allotted to 4 dietary treatments ($n = 15$ sows/treatment) in a 2 × 2 factorial arrangement with consideration for their parity number and weight. The dietary treatments included 2 fat levels (0% vs. 3% SO) and 2 emulsifier contents (0% vs. 0.1% SSL). Treatments included 1) Control (without SO and SSL), 2) SO (3% SO without SSL), 3) SSL (0.1% SSL without SO), and 4) SO + SSL (3% SO and 0.1% SSL). The experiment started on d 107 of gestation and lasted until the end of sows' estrus. Except for the energy of diets, other nutrient levels were similar among the experimental diets and were adequate for lactating sows according to the nutrient concentrations recommended by NRC (2012). The compositions of the experimental diets are listed in Table 1.

During lactation, sows were fed twice daily at 0800 and 1500 h and had access to water ad libitum. Sows were initially fed an average of 3.0 kg/d before farrowing.

Table 1. Composition of experimental diets for lactating sows (as-fed basis)¹

Item	Control	SO	SSL	SO + SSL
Ingredients, %				
Corn	68.1	64.0	68.0	63.9
Wheat bran	4.0	4.0	4.0	4.0
Soybean meal (43% CP)	21.4	22.8	21.4	22.8
Fish meal (67% CP)	2.7	2.3	2.7	2.3
Soybean oil	—	3.0	—	3.0
SSL	—	—	0.1	0.1
L-Lysine-HCl (98%)	0.1	0.1	0.1	0.1
Dicalcium phosphate	1.0	1.1	1.0	1.1
Limestone	0.9	0.9	0.9	0.9
Choline chloride (50%)	0.25	0.25	0.25	0.25
Salt	0.55	0.55	0.55	0.55
Premix ²	1.0	1.0	1.0	1.0
Composition, ³ %				
ME, Mcal/kg	2.97	3.12	2.97	3.12
DM	89.33	89.77	89.75	89.85
CP	18.79	18.75	18.65	18.65
EE	3.54	6.13	3.64	6.05
Lys	0.96	0.97	0.96	0.97
Met + Cys	0.56	0.55	0.56	0.55
Ca	1.06	1.06	1.04	1.06
P	0.47	0.46	0.44	0.46
Na	0.22	0.22	0.22	0.22
Cl	0.32	0.32	0.32	0.22

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate, EE = ether extract. A dash (—) indicate not applicable.

²Supplied per kilogram of diet: 14,000 IU vitamin A, 2,000 IU vitamin D₃, 140 mg vitamin E, 3.60 mg vitamin K₃, 2.00 mg vitamin B₁, 5.20 mg vitamin B₂, 3.60 mg vitamin B₆, 0.015 mg vitamin B₁₂, 12.80 mg pantothenic, 28.00 mg niacin, 0.52 mg biotin, 0.48 mg folic acid, 10 mg Cu as CuSO₄·5H₂O, 108 mg Zn as ZnSO₄, 0.3 mg Se as Na₂SeO₃·H₂O, 116 mg Mn as MnSO₄·H₂O, 180 mg Fe as FeSO₄·H₂O, and 0.4 mg I as Ca(IO₃)₂.

³DM, CP, EE, Ca, and P were analyzed values. ME, Lys, Met + Cys, Na, and Cl were calculated values.

On the day of farrowing, sows were fed 0.5 kg starting from the day after farrowing, and the ration was gradually increased by 1.0 kg/d until the maximum ration was reached at approximately 7 d postpartum. Then, a diet was offered semi-ad libitum during the following days of lactation. In other words, daily allocations were individually adjusted so that sows were able to empty the trough between feedings. The feed consumption of sows was recorded daily, and the weight of sows was obtained on d 107 of gestation and weaning. The intake of creep feed per litter was not recorded. Cross fostering took place for a few cases (within 24 h of farrowing) within the same treatment group, which affected 6 litters. The number of piglets per sow ranged from 9 to 12 piglets.

