Efficacy of energy supplementation on growth performance and immune response of suckling pigs

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ABSTRACT: Three studies were performed to determine the effects of oral energy sources on the performance, immune status, and intestinal morphology of piglets. In Exp. 1, 50 litters were selected based on genotype and parity order to determine the optimum amount of supplemental energy for neonatal pigs. They were distributed according to a 5×5 Latin square design, in which columns were represented by 5 sows and rows were represented by 5 newborn weight categories. Treatments consisted of 2 oral doses of 0, 2, 4, 8, or 16 mL of rice bran oil (RBO). There was a positive response of RBO on BW with a numerical difference ($P = 0.12$) and a significant linear effect ($P = 0.04$) at weaning. In Exp. 2, litters ($n = 340$) were randomly allotted to a 2×2 factorial arrangement of treatments: RBO supplemented either through oral doses (without supplementation or with 2 mL of RBO) or through prestarter feed (without supplementation or with 2% of RBO replacing 2% of soybean oil). Piglets orally receiving RBO showed a numerical increase in BW at weaning ($P = 0.101$) compared with the control group. Moreover, piglets supplemented by prestarter feed tended to increase feed intake ($P = 0.084$). In Exp. 3, litters ($n = 245$) were selected based

on genotype and parity order and they were distributed according to a 7×7 Latin square design planned in the same way as in Exp. 1. Each neonatal pig within a litter was randomly assigned to 1 of 7 treatments: 1) control (no supplementation), 2) 2 mL of RBO enriched with omega-3 fatty acids, 3) 2.33 mL of pure glycerin, 4) 1.3 mL of soybean oil, 5) 1.4 mL of linseed oil, 6) 1.68 mL of coconut oil, and 7) 2 mL of RBO. Animal performance was analyzed using 2 data sets: all data (average initial BW of 1.479 kg) and low birth weight (LBW) piglet data (≤ 1.220 kg initial BW with average of 0.985 kg). Body weight or BW gain (BWG) were not different among treatments ($P > 0.10$) when all data were analyzed. However, LBW piglets fed coconut oil tended to increase BW ($P = 0.099$) during the first week. In conclusion, the oral use of RBO may increase BW at weaning and the supplementation by prestarter feed may enhance the feed intake of piglets. In addition, coconut oil may increase BW of LBW piglets in the first week of life without affecting mortality, immune response, or gut morphology. The routine practice of oral supplementation of energy for newborn pigs could be an important tool in swine production.

Key words: coconut oil, glycerin, linseed oil, rice bran oil, soybean oil

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INTRODUCTION

The swine industry has shown a great technological progress during the last years, especially due to major advances in genetics. A high number of piglets produced per litter has been observed, sometimes more than 15 piglets (Guo et al., 2015), which is desirable to improve production efficiency by enhancing the number of finished pigs. However, increasing litter size may result in rising heterogeneity between littermates by enhancing piglets with lower birth weight, which may lead to increased pig mortality (Rutherford et al., 2013).

Most preweaning deaths occur during the first 3 d after birth. This is a critical period, in which piglets must quickly switch from carbohydrates as energy sources provided by the uterus to mostly lipids supplied by milk (Lin et al., 2015). Before the establishment of suckling, the newborn depends on its own scarce hepatic glycogen stores to maintain blood glucose (Gu and Li, 2003), showing the importance of milk consumption. The concentration of milk fat is increased from 6% at birth to 10% after 24 h, confirming milk fat as the primary energy source for newborn pigs after birth (Lin et al., 2015). Unfortunately, several piglets do not have access to milk due to reduced number of teats and intense competition between littermates, leading these animals to face a critical situation, usually resulting in starvation and death.

The administration of alternative sources of energy in the first 48 h after birth appears to provide a promising approach to reducing losses during the lactation period. The hypothesis that a supplementary energy source stimulates performance by sparing stored nutrients and increasing available energy was tested through studying the effects of different energy sources on performance, immune status, and intestinal morphology of neonatal pigs.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee of the Federal University of Pelotas, Pelotas, Brazil, reviewed and approved the experimental protocol (3979/13).

Animals, Experimental Design, and Dietary Treatments

Experiments were conducted in 2 different commercial farms located in southern Brazil.

Experiment 1—Rice Bran Oil Level. Fifty litters were selected based on genotype and parity, and they were

distributed according to a 5×5 Latin square design, with sows being the columns and piglet weight categories the rows. Each piglet was considered an experimental unit. After all piglets in the same litter were born, birth weights were recorded and the 5 piglets with BW closest to the litter average were chosen and each one was assigned to a different treatment. Treatments consisted of 0, 2, 4, 8, or 16 mL of rice bran oil (RBO). Piglets were fed by a gastric tube immediately after ingestion of colostrum and 24 h later.

