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Use of crude glycerol, a biodiesel coproduct, in diets for lactating sows[1,2]

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ABSTRACT: An experiment was conducted to evaluate the effect of dietary crude glycerol in lactating sow diets on sow and litter performance under heat stress conditions. Mixed parity (range = 0 to 13) sows (n = 345; 253 ± 24 kg of BW) were assigned randomly within gestation housing location and parity to 1 of 4 dietary treatments. Treatments consisted of a corn-soybean-based control diet (CON) and 3, 6, or 9% glycerol added at the expense of corn and soybean meal. Liquid crude glycerol was incorporated in the complete diet at the time of mixing. Dietary treatments were imposed on d 109 of gestation (2.25 kg/d) when sows were moved into farrowing rooms. Heat index during lactation in farrowing rooms exceeded 25°C for all sows. At farrowing, sows were allowed ad libitum access to feed throughout lactation. Dietary treatment tended (P = 0.08) to influence ADFI of sows (CON = 6.04 kg/d; 3% = 6.21 kg/d; 6% = 5.69 kg/d; 9% = 6.00 kg/d; pooled SE = 0.18). Up to 9% crude glycerol in the diet had no effect on sow BW and backfat loss, weaning-to-estrus interval, preweaning mortality of piglets, and ADG of piglets. Increasing dietary glycerol linearly reduced (P = 0.10) litter size at weaning (CON = 9.50; 3% = 9.60; 6% = 9.36; 9% = 9.39; pooled SE = 0.08). Daily water consumption was not affected by dietary treatment. Crude glycerol did not affect respiration rates or rectal body temperatures, indicating no efficacy in reducing heat stress of sows. Plasma glycerol concentrations increased linearly ($P < 0.05$) as dietary crude glycerol increased (CON = 1.21 μM; 3% = 1.69 μM; 6% = 7.21 μM; 9% = 29.04 μM; pooled SE = 1.58), but plasma glucose concentrations were not affected. Crude protein content of the milk of sows was not affected (P = 0.16) by dietary treatment. Dry matter (P = 0.07) and crude fat (P = 0.09) content of the milk of the sows tended to increase linearly (DM basis: CON = 17.84%; 3% = 18.43%; 6% = 18.98%; 9% = 18.48%; pooled SE = 0.34; crude fat: CON = 4.78%; 3% = 4.91%; 6% = 5.50%; 9% = 5.24%; pooled SE = 0.30), whereas milk ash concentration tended (P = 0.09) to decrease linearly with increasing dietary glycerol (CON = 0.77%; 3% = 0.79%; 6% = 0.74%; 9% = 0.74%; pooled SE = 0.02). Increasing dietary crude glycerol linearly increased ($P < 0.05$) lactose concentration in the milk of sows (CON = 5.16%; 3% = 5.30%; 6% = 5.43%; 9% = 5.46%; pooled SE = 0.10). Results from this study indicate that lactating sows fed diets containing up to 9% crude glycerol perform similarly to sows fed a standard corn-soybean meal diet.

Key words: glycerol, lactation, sow

INTRODUCTION

Production and use of renewable fuels has increased dramatically in the United States (NBB, 2009; RFA, 2009). Although the production and use of renewable fuels has many benefits, there are challenges associated with utilization of the coproducts. Expansion of biodiesel production has caused an influx of crude glycerol that is not needed for further purification in food, pharmaceutical, and cosmetic industries (Thompson and He, 2006). Lammers et al. (2008b) found that crude glycerol containing 86.95% pure glycerol has a ME content of 3,207 kcal/kg, which is 94% the ME content of

corn (NRC, 1998). Consequently, crude glycerol may have practical applications as an energy source in swine diets.

Glycerol can play an important role in water balance of the body. Glycerol ingestion can enhance water retention of endurance athletes (Robergs and Griffin, 1998; Coutts et al., 2002). Consumption of glycerol-containing water decreased heart rate and rectal temperature of human endurance athletes exercising in heat-stress conditions (Montner et al., 1996; Anderson et al., 2001). Pigs respond to temperature and humidity conditions much like humans (Rozeboom et al., 2000).

In addition to its influence on water balance, dietary glycerol increased plasma glycerol in pigs (Kijora and Kupsch, 1996) and glycerol can be a precursor to glucose production (Robergs and Griffin, 1998). Glucose supply to the mammary gland is the limiting substrate for lactose and consequently milk production (Boyd et al., 1995; Boyd and Kensinger, 1998). Therefore, we hypothesized that dietary crude glycerol in lactating sow diets may reduce heat stress in sows during hot weather and may enhance milk yield of sows and litter growth rate. The objective of this study was to determine the effects of feeding crude glycerol to lactating sows on sow and litter performance during heat stress conditions.