On the morning of weaning (d 21 of lactation), the sows were deprived of feed and moved into gestation stalls. After weaning, the sows received their respective lactation diets until the end of estrus. The weaning-estrus interval (WEI) was monitored daily at 0830, 1530,

Table 2. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on body condition and feed intake¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of sows	15	15	15	15				
BW, kg								
d 107 of gestation	278.50	288	293	291.83	4.675	0.677	0.365	0.595
Weaning	244.83	258.75	259.50	261.50	4.285	0.378	0.336	0.507
Loss	33.67	29.25	33.50	30.33	1.565	0.268	0.892	0.853
Back fat thickness, mm								
d 107 of gestation	25.58	28.34	25.99	23.97	0.927	0.845	0.293	0.204
Weaning	21.60	24.98	21.61	21.43	0.889	0.376	0.328	0.325
Loss	3.98 ^{a,b}	3.36 ^{a,b}	4.38 ^a	2.53 ^b	0.299	0.040	0.716	0.299
ADFI, kg/d	5.75 ^a	5.47 ^b	5.74 ^a	5.49 ^b	0.059	0.029	0.964	0.911
ME, Mcal/d	17.01	17.03	16.99	17.08	0.173	0.883	0.963	0.911
WEI, d	3.72	3.91	3.92	3.54	0.884	0.718	0.718	0.266

^{a,b}Mean values within a row without a common superscript differ significantly ($P < 0.05$).

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate, WEI = weaning to estrus interval.

and 2230 h using boar stimuli. To calculate the WEI, the beginning of the estrous period was characterized as the midpoint between the time of the first observed positive response to back pressure (immobilization reflex).

Sample Collection and Measurements

Samples of experimental diets were collected and analyzed for DM, ether extract (EE), CP, Ca, P, and HCl-insoluble ash using the procedures of the Association of Official Analytical Chemists (AOAC, 1990).

The back fat thickness of each sow was measured at the P2 position (left side of the 10th rib and 6 cm lateral to the spine) with a B-mode ultrasonic device (Renco Lean Meater type 7, Minneapolis, MN) on d 107 of gestation and d 21 of lactation. Measurement of live weight (within 12 h after farrowing) and the numbers of total born, born alive, and stillborn were recorded.

Blood samples (5 mL) were obtained using heparin tubes from an ear vein of 8 sows per treatment on d 1 and 11 of lactation. Blood samples were centrifuged at 4 °C, 1,000 × *g* for 15 min to obtain the plasma, and the plasma was immediately transferred to several 1.5-mL Eppendorf tubes and stored at -20°C for further analyses. Plasma biochemistry parameters were analyzed with a Unicel Dx C 800 Synchron (Clinical System, Beckman Coulter, Fullerton, CA).

Approximately 30 mL of milk were collected from 8 sows per treatment on d 1 and 11 of lactation by infusing the sow with 10 IU of oxytocin (Jilin Huamu Animal Health Products Co. Ltd., Changchun, China) via intravenous injection and then manually milking the first, third, and fifth mammary glands on one side of the sow. Otherwise, the 2 sampling points of colostrum and milk were from the same sow per treatment. Milk samples were immediately frozen at -20°C until further analysis.

The compositions of milk were analyzed using an infrared milk analyzer (MilkoScan, Foss Electric, Hillerød, Denmark). The MFG size distribution of the milk was measured by laser light scattering using a Mastersizer (CILAS L1064, CILAS, Orleans, France).

Fecal samples were collected 3 times on d 14, 15, and 16 of lactation to determine fecal nutrient digestibility of 8 sows per treatment. Individual fecal samples of each sow for these 3 d were mixed together, homogenized, and pooled per sow and then stored at -20°C until further analysis. The fecal samples were analyzed for DM, EE, Ca, P, and HCl-insoluble ash to calculate the apparent total tract digestibility (ATTD) of nutrients. In this study, no extra acid-insoluble substances were added as indicator substances, and the ATTD of nutrients was calculated according to the methods of procedures (Gerritsen et al., 2010). The ATTD were calculated using the following equation:

$$\text{Digestibility} = (\text{N}_{\text{feed}} - \text{N}_{\text{feces}} \times \text{M}_{\text{feed}} / \text{M}_{\text{feces}}) / \text{N}_{\text{feed}}$$

where N_{feed} and N_{feces} are the nutrient content in the experimental diet and feces (%), respectively, and M_{feed} and M_{feces} are the content of the HCl-insoluble ash in the experimental diet and feces (%), respectively.

Statistical Analysis

All data were analyzed by ANOVA using a 2 × 2 factorial arrangement of treatments with the GLM procedure (SPSS 23.0; IBM-SPSS Inc., Chicago, IL). The results were presented as the mean values and the SEM. The model accounted for the effects of SO, SSL, and their interactions. Differences were considered significant if $P < 0.05$.