Experiment 2—Rice Bran Oil by Oral Supplementation or in Prestarter Diet. A total of 340 litters were randomly allotted to 4 treatments in a randomized complete block design based on the genotype and parity of the sows. Treatments were arranged as a 2×2 factorial with RBO oral supplementation—0 or 1 mL—and RBO in the prestarter diet—0 or 2% (replacing 2% of soybean oil). The litter was considered the experimental unit. Rice bran oil contained 1% of γ -oryzanol, 200 IU of vitamin E, and omega-3, omega-6, and omega-9 (linolenic acid, linoleic acid, and oleic acid, respectively; minimum 70%) fatty acids. Piglets were fed 1 mL of RBO immediately after ingestion of colostrum and 24 h later. The RBO supplementation through the prestarter feed was performed by replacing the same amount of soybean oil of the diet. Piglets were given ad libitum access to the prestarter diet from the 7 d dose to weaning.

Experiment 3—Different Energy Sources. A total of 245 litters, selected based on genotype and parity, were distributed according to a 7×7 Latin square design (as seen in Exp. 1), in which each piglet was considered the experimental unit. After all piglets were born in a litter, birth weights were recorded, and the 7 piglets with BW closest to the litter average were chosen, and each one received a different treatment. Treatments consisted of 2 doses (as shown in the Exp. 1) containing one of the following: 1) control (no supplementation), 2) 2 mL of RBO enriched with omega-3, 3) 2.33 mL of pure glycerin, 4) 1.3 mL of soybean oil, 5) 1.4 mL of linseed oil, 6) 1.68 mL of coconut oil, and 7) 2 mL of RBO. The RBO used on this trial was the same used in Exp. 1 and 2. The RBO enriched with omega-3 is a mixture of degummed and neutralized RBO along with canola oil, sunflower oil, and corn oil. Doses used in the third trial were based on the results of the RBO experiments presented in this paper, and all treatments doses were calculated to contain the same amount of energy (10.95 kcal ME/dose), which was based on Sbardella et al. (2012) results.

In Exp. 1 and 3, piglets were individually weighed on day 7 after birth and at weaning, and piglet mortality was recorded daily.

Blood Sampling

In Exp. 1 and 3, blood samples were aseptically collected from the jugular vein into syringes without anticoagulant. Serum samples were separated by centrifuging at $1,500 \times g$ at 4°C for 10 min and frozen at -80°C until further analysis.

Experiment 1—Rice Bran Oil Level. Ten piglets per treatment, totaling 50 piglets, from 2 complete 5×5 Latin squares were used for blood collection. The samples were taken 4 h after the first supplementation and 24 h following this one. Serum samples were used to quantify glucose, triglycerides, urea, creatinine, aspartate aminotransferase (AST), and alanine aminotransferase (ALT), as indicators of metabolism status. Blood chemistry concentrations were measured using commercial test kits (Labtest Diagnóstica S.A., Lagoa Santa, Brazil).

Experiment 3—Different Energy Sources. Seven piglets per treatment, totaling 48 piglets, from 1 complete 7×7 Latin square were used for blood collection. Samples were taken 4 h after the first supplementation and on day 7 after birth. The same blood chemistry parameters described in Exp. 1 were measured in Exp. 3. Serum samples collected on day 7 were also used to measure immunological responses, such as tumor necrosis factor α (TNF α), IL-1, and IL-6. Serum TNF α concentration was measured by ELISA following the manufacturer's procedure (number KSC3011; Invitrogen, Camarillo, CA). Serum IL-1 and IL-6 concentrations were measured by ELISA following the manufacturer's procedure (number ab100754 and ab100755, respectively; Abcam, Cambridge, MA). The results were expressed as picograms per milliliter.

Delayed-Type Hypersensitivity

A delayed-type hypersensitivity (DTH) test was performed to assess in vivo cellular immunity in Exp. 3. Fourteen piglets per treatment, totaling 98 piglets, from 2 complete 7×7 Latin squares were used. The DTH solution was prepared by diluting 20 mg of phytohemagglutinin (PHA; Sigma-Aldrich, Saint Louis, Missouri) in 100 mL of PBS, which represents 200 μg PHA/mL. On day 7 after birth, 0.1 mL of the solution was intradermally injected in the base of the ear in each piglet. As

a negative control, 0.1 mL of PBS solution was injected in the opposite ear of the same subject. Six-millimeter needles were used to inject DTH and PBS solutions. The skin thickness was measured immediately and 24, 48, and 72 h after injection using a digital micrometer (Caliper model; Mitutoyo Corporation, Kawasaki-Shi, Japan).