MATERIALS AND METHODS

The experimental protocol used in this study was approved by the Institutional Animal Care and Use Committee of the University of Minnesota.

Animals and Facilities

The experiment was conducted at the University of Minnesota's Southern Research and Outreach Center, Swine Research Facility, in Waseca. Three hundred forty-five mixed-parity (range = 0 to 13) sows (English Belle, GAP Genetics, Winnipeg, Manitoba, Canada) with an initial BW of 253 ± 24 kg were used. Sows were housed in large-group pens equipped with electronic sow feeders (n = 193) or in individual stalls (n = 152) during gestation. The sows assigned to the experiment represented 7 contemporary farrowing groups as part of the Research Center's normal production flow. The experiment began July 24, 2007, and ended November 12, 2007. During this time, average farrowing room heat index temperature (NOAA, 2008) ranged from 25.5 to 27.5°C.

On d 109 of gestation, sows were weighed and backfat depth was determined ultrasonically (Lean-Meater, Renco Corp., Minneapolis, MN) at the last rib. Measurements were taken about 60 mm from the midline on both the right and left side. Sows were moved into environmentally controlled farrowing rooms (n = 8) and placed in individual farrowing stalls (2.13 m long × 0.97 m high × 0.66 m wide; 16 stalls per room) with

Table 1. Analyzed composition of crude glycerol[1]

Item	As-fed, %
Glycerol	86.1
Chloride	3.65
Sodium	2.36
FFA	0.20
Methanol	<0.01

[1]Analyzed by Minnesota Valley Testing Laboratories, New Ulm, MN.

fully slatted floors. Each farrowing stall was equipped with a feeder and a nipple waterer to provide sows with ad libitum access to feed and water. A heat pad (Osborne Industries Inc., Osborne, KS) and a heat lamp were available for newborn piglets. Dietary treatments were assigned to the sows when they moved into a farrowing room.

Dietary Treatments

One lot of crude glycerol was obtained from a biodiesel production facility (SoyMor Biodiesel LLC, Albert Lea, MN) and analyzed for glycerol, Na, Cl, FFA, and methanol content at a commercial laboratory (Minnesota Valley Testing Laboratories, New Ulm, MN; Table 1) before diet formulation. Crude glycerol used in this experiment had a methanol content of less than 100 mg/kg and was representative of crude glycerol available to the commercial feed industry (Kerr et al., 2009). Dietary treatments included 4 corn-soybean meal-based diets with 0, 3, 6, and 9% crude glycerol (Table 2). All dietary treatments were formulated on a standardized ileal digestible AA basis with the ME-to-standardized ileal digestible Lys ratio equalized across experimental diets. Calcium-to-available P ratios were similar across experimental diets. Supplemental sodium chloride was adjusted in the 3, 6, and 9% crude glycerol diets to account for the sodium chloride content of the crude glycerol. Diets were formulated using nutrient concentrations for feed ingredients listed in NRC (1998). Nutrient specifications for the crude glycerol were obtained from laboratory analysis and ME values reported by Lammers et al. (2008b). Experimental diets were formulated to meet or exceed NRC (1998) nutrient recommendations for lactating sows with average prefarrowing BW of 217 kg, expected litter size of 10, and expected piglet ADG of 256 g. One lot of corn, soybean meal, and crude glycerol was used during the entire experiment.

Management and Data Collection

Rooms were ventilated mechanically and thermostats were set to 24°C. Rooms were cooled only by the cool cell ventilation system of the facility with no supplemental cooling provided to sows. Daily temperature and relative humidity were recorded during the afternoon feed-

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

Item	Crude glycerol inclusion, %			
	0	3	6	9
Ingredient, %				
Corn	65.35	62.23	59.20	55.90
Soybean meal 47.5% CP	28.10	28.40	28.60	28.90
Crude glycerol	0.00	3.00	6.00	9.00
Choice white grease	2.50	2.50	2.50	2.50
Dicalcium phosphate	2.00	2.00	2.00	2.00
Limestone	1.00	1.00	1.00	1.00
Salt	0.35	0.17	0.00	0.00
Vitamin-mineral premix[1]	0.50	0.50	0.50	0.50
Biotin premix[2]	0.20	0.20	0.20	0.20
Nutrient content				
DM, %	87.43	87.57	87.60	87.46
Calculated ME,[3] kcal/kg	3,384	3,383	3,383	3,376
CP, %	17.56	17.17	16.43	17.81
Glycerol, %	0.00	2.68	5.20	6.77
Total Ca, %	0.92	0.91	0.70	0.69
Total P, %	0.71	0.77	0.63	0.63
Salt (NaCl), %	0.30	0.30	0.40	0.50
Total Lys, %	0.97	0.93	0.98	1.06
Total Met + Cys, %	0.51	0.51	0.52	0.54
Total Thr, %	0.65	0.64	0.66	0.70
Total Trp, %	0.20	0.20	0.20	0.22
Calculated ME:Lys,[4] kcal/g	349	364	345	318