Table 3. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on the performance of piglets¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of litters	15	15	15	15				
Litter size								
Total born	11.47	11.46	11.33	11.87	0.249	0.606	0.790	0.599
Alive at birth	10.87	10.92	11.00	11.27	0.248	0.752	0.641	0.837
Stillborn	0.60	0.54	0.33	0.60	0.102	0.624	0.624	0.434
Alive at weaning	10.13	10.31	9.67	9.20	0.234	0.756	0.098	0.496
Litter weight								
Birth, kg	16.57	16.28	15.75	16.19	0.434	0.935	0.610	0.682
Weaning, kg	60.05	57.66	53.80	52.51	1.544	0.552	0.069	0.859

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate.

RESULTS

Sow and Litter Performance

The effects of maternal dietary treatment on sow body condition during lactation are presented in Table 2. Sows fed diets without SO consumed more feed than sows fed 3% SO diets ($P < 0.05$), but energy intake was not affected ($P > 0.05$). Also, back fat loss was greater for sows in the Control, SO, and SSL groups compared to sows in the SO + SSL group ($P < 0.05$). However, the supplemented 3% SO and/or 0.1% SSL had no effect on sow loss in BW during lactation ($P > 0.05$). In addition, over the 21-d lactation, there was no effect of supplemental dietary SSL or SO × SSL interaction on sow body condition during lactation and WEI ($P > 0.05$).

Litter size and BW at birth were not affected by the different dietary treatments ($P > 0.05$; Table 3). In addition, a difference in weaning litter weight was not observed for sows fed dietary fat compared to sows fed a diet without SO.

The Digestibility of Nutrients

The results of the ATTD of DM, EE, CP, Ca, and P are shown in Table 4. During lactation, digestibility of EE, CP, Ca, and P significantly increased when SSL was added to the diet compared to no SSL supplemen-

tation ($P < 0.05$). However, there were no effects of supplemental dietary SO or SO × SSL interaction on the ATTD of nutrients during lactation ($P > 0.05$). In addition, the ATTD of DM had a tendency to increase with the supplementation of SSL ($P < 0.1$).

Composition of Colostrum and Milk

The composition of colostrum and milk as affected by an emulsifier and fat is presented in Table 5. No differences among the dietary treatments were observed in the colostrum composition of fat, protein, lactose, and total solids ($P > 0.05$).

Higher concentrations of fat, protein, and total solids in milk on d 11 of lactation were noticed in sows in the SO + SSL group compared to sows in other groups ($P < 0.05$). In addition, for milk on d 11 of lactation, there were significant interaction effects between SSL and SO in the concentration of milk fat and total solids ($P < 0.05$).

Distribution of Milk Fat Globule Size

The effects of SO and SSL supplementation during lactation on MFG size are presented in Table 6. The D_A , D_{10} , and D_{50} (D_A is the average diameter of milk fat globules, D_{10} is the diameter that represents 10% of the globule volume, with 50% for D_{50}) of MFG on d 11 of lactation were smaller in sows fed

Table 4. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on the nutrient digestibility¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of sows	8	8	8	8				
DM, %	73.60	73.23	76.66	79.10	1.217	0.468	0.075	0.348
EE, %	68.50 ^a	55.80 ^b	70.85 ^a	69.78 ^a	2.250	0.094	0.049	0.153
CP, %	49.58 ^b	44.38 ^b	52.20 ^b	69.22 ^a	3.081	0.019	<0.001	0.169
Ca, %	69.55 ^b	72.98 ^b	82.87 ^a	87.31 ^a	1.727	0.052	<0.001	0.786
P, %	67.72 ^b	78.80 ^b	80.68 ^a	87.10 ^a	1.292	0.419	0.002	0.225

^{a,b}Mean values within a row without a common superscript differ significantly ($P < 0.05$).

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate, EE = ether extract.

Table 5. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on the composition of milk¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of sows	8	8	8	8				
Colostrum, %								
Lactose	2.18	2.32	2.89	2.59	0.129	0.742	0.063	0.396
Fat	4.73	4.76	4.13	4.16	0.210	0.947	0.182	0.992
Protein	16.67	16.29	19.27	18.16	0.591	0.521	0.066	0.753
Total solids	26.02	28.19	23.76	26.25	0.728	0.111	0.147	0.908
Milk (d 11 of lactation), %								
Lactose	4.96	5.26	5.26	5.01	0.063	0.854	0.854	0.051
Fat	6.20 ^b	6.29 ^b	5.90 ^b	8.23 ^a	0.277	0.011	0.070	0.017
Protein	4.93 ^b	5.18 ^b	5.19 ^b	5.78 ^a	0.080	<0.001	<0.001	0.110
Total solids	16.05 ^b	16.81 ^b	16.43 ^b	19.17 ^a	0.334	0.001	0.008	0.046

^{a,b}Mean values within a row without a common superscript differ significantly ($P < 0.05$).