Intestinal Sampling

In Exp. 3, 7 piglets per treatment from a complete 7×7 Latin square were selected and euthanized on day 7, and the gastrointestinal tract was quickly removed and identified. Middle portions of the duodenum, jejunum, and ileum of each pig were collected and 5-cm sections were obtained. Each section was gently flushed and submerged into an individually marked container of 10% formaldehyde-phosphate buffer for further microscopic morphology evaluation. Samples were sent to the Embrapa Histopathology Laboratory (Concordia, Brazil) for further analysis. Samples were embedded in paraffin thin sectioned, and secured on microscope slides with hematoxylin and eosin staining. Slides were evaluated using an AxioCam ICc3 (Carl Zeiss, Göttingen, Germany) attached to a microscope (Axio Scope A1; Carl Zeiss, Göttingen, Germany) with $40\times$ magnification. An average of 10 measurements of villus height, villus width, and crypt depth were taken from each slide, according to [Shen et al. \(2009\)](#).

Statistical Analysis

All data were checked for normality and homogeneity of variance using the Jarque-Bera test. In Exp. 1, data were analyzed by ANOVA using the MIXED procedure of SAS 9.3 (SAS Inst. Inc., Cary, NC) and means were presented as least squares means ($\pm\text{SEM}$). The statistic model included the fixed effect of RBO, in which sow and weight order were included as random effects. Orthogonal polynomial contrast coefficients were used to determine linear and quadratic effects of increasing RBO level. In Exp. 2, data were analyzed by ANOVA using GLM procedures of SAS 9.3 and reported as least squares means ($\pm\text{SEM}$). The statistical model included the main effects of RBO oral supplementation, RBO supplementation by prestarter feed, RBO oral supplementation $\times$ RBO supplementation $\times$ prestarter feed interaction, and blocks. Data were adjusted for the number of piglets in the litter by covariate analysis. In Exp. 3, data were analyzed by using MIXED procedure of SAS 9.3 and means

were presented as least squares means ($\pm$ SEM). As shown in Table 2, 2 data sets were used to evaluate performance: 1) all collected data (average initial BW of 1.479 kg, ranging from 0.750 to 2.250 kg) and 2) low birth weight (LBW; average initial BW of 0.985 kg, ranging from 0.750 to 1.220 kg) data. Piglet birth weight characterization was based on Getty et al. (2015). The statistic model included the fixed effect of dietary treatment, whereas random effects included farm, season, sows, and weight order. To analyze data from blood, DTH, and intestinal morphology, the statistic model included the fixed effect of dietary treatment; the random effects included sows and weight categories of piglets. Differences between means were identified by Tukey's test at $P < 0.05$, whereas trends were indicated when $P = 0.05$ to 0.10. Differences in mortality rates were assessed by the χ^2 method with PROC FREQ (SAS Inst. Inc.) in all experiments.

RESULTS

Experiment 1

Body weight did not differ among treatments on day 7, but a numerical increase ($P = 0.12$) was observed at weaning, with a significant linear effect ($P = 0.04$), although treatment response was not clear, except that piglets receiving 2 mL of RBO showed some improvement for this variable (Table 1). Besides, piglets from this treatment presented glucose and triglyceride concentrations (8 h after colostrum feeding) numerically higher (8.76 and 44.24%, respectively) than the control group. Serum creatinine, AST, ALT, and urea concentrations were not affected ($P > 0.10$) by RBO supplementation, at either 8 or 32 h after colostrum feeding. No difference was detected in mortality among treatments.

Table 1. Effects of increasing levels of rice bran oil (RBO) as a supplementation source (Exp. 1), and effects of RBO by oral supplementation or in prestarter diet for suckling pigs (Exp. 2)

A. Exp. 1									
Item	RBO, mL					SEM	P value	Linear	Quadratic
	0	2	4	8	16				
BW, kg									
At birth	1.48	1.47	1.48	1.47	1.49	0.03	0.97	0.79	0.62
Day 7	2.80	2.84	2.81	2.83	2.73	0.07	0.46	0.33	0.20
Weaning day	6.02	6.10	5.93	6.00	5.66	0.19	0.12	0.04	0.18
Blood chemistry (8 h after colostrum feeding)									
Creatinine, mg/dL	1.20	1.20	1.05	1.18	1.14	0.12	0.63	0.59	0.45
Glucose, mg/dL	93.60	101.80	95.30	93.40	93.30	7.70	0.63	0.53	0.48
AST, ¹ units/L	181.60	159.40	167.10	174.80	172.50	14.61	0.49	0.92	0.24
ALT, ² units/L	40.00	37.20	35.60	32.80	39.60	2.95	0.49	0.75	0.16
Triglycerides, mg/dL	44.30	63.90	50.50	49.90	42.70	11.05	0.59	0.59	0.28
Urea, mg/dL	26.30	25.40	24.40	28.80	25.90	2.21	0.15	0.49	0.76
Blood chemistry (32 h after colostrum feeding)									
Creatinine, mg/dL	0.66	0.58	0.66	0.66	0.60	0.06	0.71	0.81	0.88
Glucose, mg/dL	114.20	120.11	112.20	119.10	109.00	8.17	0.70	0.60	0.49
AST, units/L	115.40	115.44	103.50	122.10	121.00	13.79	0.65	0.60	0.48
ALT, units/L	49.00	46.22	53.10	49.10	44.78	4.79	0.74	0.76	0.49
Triglycerides, mg/dL	103.22	105.89	107.30	108.60	100.44	17.80	0.99	0.77	0.97
Urea, mg/dL	36.60	28.89	29.00	31.40	30.33	4.27	0.29	0.16	0.20
B. Exp. 2									
Items	Oral supplementation			Supplementation in prestarter feed				P value	
	Without RBO	2 mL of RBO	SEM	Without RBO	2% of RBO	SEM	P value		
BW, kg									
At birth		1.358	1.370	0.02	0.575	1.365	1.363	0.02	0.913
Weaning day		5.436	5.745	0.14	0.101	5.673	5.508	0.14	0.392
Feed intake, kg									
Total period		0.365	0.378	0.14	0.506	0.355	0.389	0.14	0.084