[1]Vitamin-mineral premix supplied the following per kilogram of diet: vitamin A, 11,013 IU; vitamin D, 2,753 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; thiamine, 1 mg; riboflavin, 10 mg; niacin, 55.1 mg; pantothenic acid, 33 mg; pyridoxine, 1.7 mg; folic acid, 1.7 mg; vitamin B_{12}, 0.1 mg; I, 2.2 mg from ethylenediamine dihydriodide; Se, 0.3 mg from sodium selenite; choline, 495 mg from choline chloride; and metal polysaccharide complexes of zinc sulfate (90.3 mg of Zn), iron sulfate (54 mg of Fe), manganese sulfate (18 mg of Mn), and copper sulfate (5.40 mg of Cu).

[2]Biotin premix supplied 0.51 mg of biotin (JBS United Inc., Sheridan, IN) per kg of diet.

[3]Calculated ME from corn, soybean meal, choice white grease (NRC, 1998), and crude glycerol (Lammers et al., 2008b).

[4]Calculated ME:Lys from corn, soybean meal, choice white grease (NRC, 1998), crude glycerol (Lammers et al., 2008b), and Lys (analyzed value).

ing. Farrowing room temperature and relative humidity were used to calculate heat index (NOAA, 2008). Sows were fed twice daily at 0700 and 1430 h. Sows were fed 2.25 kg/d of their respective dietary treatments from d 109 of gestation until farrowing (d 0 of lactation). At farrowing, the amount of feed offered was gradually increased to allow for ad libitum intake from d 5 until weaning at about 18 d postpartum. Feed offered was weighed and added to each feeder twice daily. Amount of feed offered was adjusted daily to avoid accumulation of uneaten feed in the feeder. Uneaten feed was weighed and recorded at weaning and subtracted from total feed offered to determine average daily feed disappearance.

Sows were weighed and their backfat depth was recorded within 24 h after farrowing. Parity, farrowing date, litter size (total number born, total born alive, number after cross-fostering, and at weaning), and preweaning deaths were also recorded. Litters were cross-fostered to adjust litter size to about 10 piglets per sow. Cross-fostering was completed within 48 h after farrowing and within dietary treatment. Litter weights were measured and recorded at birth, and after cross-fostering.

Sow respiration rates were measured as an indicator of heat stress 3 d before weaning at 1600 h after the sows had settled down from their afternoon feeding. Respiration rates were measured by counting the flank movements of the sow for 10 s and multiplying the observed movements by 6 to determine breaths per minute.

Piglets were weaned at 18 ± 1 d of age. Litter weight was recorded at weaning. At weaning, sow BW and backfat depth were recorded to assess body condition and BW changes during lactation. Sows were then returned to their respective gestation housing system. Sows were monitored daily for estrus using a mature boar through d 10 postweaning.

Feed Sample Collection and Analysis

Feed samples were collected from every batch of experimental feed mixed, and 2 samples were analyzed from each experimental diet. Samples were selected randomly for analysis of DM, CP, AA, Ca, P, NaCl, and glycerol concentrations. Dry matter was analyzed using the vacuum oven method (method 934.01; AOAC, 2006); CP was determined using the Kjeldahl method

[method 984.13 (A–D), AOAC, 2006]; a complete AA profile was determined [method 982.30 E (A, B, C), AOAC, 2006] using an AA analyzer (model L8800, Hitachi High Technologies America Inc., Schaumburg, IL); Ca, P, and NaCl were analyzed using the inductively coupled plasma spectroscopic method [method 958.01 (A, B, D), AOAC, 2006; ICP-OES Optima 2000 DV; Perkin-Elmer, Waltham, MA]; and glycerol was determined by GLC using the trimethylsilyl derivative method (Mattick and Rice, 1970; model 7890A, Agilent Technologies, Santa Clara, CA).

Physiological Measurements

A subset of 84 sows were selected randomly (initial BW = 256 ± 23 kg; 21 sows/treatment) for intensive data collection. Parities of selected sows ranged from 3 to 6. This subset of sows included 47 females from group gestation housing and 37 from individual gestation housing.