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate.

0.1% SSL diets compared to sows not fed SSL ($P < 0.05$). However, no differences in the MFG size were noted in colostrum ($P > 0.05$). In addition, no significant interactions were observed between SSL and SO in colostrum and milk.

Plasma Biochemistry Parameters of Sows

The concentrations of plasma metabolite parameters on d 1 and 11 of lactation are shown in Table 7. There were no effects of SSL and SO on the cholesterol (CHOL), triglyceride (TG), high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C) in the plasma of sows on d 1 after farrowing ($P > 0.05$). For the plasma on d 11 of lactation, supplementation of the 3% SO diet compared with the 0% SO diet resulted in a tendency toward higher concentrations of CHOL, HDL-C, and

LDL-C ($P < 0.1$). However, no SO × SSL interaction effect was noted on d 11 of lactation ($P > 0.05$).

DISCUSSION

Sow and Litter Performance

Fat is extensively used as a supplemental energy source in swine diets (Rosero, 2012), and the benefits from supplementation of fat in later gestation and/or lactating sows' diets have been reported by several researchers. For example, supplementation of tallow positively affected the fat content of milk and weight gain for litters (Tilton et al., 1999). In addition, van den Brand et al. (2000) found that dietary high-level fat as an energy source results in a higher milk energy output and energy retention in piglets. In the present study, sows fed a 3% SO diet lost less back fat compared to sows fed a diet without SO during lactation,

Table 6. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on milk fat globule size¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of sows	8	8	8	8				
Colostrum, μm								
D ₁₀ ²	0.90	1.09	0.93	1.04	0.037	0.056	0.097	0.545
D ₅₀	1.79	2.01	1.9	2.14	0.061	0.065	0.337	0.944
D ₉₀	4.05	4.40	4.29	4.68	0.248	0.482	0.621	0.969
D _A ³	2.17	2.47	2.30	2.51	0.087	0.171	0.630	0.788
Milk (d 11 of lactation), μm								
D ₁₀ ²	1.45 ^a	1.46 ^a	1.32 ^b	1.36 ^{a,b}	0.019	0.348	0.001	0.535
D ₅₀	3.23 ^a	3.18 ^a	2.78 ^b	2.95 ^{a,b}	0.065	0.610	0.007	0.340
D ₉₀	6.12	6.66	5.20	5.47	0.266	0.439	0.051	0.792
D _A ³	3.53 ^{ab}	3.69 ^a	3.06 ^b	3.20 ^{a,b}	0.104	0.451	0.023	0.976

^{a,b}Mean values within a row without a common superscript differ significantly ($P < 0.05$).

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate.

²D₁₀ is the diameter that represents 10% of the globule volume, with 50% for D₅₀ and 90% for D₉₀.

³D_A is the average diameter of milk fat globules.

Table 7. Effects of feeding sodium stearoyl-2-lactylate diets to lactating sows on plasma biochemistry index¹

Item	Treatment				SEM	P-value		
	Control	SO	SSL	SO + SSL		SO	SSL	SO × SSL
No. of sows	8	8	8	8				
Sow (d 1 of lactation)								
CHOL, mmol/L	1.23	1.43	1.53	1.55	0.071	0.448	0.152	0.527
TG, mmol/L	0.25	0.31	0.27	0.23	0.022	0.782	0.521	0.239
HDL-C, mmol/L	0.54	0.58	0.56	0.62	0.041	0.558	0.719	0.864
LDL-C, mmol/L	0.66	0.80	0.86	0.86	0.046	0.470	0.174	0.481
Sow (d 11 of lactation)								
CHOL, mmol/L	1.74	1.92	1.70	2.06	0.078	0.097	0.741	0.537
TG, mmol/L	0.20	0.32	0.27	0.25	0.030	0.658	0.778	0.169
HDL-C, mmol/L	0.78	0.87	0.62	0.88	0.047	0.059	0.424	0.346
LDL-C, mmol/L	0.82	0.96	0.94	1.15	0.049	0.062	0.102	0.681

¹Abbreviations: SO = soybean oil, SSL = sodium stearoyl-2-lactylate, CHOL = cholesterol, TG = triglyceride, HDL-C = high-density lipoprotein cholesterol, LDL-C = low-density lipoprotein cholesterol.