¹AST = aspartate aminotransferase.

²ALT = alanine aminotransferase.

Experiment 2

No significant interaction was detected among RBO oral supplementation and RBO supplementation by prestarter feed. Therefore, we assumed the effects were independent, and the results of RBO oral supplementation and RBO supplementation by prestarter feed main effects are presented separately on [Table 1](#). Piglets receiving 2 RBO oral doses showed a numerical increase of weaning weight compared with the control group (5.745 vs. 5.436 kg; $P = 0.101$), whereas no enhancement in feed intake was observed ($P = 0.506$). Body weight at weaning was not affected by RBO in prestarter feed; however, feed intake tended to increase compared with the control group (0.355 vs. 0.389 kg; $P = 0.084$). As in Exp. 1, piglet mortality was not affected by treatments.

Experiment 3

There was no difference ($P > 0.10$) in either BW or BW gain (BWG) among treatments when all piglets were used in the statistical analysis. However, LBW piglets fed coconut oil showed a tendency to increase BW (8.19%; $P = 0.099$) and numerically increase BWG from 0 to 7 d of life (14.29%; $P = 0.104$). Piglet mortality was not affected by energy supply. Differences in serum creatinine, glucose, AST, ALT, and urea were not detected ([Table 2](#)). However, serum triglycerides concentration was higher in piglets fed glycerin ($P < 0.0001$) 4 h after oral supplementation. On day 7, serum triglycerides concentration was greater in piglets fed RBO ($P = 0.026$) compared with piglets fed coconut oil, but means from other treatments did not differ among them. There were no effects of energy supplementation on immunological and DTH response and intestinal morphology on 7-d-old pigs.

DISCUSSION

Rice bran oil contains mostly long-chain fatty acids (LCFA), represented, on average, by 41% oleic acid (C18:1), 32% linoleic acid (C18:2), and 19% palmitic acid (C16:0). Besides, it also provides other valuable nutritional constituents, such as oryzanol, tocopherols, and tocotrienols, with antioxidant properties ([Danielski et al., 2005](#)) and lower serum cholesterol potential ([Wilson et al., 2007](#)). Previous studies have demonstrated different performance results regarding rice oil inclusion in diets of weaning pigs ([Lima et al., 2009](#); [Sbardella et al., 2012](#)); however, there is a lack of data about the rice oil supplementation for neonatal pigs.

One of the objectives of Exp. 1 was to investigate the best dose of RBO for newborn pigs. Our data showed that piglets fed 2 mL of RBO had an increase on BW, which may be associated with a greater fatty acid oxidation, resulting in higher blood glucose levels and, consequently, increasing available energy. Long-chain fatty acids have been reported to reduce hypoglycemia in newborn pigs ([Lepine et al., 1991, 1993](#)). On the other hand, it is reported in the literature that piglets have a limited capacity to oxidize fat for energy production at birth ([Lin et al., 2015](#)); however, sow milk is rich in oleic acid ([Rosero et al., 2015](#)), which is the major fatty acid component of RBO, which may influence the results.

In Exp. 2, piglets that received 2 RBO oral doses of 1 mL showed an increase of 0.310 kg in BW at weaning. This may help the animals face the postweaning period by enhancing BWG and decreasing the time to reach slaughter weight. This information may be confirmed based on the Gompertz function ([Whittemore and Green, 2001](#)), which can estimate that this increased in BW at weaning reduces 3.34 d to reach 100 kg of BW. Moreover, the replacement of 2% soybean oil in the prestarter feed per 2% RBO enhanced feed intake, which is probably related to a higher palatability of the diet. Furthermore, increasing creep feed intake by piglets in this phase is important for the development of enzymatic systems, by improving the digestive tract ([Xu and Cranwell, 2003](#)) and possibly improving pig performance in postweaning period.