Farrowing stalls of selected sows were equipped with a water meter (model DLJSJ50, Daniel L. Jermand Co., Hackensack, NJ) that was plumbed directly into the water supply line for the nipple drinker in the stall. Water meter readings were recorded on d 109 of gestation, d 0 and 10 of lactation, and at weaning to calculate average daily water disappearance (**ADWD**). Body temperatures of sows were measured rectally about 2 h after the afternoon feeding using a digital thermometer 3 d before piglets were weaned. After the piglets were weaned, sows received 1 mL of oxytocin (20 USP) via an intramuscular injection. Composite milk samples from all functional teats (total volume ≥10 mL) were collected manually and analyzed for ash, DM, crude fat, CP, and lactose concentrations. The AOAC (2006) official methods were used to analyze ash (method 942.05), DM (method 934.01) using the vacuum oven method, crude fat [method 920.39 (A)] using ether extraction, and CP [method 984.13 (A-D)] using the Kjeldahl method, and lactose was analyzed using GLC (Prager and Miskiewicz, 1979; model 7890A, Agilent Technologies).

Blood samples were collected from sows 3 d before piglets were weaned about 3 h after the morning feeding. Blood collection (approximately 10 mL) was achieved via venipuncture of a jugular vein with a 20-gauge × 3.81 cm needle into vacuum tubes. Tubes for the isolation of blood glucose contained sodium fluoride (30 mg, Becton, Dickinson and Company, Franklin Lakes, NJ), and tubes for the isolation of blood glycerol contained sodium heparin (143 USP units; Becton, Dickinson and Company) as an anticoagulant. Blood samples were maintained at room temperature for about 60 min and then were centrifuged. Plasma was harvested by centrifugation at 2,900 × g at room temperature for 10 min.

Plasma glucose and glycerol were analyzed using commercially available kits (Sigma-Aldrich, St. Louis, MO) which allowed for quantitative enzymatic deter-

mination of glucose and glycerol with a color endpoint. Plasma glucose and glycerol were analyzed according to kit directions, with the standard curve for glucose determination consisting of glucose concentrations of 1, 0.50, 0.25, 0.125, 0.0625, and 0 mg/mL. Each plasma sample was analyzed in duplicate.

Statistical Analysis

Data were analyzed as a completely randomized design using PROC MIXED (SAS Inst. Inc., Cary, NC). The statistical model for sow and litter performance included the fixed effects of dietary treatment, gestation location, parity group, diet × gestation location, diet × parity, and gestation location × parity. Farrowing group was included as a random effect. To determine parity effects, sows were grouped into 1 of 3 parity groups based on parity on d 109 of gestation. Parity groups were defined as parity group 1 = gilts to first-parity females; parity group 2 = second to sixth parity; and parity group 3 = seventh- to thirteenth-parity sows. Lactation length was included as a covariate in the analysis of affected variables. Temperature and relative humidity in farrowing rooms differed across farrowing groups and rooms, so these factors were used as covariates in analysis of affected variables. Because of differences in litter size after cross-fostering for sows of different parities, litter size after cross-fostering was used as a covariate in the analysis of litter size at weaning, litter weight at weaning, and BW gain of litters.

The statistical model for analysis of milk composition data included the effects of dietary treatment, gestation location, and treatment × gestation location, with farrowing group as a random effect and lactation length as a covariate. Lactation length was used as a covariate because it explained a meaningful portion ($P < 0.05$) of the variation in milk components. The statistical model for respiration rate and body temperatures of selected sows included dietary treatment and gestation location as fixed effects and farrowing group as a random effect. Repeated measures in time were used to analyze sow BW, backfat depth, and ADWD.

Orthogonal polynomial contrasts were used to determine linear, quadratic, and cubic effects of dietary glycerol level. Means separation was achieved by the PDIFF option of SAS with the Tukey-Kramer adjustment. Pooled SE (**PSE**) was calculated by averaging the SE calculated by PROC MIXED for the variable of interest. The variance structure of each variable was tested for homogeneity by performing model fitting procedures within PROC MIXED of SAS. Variables that did not have homogeneous variances had their models fitted to their variance structure to minimize the Akaike information criterion. All reported means are least squares means. The significance level was set at $P < 0.05$, with $0.05 < P < 0.10$ considered a trend. Chi-squared analysis was used to analyze the percentage of sows returning to estrus before 11 d postweaning.