which might be due to the relative higher-energy value of a 3% SO diet compared to a diet without SO supplementation. In addition, sows fed diets without SO consumed more feed than sows fed 3% SO diets, but energy intake was not affected. In agreement with the findings of the present study, Weeden et al. (1994) did not notice any difference in energy intake when adding 3% SO to the lactating diets of sows, but the ADFI was decreased significantly in sows receiving 3% SO compared to sows that were not fed supplemental SO. Some researchers reported that chickens fed low-energy diets showed higher ADFI (Azman and Ciftci, 2004; Jin et al., 2012). In this study, for litter size and weight at birth, no differences among the dietary treatments were observed. One possible reason is that it seems unlikely that the variations in dietary supplemental SSL and/or SO within a short period of feeding could change the litter size and weight at birth. In the present experiment, supplementation with SO and SSL had no interactive effect on sow and litter performance. One possible explanation might be that the addition of SO in diets just increased the energy value rather than improving the digestibility of crude fat. Actually, in this study, the control diet (no added fat) had greater fat digestibility than diets with added fat. Similarly, Zhao et al. (2017) found a tendency in which the digestibility of cottonseed oil decreased as the inclusion level of cottonseed oil increased. Then, fat digestibility was increased for sows fed SO plus SSL compared to sows fed SO without an emulsifier. Supplementation of SSL in corn-soybean diets including SO increased the digestibility of nutrients; however, there was no direct relationship between energy value and nutrient digestibility. Additionally, Jones et al. (1992) also concluded that the addition of emulsifiers increased digestibility of nutrients but had a minimal effect on growth performance in weanling pigs.

Apparent Total Tract Digestibility of Nutrients

A few studies observed beneficial effects of SSL supplementation on the growth performance or digestibility of nutrients of broilers and growing pigs (Chronakis et al., 2004; Gheisar et al., 2015). In this study, higher digestibility of nutrients (EE, CP, Ca, and P) was observed in the diet including 0.1% supplemental SSL. One possible mechanism is that addition of SSL to the diet can effectively decrease the size of fat globules and increase the total available surface for enzymatic digestion. In agreement with this result, Gheisar et al. (2015) reported that the addition of lysolecithin and SSL to diets improved the digestibility of energy and nitrogen. Danek et al. (2005) noted that supplementation of a lecithin emulsifier (0.1%) in the feed mixture for piglets after weaning improved the digestibility of crude fat. Neto et al. (2011) suggested that broilers fed a diet with poultry offal fat and supplemented with an emulsifier showed higher digestibility of EE. However, lower digestibility of EE was noted in the diets with 3% supplemental SO compared to other diets. Li et al. (2011) reported that adding fat to the diet of lactating sows did not significantly affect the digestibility of crude fat. One possible reason was that the varying results may be associated with differences in feed palatability, source, and character of diets.

Composition of Colostrum and Milk

The effects of dietary fat supply on the composition of colostrum and milk in sows has been extensively described (Tilton et al., 1999; Lauridsen and Danielsen, 2004). Tilton et al. (1999) concluded that milk composition is changed and litter energy gain is increased in sows consuming tallow-supplemented diets. In this study, higher concentrations of fat, protein, and total solid in milk on d 11 of lactation were noted in sows fed

0.1% SSL and/or 3% SO diets. The higher energy value of SO might contribute to the differences in milk composition. Probably, the reason is that in the metabolic process, oil produced the lowest heat increment compared to protein and carbohydrates, which suggests that adding fat to the diet of lactating sows could improve the efficiency of dietary fat transforming into milk fat. In agreement with the present study, Shurson and Irvin (1992) found a higher milk fat concentration in sows fed a fat-rich diet compared to the control group. In addition, Jones et al. (2002) reported that the fat concentration of milk increased in response to dietary fat. Chapman et al. (2000) showed that rats consuming a high-fat diet increased the activity of lipoprotein lipase in blood and breast tissues, which promoted the release of fatty acids and the absorption of fatty acids by breast cells in the blood and also improved the fat and energy content of milk. For colostrum, no differences among the dietary treatments were noted in the colostrum composition. One possible reason is that the variations in dietary supplemental emulsifier and/or fat within a short period of feeding are not able to change the milk composition.

Distribution of Milk Fat Globule Size

Little research has studied the effects of SSL on MFG size and the composition of sow milk. In sow milk, MFG are differently dispersed with reduced diameters, which offers a greater attack surface compared to bovine milk (Faustini et al., 2010). They are composed of a triglyceride core and are surrounded by a natural biological membrane (Fauquant et al., 2005). Faustini et al. (2010) concluded that MFG diameter increases with milk fat content, whereas an inverse relationship, although not significant, was observed between globular diameter and lactation day. Wiking et al. (2003) reported that the MFG in milk had a high level of fat with a large average diameter.