Soybean oil, linseed oil, and RBO used in the third study were composed mostly of LCFA, which is only secondarily used as a fuel by newborn piglet enterocytes during the first 2 d of life, whereas glucose is considered to be the highest energy precursor during this period. Therefore, the colostrum and milk fatty acids are primarily preserved to adipose tissue formation ([Cherbuy et al., 2012](#)). There is a high esterification capacity of LCFA in piglets; however, the mitochondrial intestinal oxidation is limited ([Lin et al., 2015](#)) due to the low activity of pig liver carnitine palmitoyltransferase I, which is expected to double its activity during the first 48 h of life ([Xi et al., 2012](#)). Based on this information, a possible “extra caloric” effect of fat may have occurred in the piglets supplemented with RBO and coconut oil. This “extra caloric” effect may have happened because of a reduction of intestinal transit due to supplemental fat, enabling a better enzymatic action in fats, carbohydrates, and proteins ([Mateos and Sell, 1980](#)).

Table 2. Effects of different energy source on performance, blood chemistry, immune system, and gut morphology of newborn pigs (Exp. 3)

Treatments									
Item	Control	RBO ¹ enriched	Glycerin	Soybean oil	Linseed oil	Coconut oil	RBO	SEM	P value
All piglets									
Birth weight, kg	1.470	1.481	1.476	1.482	1.482	1.485	1.478	0.05	0.292
Day 7 weight, kg	2.798	2.783	2.749	2.763	2.789	2.815	2.805	0.31	0.265
Weaning weight, kg	5.606	5.614	5.454	5.508	5.494	5.610	5.567	0.82	0.241
BWG ² (from day 0 to 7), kg	0.071	0.070	0.069	0.069	0.070	0.072	0.072	0.31	0.256
BWG (from day 8 to weaning), kg	0.221	0.221	0.212	0.215	0.214	0.221	0.219	0.05	0.192
Low weight piglets									
Birth weight, kg	1.199	1.195	1.197	1.203	1.197	1.219	1.197	0.03	0.790
Day 7 weight, kg	2.271 ^a	2.266 ^{ab}	2.217 ^a	2.201 ^a	2.315 ^{ab}	2.457 ^b	2.155 ^a	0.09	0.099
Weaning weight, kg	4.798	4.728	4.513	4.670	4.546	4.754	4.643	0.23	0.943
BWG (from day 0 to 7), kg	0.063	0.062	0.059	0.058	0.065	0.072	0.058	0.01	0.104
BWG (from day 8 to weaning), kg	0.202	0.196	0.184	0.194	0.187	0.198	0.195	0.01	0.923
Blood chemistry (8 h after colostrum feeding)									
Creatinine, mg/dL	1.39	1.19	1.21	1.21	1.32	1.44	1.21	0.18	0.369
Glucose, mg/dL	119.14	98.29	98.29	102.00	93.64	101.57	110.57	14.26	0.541
AST, ³ units/L	176.00	141.86	142.57	150.57	181.90	163.71	159.00	21.53	0.514
ALT, ⁴ units/L	90.14	83.71	80.00	77.86	88.25	81.71	77.57	9.34	0.794
Triglycerides, mg/dL	67.29 ^b	65.57 ^b	698.14 ^a	97.71 ^b	81.82 ^b	68.71 ^b	61.86 ^b	58.09	<0.0001
Urea, mg/dL	23.86	26.71	25.29	31.14	30.74	28.86	27.43	2.71	0.088 ⁵
Blood chemistry (on day 7)									
Creatinine, mg/dL	0.88	1.00	1.05	0.96	0.81	0.94	1.08	0.13	0.774
Glucose, mg/dL	124.74	130.00	126.99	122.71	132.67	127.03	125.00	7.68	0.934
AST, units/L	77.97	91.86	108.92	99.57	83.58	93.47	93.00	12.54	0.691
ALT, units/L	66.87	74.00	84.75	68.57	65.70	66.08	66.14	5.57	0.140
Triglycerides, mg/dL	93.65 ^{ab}	70.57 ^{ab}	111.36 ^{ab}	80.29 ^{ab}	111.69 ^{ab}	63.69 ^a	119.14 ^b	14.76	0.026
Urea, mg/dL	18.18	33.86	21.03	26.86	18.99	17.82	26.57	5.46	0.170
Immunological responses									
TNF α , ⁵ pg/mL	0.15	0.15	0.15	0.15	0.13	0.15	0.14	0.01	0.721
IL-2, pg cytokine/mL	0.32	0.43	0.43	0.79	0.43	0.19	0.34	0.23	0.484
IL-6, pg cytokine/mL DHT, ⁶ mm	0.16	0.19	0.11	0.14	0.21	0.13	0.15	0.04	0.638
At 24 h	5.43	5.69	5.89	5.81	6.36	5.53	6.46	0.59	0.873
At 48 h	0.83	2.76	1.23	1.98	4.53	1.55	2.86	1.13	0.303
Intestinal morphology, μ m									
Duodenum									
Villus height	97.35	101.52	97.14	97.56	96.67	96.59	84.97	7.26	0.753
Crypt depth	47.22	43.38	41.93	37.84	45.23	42.02	38.33	3.23	0.161
Villus height:crypt depth ratio	2.11	2.31	2.36	2.63	2.31	2.38	2.28	0.21	0.647
Jejunum									
Villus height	152.84	109.68	152.45	99.16	104.18	113.57	117.80	15.42	0.089 ⁷
Crypt depth	39.91	34.67	73.58	32.17	28.91	29.22	21.14	17.81	0.525
Villus height:crypt depth ratio	4.26	3.18	4.03	3.36	3.61	4.01	3.74	0.60	0.814
Ileum									
Villus height	81.68	73.22	76.57	80.71	69.42	77.01	83.23	6.34	0.698
Crypt depth	36.06	33.53	32.09	32.93	33.40	32.78	35.51	2.17	0.855
Villus height:crypt depth ratio	2.28	2.19	2.40	2.44	2.10	2.42	2.61	0.18	0.355