Table 3. Average farrowing room temperature and humidity across contemporary farrowing groups

Farrowing room conditions	Dates of farrowing groups[1]							Pooled SE	P-value
	Jul 24 to Aug 19	Aug 7 to Sep 2	Aug 21 to Sep 16	Sep 5 to Sep 30	Sep 18 to Oct 14	Oct 2 to Oct 28	Oct 16 to Nov 11		
Temperature,[2] °C	26.2	25.4	24.7	25.5	25.5	24.7	24.3	0.16	<0.01
Relative humidity,[2] %	68.5	69.1	61.0	58.3	61.4	57.5	49.4	0.40	<0.01
Heat index,[3] °C	27.5	26.5	25.8	26.3	26.4	25.8	25.5	0.17	<0.01

[1]Jul = July; Aug = August; Sep = September; Oct = October; and Nov = November.

[2]Recorded once daily during afternoon feeding.

[3]Calculated with the following: heat index $= -42.379 + [2.04901523 \times T_F] + [10.14333127 \times RH] - [0.22475541 \times T_F \times RH] - [(6.83783 \times 10^{-3}) \times T_F^2] - [(5.481717 \times 10^{-2}) \times RH^2] + [(1.22874 \times 10^{-3}) \times T_F^2 \times RH] + [(8.5282 \times 10^{-4}) \times T_F \times RH^2] - [(1.99 \times 10^{-6}) \times T_F^2 \times RH^2]$, where T_F = temperature in degrees Fahrenheit and RH = relative humidity expressed as a whole number percent (NOAA, 2008).

RESULTS AND DISCUSSION

Temperature and Relative Humidity

Average temperature and relative humidity of the farrowing rooms were different ($P < 0.01$) across farrowing groups (Table 3). Sows are more sensitive to heat than other ages of pigs, especially during lactation (Charles, 1994; Makkink and Schrama, 1998). Quiniou and Noblet (1999) and Rozeboom et al. (2000) indicated that sows have similar feed intake, BW change, and piglet growth rate during lactation when farrowing room temperature ranges between 18 to 21°C. Sow performance drastically decreases when environmental temperature exceeds 21°C because of heat stress. Pigs sense heat based on temperature and relative humidity much like humans (Rozeboom et al., 2000). Consequently, heat index, a measurement combining temperature and relative humidity (NOAA, 2008), must be considered to assess the magnitude of heat stress experienced by the sows. All 7 farrowing groups experienced room temperature and heat index temperatures above 24°C and therefore experienced some degree of heat stress (Johnston et al., 1999; Quiniou and Noblet, 1999; Eichen et al., 2008) during their lactation period.

Sow and Litter Performance

Only a few interactions were observed between dietary treatment and other factors in the statistical model. Therefore, the focus of the discussion will be on the main effects of glycerol treatments on sow and litter performance. Neither parity of sows nor lactation length was different across dietary treatments (Table 4). Dietary treatments had no effect on sow BW at d 0 and weaning, BW change during lactation, backfat depth at d 0 and weaning, backfat change during lactation, and percentage of sows returning to estrus within 10 d of weaning. However, there was an interaction between diet and parity group for backfat depth of sows at farrowing and weaning. Parity group 1 sows fed 3, 6, or 9% glycerol had more ($P < 0.05$) backfat at farrowing (18.6, 19.8, and 18.3 mm, respectively) and weaning (16.1, 18.1, and 16.3 mm, respectively) than

similarly aged sows fed the CON diet (farrowing, 17.1 mm; weaning, 14.9 mm). In contrast, older sows (parity groups 2 and 3) fed the CON diet had more ($P < 0.05$) backfat depth at farrowing (parity group 2, 15.1 mm; parity group 3, 16.7 mm) and weaning (parity group 2, 14.1 mm; parity group 3, 15.7 mm) than older sows fed 3, 6, or 9% glycerol (farrowing: 14.6, 13.8, and 14.1 mm, respectively, in parity group 2 and 15.0, 15.9, and 17.3 mm, respectively, in parity group 3; weaning: 13.1, 12.9, and 13.0, respectively, in parity group 2 and 14.5, 14.7, and 16.1 mm, respectively, in parity group 3).

Overall, there was a tendency ($P = 0.08$) for ADFI to differ among dietary treatments. Specifically, sows fed the 3% glycerol diet consumed more feed ($P < 0.05$) than those assigned to 6% glycerol. Sows fed the CON diet had similar ADFI compared with sows fed the 3, 6, and 9% glycerol diets. The decrease in ADFI of sows fed the 6% glycerol diet relative to sows fed the 3% glycerol diet is puzzling in light of research conducted with growing-finishing pigs. Some researchers (Kijora and Kupsch, 1996; Lammers et al., 2008a) demonstrated that feeding increasing amounts of crude glycerol up to 15% did not influence ADFI of pigs. In contrast, Stevens et al. (2008) reported a linear increase in ADFI of growing-finishing pigs as crude glycerol increased from 0 to 15% in the diet. Wean-to-estrus interval and percent of sows returning to estrus before 11 d postweaning was similar for all dietary treatments. Dietary treatment and gestation housing type interacted ($P < 0.05$; data not shown) to influence weaning-to-estrus interval. Sows housed in stalls during gestation that were fed CON or 9% glycerol lactation diets had longer weaning-to-estrus intervals (8.1 and 10.9 d, respectively) than sows housed in groups during gestation and fed the CON or 9% glycerol diets (6.1 and 4.5 d, respectively).