These observations can help us to achieve a better understanding of the relationships between MFG diameter, lipid composition, and the nutritional characteristics of milk. Milk fat globules can be seen as lipoprotein complexes with micro- and nanoparticle characteristics (Argov et al., 2008) that influence the processes of release and absorption in the gut (Argov et al., 2008; Faustini et al., 2010). Soybean lecithin is a natural surfactant, and the presence of a single surfactant results in a dramatic lowering of the MFG size; the near absence of surfactants results in a larger value for the size of the fat globules (Robin et al., 1992). As a food emulsifier, SSL is rarely used in the feed industry. In previous studies, some researchers found that the role of SSL was similar to feeding emulsifiers (such as lysophospholipids and lecithin) that had been used extensively in feed

industry. For example, Gheisar et al. (2015) suggested that the addition of SSL to the diet of broiler chickens in the late feeding stage is beneficial to the growth performance and digestibility of energy and nitrogen. In the present research, D_A , D_{10} , and D_{50} of MFG size on d 11 of lactation were smaller in sows fed 0.1% SSL diets compared to sows not fed SSL. The reason might be that the addition of emulsifiers in the diet promoted the digestibility of fat and broke fat down into smaller fat droplets in the body, which ultimately reduced fat globule particle size in milk. However, different dietary fat contents or emulsifier levels had no significant effect on the MFG size of colostrum. It seems unlikely that the variations in dietary supplemental SSL and/or SO within a short period of feeding can change the MFG diameter.

Plasma Biochemistry Parameters of Sows

The concentrations of CHOL, HDL-C, LDL-C, and TG in plasma are indicators of the level of fat metabolism in the body and the effects of digestibility of fat and carbohydrates. If these indicators are higher in an animal, it can be shown that the dietary fat utilization is higher. In this study, a higher concentration of CHOL was observed, and it could be speculated there was a higher fat level in the diet of lactating sows with a 3% SO supplement compared to the diet without SO. Supplementing 3% SO in the diet resulted in a tendency toward a higher concentration of CHOL, HDL-C, and LDL-C and a higher CHOL, HDL-C, and LDL-C content on the d 11 of lactation compared to feeding the 0% SO diet. Allan et al. (2001) found a primary effect of fat intake on HDL-C concentration. Thorning et al. (2016) reported that intake of a diet with reduced fat tended to result in higher CHOL and HDL-C compared to intake of a butter diet. Low-density lipoprotein cholesterol is the main form of endogenous cholesterol transport synthesis of tissue in the liver and also reflects the decomposition and transport of lipids in the body and the ability of fat to metabolize in the liver. The ratio of HDL-C/LDL-C is an index of measuring body fat content, and there is a negative correlation between cardiovascular disease and the value of HDL-C/LDL-C. However, in the present study, different dietary fat contents or emulsifier levels had no significant effect on CHOL, TG, HDL-C, and LDL-C profiles on d 1 of lactation. It seems unlikely that variations in dietary fat level or emulsifier content within a short period of feeding can change blood profiles.

Conclusion

The results of this study demonstrate that supplementation of SSL and SO during lactation increased the concentrations of milk fat, proteins, and total solids and

reduced the back fat loss of sows, but no clear benefits were observed for shortening WEI of sows after weaning. Moreover, supplementation of SSL during lactation improved the digestibility of nutrients and decreased the MFG size compared to no SSL supplementation.