^{a,b}Means within a row and without a common superscript differ by Tukey's test ($P < 0.05$).

¹RBO = rice bran oil.

²BWG = BW gain.

³AST = aspartate aminotransferase.

⁴ALT = alanine aminotransferase.

⁵TNF α = tumor necrosis factor- α .

⁶DHT = delayed-type hypersensitivity.

⁷There was no difference between treatments by a Tukey's test.

Triglycerides composed of medium-chain fatty acids (MCFA) and glycerol are more soluble in water than LCFA; consequently, they are able to diffuse directly into the enterocyte to the portal vein, without needing l-carnitine to go through the inner membrane of mitochondria (Gu and Li, 2003). Coconut oil contains about 47% of lauric acid (C12; Dayrit, 2015), which could represent a promising source of energy for suckling pigs. Nevertheless, the literature findings are contradictory, probably because of the difference between amount and time of supplemented doses. Santos et al. (2015) provided two 3-mL doses of coconut oil for piglets 12 h after birth and 36 h after the first dose. Those authors did not find effects of coconut oil on weaning weight for either regular weight (>1.0 kg) or LBW piglets (<1.0 kg). In our study, we also have not found any evidence of coconut oil benefits at weaning. Therefore, there were an increase on BW and BWG on day 7, when data from LBW (<1.220 kg) were analyzed separately, which may be related to a sparing action of the stored carbohydrates and protein in the newborn (Benevenga et al., 1989).

Glycerol is an important precursor of glucose in the metabolism, leading to the hypothesis that glycerin may turn out to be a fast energy source (Kerr et al., 2009). Nevertheless, performance improvements were not related to the use of this treatment in this study. Concerning blood chemistry, piglets fed glycerin presented high-serum triglyceride concentrations. Dietary triglycerides must be hydrolyzed to free fatty acids and monoglycerides to be absorbed by the enterocytes. Once they are absorbed, lipids are repackaged, forming chylomicrons, which are absorbed into the lymph system to be transported to the cells (Gu and Li, 2003). Orally provided glycerol might have been used in the process of repacking, because sow's milk is rich in long chain fatty acids, which is required to form the micelle to be transported and possibly preventing glycerol to be used as a fast energy source.

Hess et al. (2008), using 1-d-old pigs fed polyunsaturated fatty acids (arachidonic acid or eicosapentaenoic acid), did not show any difference in serum creatinine, ALT, AST, or triglycerides concentrations after 16 h of consuming, which demonstrated that this supplementation may be safe for neonates, and it corroborates our results. In the case of MCFA, pigs fed immediately after birth showed lower 24-h nitrogen excretion and enhanced blood glucose compared with control pigs given water, suggesting that MCFA could decrease the breakdown of body protein and improve energy status

(Odle et al., 1989). This could explain the higher BW and BWG in our study; however, our data did not show differences in serum urea and glucose concentration.