At farrowing, litters were cross-fostered to a minimum of 10 piglets per litter whenever possible so there was no difference in initial litter size across dietary treatments. Litter size at weaning tended to decrease linearly ($P = 0.10$) as dietary glycerol increased. Amount of glycerol in the diet did not affect preweaning mortality of piglets, weight of litters at birth (after cross-fostering), weight of litters at weaning, or ADG of piglets. Litters

Table 4. Effect of crude glycerol in lactation diets on sow and litter performance

Item	Crude glycerol inclusion, %				PSE[1]	P-value[2]			
	0	3	6	9		Trt	Lin	Q	Cubic
No. of sows	90	89	85	81	—	—	—	—	—
Parity	4.5	4.4	4.2	4.22	0.15	0.47	0.13	0.63	0.34
Lactation length, d	18.5	18.4	18.2	18.2	0.2	0.47	0.14	0.57	0.35
ADFI, kg	6.04[ab]	6.21[a]	5.69[b]	6.00[ab]	0.18	0.08	0.21	0.62	0.37
Sow BW, kg									
d 0	238.4	240.1	236.8	240.5	2.8	0.74	0.92	0.71	0.38
Weaning	237.1	238.0	234.4	237.5	2.8	0.80	0.76	0.69	0.63
Change[3]	−1.0	−2.0	−2.7	−2.0	1.3	0.85	0.53	0.55	0.75
Backfat depth, mm									
d 0	16.3	16.1	16.5	16.6	0.4	0.81	0.45	0.69	0.89
Weaning[4]	14.9	14.6	15.3	15.2	0.4	0.60	0.36	0.79	0.88
Change[4,5]	−1.4	−1.5	−1.2	−1.4	0.3	0.77	0.68	0.76	0.63
Sows that displayed estrus									
Before 11 d postweaning									
Wean-to-estrus interval, d	5.3	5.2	5.4	5.1	0.2	0.19	0.43	0.22	0.07
Sows displaying estrus, %	93	96	96	91	—	0.49	—	—	—
Litter size									
After cross-fostering[5]	9.86	9.70	9.70	9.65	0.13	0.42	0.20	0.63	0.19
Weaning[6]	9.50	9.60	9.36	9.39	0.08	0.10	0.10	0.67	0.96
Piglet preweaning mortality,[5,7] %	8.53	7.56	8.05	9.49	1.38	0.83	0.61	0.39	0.76
Litter weight, kg									
After cross-fostering	15.90	15.92	15.83	16.21	0.31	0.84	0.59	0.55	0.47
Weaning[8]	60.84	60.13	57.90	59.55	1.08	0.16	0.12	0.22	0.91
Gain[8]	44.77[x]	44.10[xy]	41.93[y]	42.85[xy]	1.00	0.07	0.03	0.34	0.53
Piglet ADG, g	259	255	248	255	6	0.36	0.31	0.21	0.96
Respiration rate of sows,[5,9] bpm	56.0	57.3	56.6	56.9	3.5	0.96	0.85	0.79	0.67

[a,b]Means within a row with different superscripts differ ($P < 0.05$).

[x,y]Means within a row with different superscripts tend to differ ($P = 0.06$).

[1]PSE = pooled SE.

[2]Trt = overall effect of dietary crude glycerol treatment; Lin = linear; Q = quadratic.

[3]Lactation length, average farrowing room temperature, and humidity used as covariates in the statistical model.

[4]Lactation length used as a covariate in the statistical model.

[5]Statistical model was fitted to variance structure.

[6]Litter size after cross-fostering used as a covariate in the statistical model.

[7]Average farrowing room temperature and humidity used as covariates in the statistical model.

[8]Litter size after cross-fostering and lactation length used as covariates in the statistical model.

[9]bpm = breaths per minute.

nursing sows fed the 6% glycerol diet tended ($P = 0.07$) to gain less BW than litters nursing sows fed the control diet. This led to a negative linear response ($P < 0.05$) in litter BW gain as glycerol increased in the diet from 0 to 6%. Presumably, the depressed BW gain of litters nursing sows fed 6% glycerol could be attributed partially to the tendency for decreased ADFI of these sows.