LITERATURE CITED

- Allan, F. J., K. G. Thompson, K. A. C. James, B. W. Manktelow, J. P. Koolaard, R. N. Johnson, and P. V. McNutt. 2001. Serum lipoprotein cholesterol and triglyceride concentrations in pigs fed diets containing fish oil, milk fat, olive oil and coconut oil. *Nutr. Res.* 21:785–795. doi:10.1016/S0271-5317(01)00267-6
- Al-Marzooqi, W., and S. Leeson. 1999. Evaluation of dietary supplements of lipase, detergent, and crude porcine pancreas on fat utilization by young broiler chicks. *Poult. Sci.* 78:1561–1566. doi:10.1093/ps/78.11.1561
- AOAC. 1990. Official methods of analysis. 15th ed. Assoc. Off. Anal. Chem., Arlington, VA.
- Argov, N., D. G. Lemay, and J. B. German. 2008. Milk fat globule structure & function; nanoscience comes to milk production. *Trends Food Sci. Technol.* 19:617–623. doi:10.1016/j.tifs.2008.07.006
- Azman, M. A., and M. Ciftci. 2004. Effects of replacing dietary fat with lecithin on broiler chicken zootechnical performance. *Rev. Med. Vet. (Toulouse)* 155:445–448.
- Chapman, C., L. M. Morgan, and M. C. Murphy. 2000. Maternal and early dietary fatty acid intake: Changes in lipid metabolism and liver enzymes in adult rats. *J. Nutr.* 130:146.
- Chronakis, I. S., A. Fredholm, A. O. Triantafyllou, and R. Oste. 2004. Complex formation in aqueous medium of partially hydrolysed oat cereal proteins with sodium stearoyl-2 lactylate (SSL) lipid surfactant and implications for bile acids activity. *Colloids Surf. B Biointerfaces* 35:175. doi:10.1016/j.colsurfb.2004.03.011
- Danek, P., A. Paseka, J. Smola, J. Ondráček, R. Bečková, and M. Rozkot. 2005. Influence of lecithin emulsifier on the utilisation of nutrients and growth of piglets after weaning. *Czech J. Anim. Sci.* 50:459–465.
- Fauquant, C., V. Briard, N. Leconte, and M. C. Michalski. 2005. Differently sized native milk fat globules separated by micro-filtration: Fatty acid composition of the milk fat globule membrane and triglyceride core. *Eur. J. Lipid Sci. Technol.* 107:80–86. doi:10.1002/ejlt.200401063
- Faustini, M., C. Colombani, D. Vigo, R. Communod, V. Russo, T. Chlapanidas, E. Munari, A. Morandotti, and M. L. Torre. 2010. Dimensional analysis of milk fat globules in sow milk: Effects of the lactation stage and fat content and comparison with vaccine milk. *Vet. Res. Commun.* 34(Suppl. 1):29–32. doi:10.1007/s11259-010-9382-5
- Gallier, S., X. Q. Zhu, S. M. Rutherford, A. Ye, P. J. Moughan, and H. Singh. 2013. In vivo digestion of bovine milk fat globules: Effect of processing and interfacial structural changes. II. Upper digestive tract digestion. *Food Chem.* 141:3215–3223. doi:10.1016/j.foodchem.2013.06.019
- Gerritsen, R., A. J. V. Dijk, K. Rethy, and P. Bikker. 2010. The effect of blends of organic acids on apparent faecal digestibility in piglets. *Livest. Sci.* 134:246–248. doi:10.1016/j.livsci.2010.06.154
- Gheisar, M. M., A. Hosseindoust, H. B. Kim, and I. H. Kim. 2015. Effects of lysolecithin and sodium stearoyl-2-lactylate on growth performance and nutrient digestibility in broilers. *Korean J. Poult. Sci.* 42:133–137. doi:10.5536/KJPS.2015.42.2.133
- Gu, X., and D. Li. 2003. Fat nutrition and metabolism in piglets: A review. *Anim. Feed Sci. Technol.* 109:151–170. doi:10.1016/S0377-8401(03)00171-8
- Jin, H. C., P. Y. Zhao, and I. H. Kim. 2012. Effects of emulsifier and multi-enzyme in different energy density diet on growth performance, blood profiles, and relative organ weight in broiler chickens. *J. Agric. Sci.* 4:161–168.
- Jones, D. B., J. D. Hancock, D. L. Harmon, and C. E. Walker. 1992. Effects of exogenous emulsifiers and fat sources on nutrient digestibility, serum lipids, and growth performance in weanling pigs. *J. Anim. Sci.* 70:3473–3482. doi:10.2527/1992.70113473x
- Jones, G. M., S. A. Edwards, A. G. Sinclair, F. E. Gebbie, J. A. Rooke, S. Jagger, and S. Hoste. 2002. The effect of maize starch or soyabean oil as energy sources in lactation on sow and piglet performance in association with sow metabolic state around peak lactation. *Anim. Sci.* 75:57–66. doi:10.1017/S1357729800052838
- Lauridsen, C., and V. Danielsen. 2004. Lactational dietary fat levels and sources influence milk composition and performance of sows and their progeny. *Livest. Prod. Sci.* 91:95–105. doi:10.1016/j.livprodsci.2004.07.014
- Lauridsen, C., and S. K. Jensen. 2007. Lipid composition of lactational diets influences the fatty acid profile of the progeny before and after suckling. *Animal* 1:952–962. doi:10.1017/S175173110700033X
- Li, B., D. W. Chen, X. Y. Lei, J. Zhang, H. Chen, Q. Mao, and B. Yu. 2011. Effects of different fatty sources on reproductive performance and nutrient digestibility of lactating sows. *Nutr. Feed.* 47:31–34.
- Lopez, C., V. Briardbion, O. Ménard, E. Beaucher, F. Rousseau, J. Fauquant, N. Leconte, and B. Robert. 2011. Fat globules selected from whole milk according to their size: Different compositions and structure of the biomembrane, revealing sphingomyelin-rich domains. *Food Chem.* 125:355–368. doi:10.1016/j.foodchem.2010.09.005
- Martini, M., F. Salari, and I. Altomonte. 2016. The macrostructure of milk lipids: The fat globules. *Crit. Rev. Food Sci. Nutr.* 56:1209. doi:10.1080/10408398.2012.758626
- Neto, A. G., A. C. Pezzato, J. R. Sartori, C. Mori, V. C. Cruz, V. B. Fascina, D. F. Pinheiro, L. A. Madeira, and J. C. Gonçalves. 2011. Emulsifier in broiler diets containing different fat sources. *Braz. J. Poult. Sci.* 13:119–125.
- NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.
- Robin, O., V. Blanchot, J. C. Vuillemand, and P. Paquin. 1992. Microfluidization of dairy model emulsions. I. Preparation of emulsions and influence of processing and formulation on the size distribution of milk fat globules. *Dairy Sci. Technol.* 72:511–531. doi:10.1051/ait:1992637
- Rosero, D. S. 2012. Response by the modern lactating sow and progeny to source and level of supplemental dietary fat during high ambient temperatures. *J. Anim. Sci.* 90:2609–2619. doi:10.2527/jas.2011-4242
- Shurson, G. C., and K. M. Irvin. 1992. Effects of genetic line and supplemental dietary fat on lactation performance of Duroc and Landrace sows. *J. Anim. Sci.* 70:2942–2949. doi:10.2527/1992.70102942x
- Soares, M., and C. J. Lopezbote. 2002. Effects of dietary lecithin and fat unsaturation on nutrient utilisation in weaned piglets. *Anim. Feed Sci. Technol.* 95:169–177. doi:10.1016/S0377-8401(01)00324-8