Immune-modulating effects of MCFA (Wang et al., 2006) and RBO (Sierra et al., 2005; Yang et al., 2014) have been described in humans as well as antimicrobial and protective effects of MCFA on the gut microarchitecture based on studies in pigs (Dierick et al., 2003). Mixing soybean oil and RBO also could modify the duodenal morphology in weaning pigs (Sbardella et al., 2012). Likewise, linseed oil (rich in 18:3 *n*-3) modifies intestinal fatty acid composition of the ileum of piglets, when provided to sows during gestation and lactation, which may have latter beneficial effects of (*n*-3) PUFA in the prevention and/or reduction of symptoms of intestinal pathologies involving epithelial barrier function defects (Boudry et al., 2009). Neonatal pigs fed PUFA (arachidonic acid and eicosapentaenoic acid) also showed a dose response of intestinal fatty acid composition (Hess et al., 2008). However, the same group (Hess et al., 2008) did not present differences in gut morphology, which confirms the data presented in this study in which differences between treatments related to gut morphology were not detected.

Results from the present study indicate that RBO oral supplementation for piglets may increase weaning weight and, when supplied through the prestarter diet, may increase feed intake. Similarly, coconut oil may increase BW and BWG of LBW piglets in the first week of life without affecting the immune system and intestinal morphology. In conclusion, the use of RBO and coconut oil as supplementary energy sources may improve the performance of suckling pigs, being an important tool to enhance the results during preweaning period.

LITERATURE CITED

- Benevenga, N. J., J. K. Steinman-Goldsworthy, T. D. Crenshaw, and J. Odle. 1989. Utilization of medium-chain triglycerides by neonatal piglets: I. Effects on milk consumption and body fuel utilization. *J. Anim. Sci.* 67:3331–3339. doi:10.2527/jas1989.67123331x
- Boudry, G., V. Douard, J. Mouro, J. P. Lallès, and I. Le Huërou-Luron. 2009. Linseed oil in the maternal diet during gestation and lactation modifies fatty acid composition, mucosal architecture, and mast cell regulation of the ileal barrier in piglets. *J. Nutr.* 139:1110–1117. doi:10.3945/jn.108.102640
- Cherbuy, C., P. Guesnet, M. T. Morel, C. Kohl, M. Thomas, P. H. Duée, and C. Prip-Buus. 2012. Oleate metabolism in pig enterocytes is characterized by an increased oxidation rate in the presence of a high esterification rate within two days after birth. *J. Nutr.* 142:221–226. doi:10.3945/jn.111.146068