Water Disappearance During Lactation

Overall ADWD was not affected by dietary treatment (Table 5). Water fulfills several physiological functions necessary for life, and many factors, including salt content of the diet, determine the water requirements of swine (NRC, 1998). The increased dietary NaCl content in the 6% (0.40% NaCl) and 9% (0.50% NaCl) glycerol diets did not increase water usage compared with sows fed CON and 3% glycerol. Daily water disappearance observed in this experiment was similar to

the ADWD values (12 to 40 L/d) reported previously by Lightfoot (1978) for lactating sows. The ADWD was calculated for 3 different time periods during this study (gestation d 109 to lactation d 0, d 0 to 10 of lactation, and d 10 of lactation to weaning). Daily water disappearance increased ($P < 0.05$) as lactation progressed (data not shown), but dietary glycerol concentration had no effect on daily water use during any time period during the experiment.

Respiration Rate and Core Body Temperature

Lactation is a very stressful time for a sow, especially in the summer when the temperature is increased, leading to heat stress conditions (Makkink and Schrama, 1998). Pigs feel negative effects of heat based on air temperature and relative humidity (Rozeboom et al., 2000). Heat stress can be assessed in pigs by measuring respiration rate and rectal temperature (Ewing et

Table 5. Effect of crude glycerol in lactation diets on water disappearance, rectal temperature, and sow milk composition

Item	Crude glycerol inclusion, %				PSE[1]	P-value[2]			
	0	3	6	9		Trt	Lin	Q	Cubic
No. of sows	21	21	21	21	—	—	—	—	—
Parity	4.6	4.6	4.4	4.3	0.26	0.80	0.34	0.88	0.66
Overall ADWD,[3] L	37.47	34.63	34.77	41.56	4.08	0.52	0.41	0.24	0.41
Rectal body temperature, °C	39.1	39.3	39.2	39.2	0.11	0.47	0.48	0.34	0.21
Milk composition, %									
DM[4,5]	17.84	18.43	18.98	18.48	0.34	0.24	0.07	0.13	0.47
CP[5]	4.94	5.01	5.22	5.01	0.10	0.16	0.23	0.13	0.77
Crude fat[4,5]	4.78	4.91	5.50	5.24	0.30	0.40	0.09	0.55	0.70
Lactose[4,5]	5.16	5.30	5.43	5.46	0.10	0.23	0.04	0.59	0.19
Ash[4,5]	0.77[xy]	0.79[x]	0.74[y]	0.74[y]	0.02	0.05	0.09	0.65	0.98

[x,y]Means within a row with different superscripts tend to differ ($P = 0.09$).

[1]PSE = pooled SE.

[2]Trt = overall effect of dietary glycerol treatment; Lin = linear; Q = quadratic.

[3]ADWD = average daily water disappearance.

[4]Statistical model was fitted to the variance structure.

[5]Lactation length was used as a covariate in the statistical model.

al., 1999; Rozeboom et al., 2000; Eichen et al., 2008). Shown previously (Table 3), all 7 farrowing groups experienced heat stress conditions with heat index temperatures ranging from 25.5 to 27.5°C. Respiration rates observed in this experiment also indicate that the sows were heat stressed (Table 4). Other researchers (Johnston et al., 1999; Eichen et al., 2008) observed respiration rates ranging from 39 to 74 breaths/min in heat-stressed sows. Respiration rates combined with heat index values above 21°C (Table 3) indicate that sows did experience mild heat stress during this experiment. However, rectal temperatures of sows were similar to normal rectal temperatures of pigs (39.2°C; Merck, 2005). It may be possible that respiration rate is a more sensitive measure of mild heat stress than is rectal temperature.

Glycerol has a role in water balance of the body. In endurance athletes, ingestion of glycerol enhances water retention (Hitchins et al., 1999; Anderson et al., 2001; Coutts et al., 2002), resulting in decreased heart rate and rectal temperature while exercising in heat stress conditions (Murray et al., 1991; Montner et al., 1996; Anderson et al., 2001). These observations led us to hypothesize that dietary glycerol might partially ameliorate negative effects of heat stress on lactating sows. However, dietary crude glycerol had no effect on respiration rate or rectal body temperature of the sows. This finding contrasts with results from human studies, indicating glycerol can help alleviate heat stress through hyperhydrating body tissues. The differing responses between our results and those with human athletes could be related to the form of glycerol supplied for ingestion. In the current study, sows consumed glycerol in dry feed, whereas in the human experiments, glycerol was ingested via a water solution. When glycerol is consumed without additional water intake, it acts as a diuretic and appears to only act as a hyperhydrating agent when ingested with added fluid (Robergs

and Griffin, 1998). It is possible that glycerol would be an effective hydrating agent and help improve heat stress tolerance if delivered to lactating sows through drinking water.