- Thorning, T. K., A. Raben, N. T. Bendsen, H. H. Jørgensen, P. Kiilerich, Y. Ardö, J. K. Lorenzen, K. Kristiansen, and A. Astrup. 2016. Importance of the fat content within the cheese-matrix for blood lipid profile, faecal fat excretion, and gut microbiome in growing pigs. *Int. Dairy J.* 61:67–75. doi:10.1016/j.idairyj.2016.04.006
- Tilton, S. L., P. S. Miller, A. J. Lewis, D. E. Reese, and P. M. Ermer. 1999. Addition of fat to the diets of lactating sows: I. Effects on milk production and composition and carcass composition of the litter at weaning. *J. Anim. Sci.* 77:2491–2500. doi:10.2527/1999.7792491x
- van den Brand, H., M. J. W. Heetkamp, N. M. Soede, J. W. Schrama, and B. Kemp. 2000. Energy balance of lactating primiparous sows as affected by feeding level and dietary energy source. *J. Anim. Sci.* 78:1520–1528. doi:10.2527/2000.7861520x
- Verger, P., M. Chambolle, P. Babayou, B. S. Le, and J. L. Volatier. 1998. Estimation of the distribution of the maximum theoretical intake for ten additives in France. *Food Addit. Contam.* 15:759–766. doi:10.1080/02652039809374707
- Weeden, T. L., J. L. Nelssen, R. C. Thaler, G. E. Fitzner, and R. D. Goodband. 1994. Effect of dietary protein and supplemental soyabean oil fed during lactation on sow and litter performance through two parities. *Anim. Feed Sci. Technol.* 45:211–226. doi:10.1016/0377-8401(94)90028-0
- Wiking, L., L. Björck, and J. H. Nielsen. 2003. Influence of feed composition on stability of fat globules during pumping of raw milk. *Int. Dairy J.* 13:797–803. doi:10.1016/S0958-6946(03)00110-9
- Zhao, J. B., Z. C. Li, M. B. Lyu, L. Liu, X. S. Piao, and D. F. Li. 2017. Evaluation of available energy and total tract digestibility of acid-hydrolyzed ether extract of cottonseed oil for growing pigs by the difference and regression methods. *Asian-Australas. J. Anim. Sci.* 30:712–719. doi:10.5713/ajas.16.0546