- Danielski, L., C. Zetzel, H. Hense, and G. Brunner. 2005. A process line for the production of raffinated rice oil from rice bran. *J. Supercrit. Fluids*. 34:133–141 doi:10.1016/j.supflu.2004.11.006
- Dayrit, F. M. 2015. The properties of lauric acid and their significance in coconut oil. *J. Am. Oil Chem. Soc.* 92:1–15. doi:10.1007/s11746-014-2562-7
- Dierick, N. A., J. A. Decuyper, and I. Degeyter. 2003. The combined use of whole *Cuphea* seeds containing medium chain fatty acids and an exogenous lipase in piglet nutrition. *Arch. Tierernähr.* 57:49–63. doi:10.1080/0003942031000086626
- Getty, C. M., F. N. Almeida, A. A. Baratta, and R. N. Dilger. 2015. Plasma metabolomics indicates metabolic perturbations in low birth weight piglets supplemented with arginine. *J. Anim. Sci.* 93:5754–5763. doi:10.2527/jas.2015-9293
- 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
- Guo, X., O. F. Christensen, T. Ostensen, Y. Wang, M. S. Lund, and G. Su. 2015. Improving genetic evaluation of litter size and piglet mortality for both genotyped and nongenotyped individuals using a single-step method. *J. Anim. Sci.* 93:503–512. doi:10.2527/jas.2014-8331
- Hess, H. A., B. A. Corl, X. Lin, S. K. Jacobi, R. J. Harrell, A. T. Blikslager, and J. Odle. 2008. Enrichment of intestinal mucosal phospholipids with arachidonic and eicosapentanoic acids fed to suckling piglets is dose and time dependent. *J. Nutr.* 138:2164–2171. doi:10.3945/jn.108.094136
- Kerr, B. J., T. E. Weber, W. A. Dozier, 3rd, and M. T. Kidd. 2009. Digestible and metabolizable energy content of crude glycerin originating from different sources in nursery pigs. *J. Anim. Sci.* 87:4042–4049. doi:10.2527/jas.2008-1676
- Lepine, A. J., R. D. Boyd, and D. M. Whitehead. 1991. Effect of colostrum intake on hepatic gluconeogenesis and fatty acid oxidation in the neonatal pig. *J. Anim. Sci.* 69:1966–1974. doi:10.2527/1991.6951966x
- Lepine, A. J., M. Watford, R. D. Boyd, D. A. Ross, and D. M. Whitehead. 1993. Relationship between hepatic fatty acid oxidation and gluconeogenesis in the fasting neonatal pig. *Br. J. Nutr.* 70:81–91. doi:10.1079/BJN19930106
- Lima, G. J. M. M., L. de Wortmann, and A. Mior. 2009. Effect of rice oil supplementation in diets for weanling pigs. *J. Anim. Sci.* 87(Suppl. 2):578.
- Lin, X., S. Jacobi, and J. Odle. 2015. Transplacental induction of fatty acid oxidation in term fetal pigs by the peroxisome proliferator-activated receptor alpha agonist clofibrate. *J. Anim. Sci. Biotechnol.* 6:11. doi:10.1186/s40104-015-0010-7
- Mateos, G. G., and J. L. Sell. 1980. Influence of carbohydrate and supplemental fat source on the metabolizable energy of the diet. *Poult. Sci.* 59:2129–2135. doi:10.3382/ps.0592129
- Odle, J., N. J. Benevenga, and T. D. Crenshaw. 1989. Utilization of medium-chain triglycerides by neonatal piglets: II. Effects of even- and odd-chain triglyceride consumption over the first 2 days of life on blood metabolites and urinary nitrogen excretion. *J. Anim. Sci.* 67:3340–3351. doi:10.2527/jas1989.67123340x
- Rosero, D. S., J. Odle, S. M. Mendoza, R. D. Boyd, V. Fellner, and E. van Heugten. 2015. Impact of dietary lipids on sow milk composition and balance of essential fatty acids during lactation in prolific sows. *J. Anim. Sci.* 93:2935–2947. doi:10.2527/jas.2014-8529
- Rutherford, K. M. D., E. M. Baxter, R. B. D'Eath, S. P. Turner, G. Arnott, R. Roehe, B. Ask, P. Sandøe, V. A. Moustsen, F. Thorup, et al. 2013. The welfare implications of large litter size in the domestic pig I: biological factors. *Anim. Welf.* 22:199–218. doi:10.7120/09627286.22.2.199
- Santos, L. S., F. R. Caldara, S. T. Machado, I. A. Nääs, L. Foppa, R. G. Garcia, R. Moura, and S. P. Machado. 2015. Sows' parity and coconut oil postnatal supplement on piglets performance. *Rev. MVZ Cordoba.* 20:4513–4521.
- Sbardella, S., B. Berencheit, C. Andrade, D. P. Perina, V. V. Almeida, and V. S. Miyada. 2012. Rice oil as a soybean oil replacement in weanling pig diets. *Livest. Sci.* 145:21–27. doi:10.1016/j.livsci.2011.12.015
- Shen, Y. B., X. S. Piao, S. W. Kim, L. Wang, P. Liu, I. Yoon, and Y. G. Zhen. 2009. Effects of yeast culture supplementation on growth performance, intestinal health, and immune response of nursery pigs. *J. Anim. Sci.* 87:2614–2624. doi:10.2527/jas.2008-1512
- Sierra, S., F. Lara-Villoslada, M. Olivares, J. Jiménez, J. Boza, and J. Xaus. 2005. Increased immune response in mice consuming rice bran oil. *Eur. J. Nutr.* 44:509–516. doi:10.1007/s00394-005-0554-y
- Wang, J., X. Wu, N. Simonavicius, H. Tian, and L. Ling. 2006. Medium-chain fatty acids as ligands for orphan G protein-coupled receptor GPR84. *J. Biol. Chem.* 281:34457–34464. doi:10.1074/jbc.M608019200
- Whittemore, C. T., and D. M. Green. 2001. Growth of the young weaned pig. In: M. A. Varley and J. Wiseman, editors, *The weaner pig: Nutrition and management*. CABI Publishing, New York, NY. p. 1–15.
- Wilson, T. A., R. J. Nicolosi, B. Woolfrey, and D. Kritchevsky. 2007. Rice bran oil and oryzanol reduce plasma lipid and lipoprotein cholesterol concentrations and aortic cholesterol ester accumulation to a greater extent than ferulic acid in hypercholesterolemic hamsters. *J. Nutr. Biochem.* 18:105–112. doi:10.1016/j.jnutbio.2006.03.006
- Xi, L., G. Matsey, and J. Odle. 2012. The effect of 5-aminimidazole-4-carboxamide ribonucleoside (AICAR) on fatty acid oxidation in hepatocytes isolated from neonatal piglets. *J. Anim. Sci. Biotechnol.* 3:30. doi:10.1186/2049-1891-3-30
- Xu, R. J., and P. Cranwell. 2003. *The neonatal pig – Gastrointestinal physiology nutrition*. Nottingham Univ. Press, Nottingham, UK.
- Yang, X., K. Wen, C. Tin, G. Li, H. Wang, J. Kocher, K. Pelzer, E. Ryan, and L. Yuan. 2014. Dietary rice bran protects against rotavirus diarrhea and promotes Th1-type immune responses to human rotavirus vaccine in gnotobiotic pigs. *Clin. Vaccine Immunol.* 21:1396–1403. doi:10.1128/CVI.00210-14