Milk Composition

Crude glycerol in sow lactation diets had no effect on CP content of the milk of sows (Table 5). As dietary crude glycerol increased from 0 to 6%, there was a linear tendency for the DM ($P = 0.07$) and crude fat ($P = 0.09$) content of milk to increase. Milk lactose content increased linearly ($P < 0.05$) as crude glycerol increased in the lactation diet. Blood glucose is the primary precursor for lactose synthesis in milk (Boyd et al., 1995; Boyd and Kensinger, 1998). The remaining milk lactose ($\leq 30\%$) is derived from glycerol and other glucose precursors (Boyd and Kensinger, 1998). The results of this experiment indicate that sows used dietary glycerol for milk lactose synthesis because milk lactose increased as dietary crude glycerol increased. Therefore, dietary crude glycerol was expected to increase milk yield. However, dietary glycerol tended ($P = 0.07$) to decrease litter BW gain and, by inference, milk yield, through a negative linear response ($P < 0.05$; Table 4) as dietary glycerol increased. This presumed decrease in milk yield may be related to litter size because milk yield increases when litter size increases because of a greater number of functional glands (Boyd et al., 1995; Etienne et al., 1998; King, 2000). Therefore, the decrease in number of pigs weaned per litter with increasing glycerol in the lactation diet may have reduced the number of functional glands and, therefore, decreased milk yield and litter BW gain. Ash content of the milk of the sows was affected ($P < 0.05$) by dietary glycerol, with sows fed 3% glycerol secreting more ash in their milk compared with sows fed 6 and 9% glycerol. Milk ash content of CON-fed sows was similar to that of

Table 6. Effect of crude glycerol in lactation diets on blood plasma concentrations of glycerol and glucose in sows

Item	Crude glycerol inclusion, %				PSE[1]	P-value[2]			
	0	3	6	9		Trt	Lin	Q	Cubic
No. of sows	21	21	21	21	—	—	—	—	—
Parity	4.6	4.6	4.4	4.3	0.26	0.80	0.34	0.88	0.66
Glycerol,[3] μM	1.21[a]	1.69[ab]	7.21[b]	29.04[c]	1.58	<0.01	<0.01	<0.01	<0.01
Glucose, mg/mL	0.73	0.74	0.75	0.72	0.03	0.81	0.98	0.38	0.75

[a–c]Means within a row with different superscripts differ ($P < 0.05$).

[1]PSE = pooled SE.

[2]Trt = overall effect of dietary crude glycerol treatment; Lin = linear; Q = quadratic.

[3]Statistical model was fitted to the variance structure.

sows fed the 3% glycerol diet. The milk composition of sows in this experiment was similar to the composition for milk of sows reported by Darragh and Moughan (1998).

Plasma Glycerol and Glucose Concentrations

Increasing dietary crude glycerol increased glycerol concentration in plasma linearly, quadradically, and cubically ($P < 0.01$; Table 6). Glycerol concentrations in blood plasma of sows fed 6% crude glycerol were greater ($P < 0.05$) than CON-fed sows. Glycerol blood plasma concentrations of sows fed 9% crude glycerol were greater ($P < 0.05$) than sows fed the other 3 dietary treatments. Crude glycerol in sow lactation diets did not affect plasma glucose concentrations. The linear increase ($P = 0.09$) of lactose in milk, as dietary crude glycerol increased, indicates that sows metabolize a portion of the excess plasma glycerol in the blood stream to glucose via gluconeogenesis, which is ultimately used in production of lactose by the mammary gland. This may be accomplished while maintaining steady-state concentrations of plasma glucose.

In summary, feeding diets containing up to 9% crude glycerol to lactating sows had no adverse effects on sow and litter performance. The increased dietary salt content, resulting from the greater dietary glycerol inclusion, had no effect on the daily water use of sows. Results from this experiment do not indicate dietary glycerol has any utility in reducing heat stress experienced by the sow during lactation because respiration rates and rectal body temperature were unaffected by diet. Increasing dietary crude glycerol seems to increase concentration of lactose in the milk of sows. Milk ash was increased by feeding 3% glycerol. Increasing dietary glycerol up to 9% increased plasma glycerol concentrations without affecting plasma glucose concentrations. Results of this study indicate that lactating sows fed diets containing up to 9% crude glycerol have acceptable performance compared with sows fed a standard corn-soybean meal diet. Based on the current results, we conclude that up to 9% crude glycerol can be added to sow lactation diets as an alternative energy source in partial replacement of corn.

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