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Use of crude glycerol, a biodiesel co-product, in diets for lactating sows

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Abstract

Since 1999 the biodiesel industry has increased exponentially. As a result, the production of crude glycerol, the co-product of biodiesel, has also increased. An experiment was conducted to evaluate the effects of crude glycerol in diets for lactating sows on sow and litter performance under heat stress conditions. Mixed parity (range = 0 to 13) sows (n = 345; 558 ± 52 lb) were assigned randomly within gestation housing location and parity to 1 of 4 dietary treatments. Treatments consisted of: a corn-soybean meal based control diet; 3% glycerol; 6% glycerol; or 9% glycerol. Dietary treatments were imposed on d 109 of gestation when sows were moved into farrowing rooms. From day 109 of gestation until farrowing, sows received 5 lbs/d of their assigned diet. Beginning at farrowing, sows were allowed *ad libitum* access to feed throughout lactation. Sows and litters were weighed on day 0 of lactation, after litter size was standardized, and at weaning. Last rib backfat depth was recorded ultrasonically on day 0 and at weaning. Respiration rates and rectal body temperatures were recorded 3 days before weaning as an indicator of heat stress. Blood samples were collected 3 days before weaning from a randomly pre-selected group of sows (n = 84; 21 sows/treatment) to determine circulating glycerol and glucose concentrations. Dietary treatment tended ($P = 0.08$) to influence average daily feed intake of sows. Females fed 6% glycerol consumed less feed than sows fed 3% glycerol. Inclusion of up to 9% crude glycerol in the diet had no effect on sow weight and backfat losses, wean-to-estrus interval for sows that returned to estrus within 10 days post weaning, pre-weaning mortality, and average daily gain of piglets. Increasing dietary glycerol tended to linearly reduce ($P = 0.10$) litter size at weaning. Average daily gain of piglets was not influenced by the sow's diet. Overall daily water consumption was not affected ($P > 0.05$) by dietary treatment. Adding glycerol to the diet did not affect respiration rates or rectal body temperatures indicating no efficacy in reducing heat stress of sows. Plasma glycerol levels increased linearly ($P < 0.05$) as crude glycerol increased in the diet. Glucose levels in blood plasma were not affected by dietary treatment. Increasing levels of crude glycerol in the diet had no effect ($P > 0.05$) on crude protein content of sow's milk. Dry matter ($P = 0.07$), crude fat ($P = 0.09$), and ash ($P = 0.09$) content of milk tended to increase linearly with increasing dietary glycerol level. Increasing levels of dietary crude glycerol linearly increased ($P < 0.05$) lactose concentration in sow's milk. Results from this study suggest

that lactating sows fed diets containing up to 9% crude glycerol perform similar to sows fed a standard corn-soybean meal control diet.

Key words: Glycerol, Lactation, Sow

Introduction

With America trying to reduce its reliance on foreign oil, the interest in renewable fuels such as ethanol from corn and biodiesel from soybean oil or animal fat has increased in the United States. There are many benefits from the production and use of these renewable fuels, but there are also challenges. One of the challenges is utilization of the co-products generated from biofuel production. Another challenge is that the production of these renewable fuels will consume raw materials (corn, animal fat and vegetable oil) that would normally be included in livestock feed as energy sources. Since 1999, the United States' production of biodiesel has increased exponentially from 500,000 gallons per year to about 450 million gallons by the end of 2007 (National Biodiesel Board, 2008). Crude glycerol can be refined into pure glycerol and used in the food, pharmaceutical, and cosmetic industries (Thompson and He, 2006). However, with the expansion of biodiesel production there is an increase in crude glycerol production, causing an influx of crude glycerol supply that is not needed for further purification. Also, purifying crude glycerol is costly and not economically feasible for small to moderate sized biodiesel production facilities (Thompson and He, 2006). The overflow of available crude glycerol has researchers looking for new uses for this product. A research group from Iowa State University found crude glycerol is a highly digestible and useful energy source in swine diets. Crude glycerol containing 86.95% pure glycerol has a metabolizable energy content of 1,456 $\pm$ 4.54 kcal/lb, which is 94% the metabolizable energy content of corn (Lammers et al., 2008a).

Glycerol also plays a role in water balance of the body. Several researchers have reported that ingestion of glycerol enhances water retention of endurance athletes. Consumption of glycerol-containing water decreased heart rate and rectal temperature of human endurance athletes exercising in heat stress conditions. Pigs feel heat based on temperature and humidity much like humans; however pigs are more sensitive to the combined effects of temperature and relative humidity because they can not sweat. Lactating sows are especially sensitive to heat. Because of glycerol's role in water retention, we theorized that crude glycerol in a sow's diet during lactation may reduce heat stress in sows during hot weather.

Glycerol in the diet increases the concentration of glycerol in blood plasma of pigs (Kijora and Kupsch, 1996). Glycerol is used by the body to make glucose. The mammary system uses glucose to make lactose for secretion in milk. Milk output is dependent on glucose because it is the limiting ingredient for milk synthesis (Boyd et al., 1995). Therefore, dietary crude glycerol may increase milk yield of sows.

Objective

The objective of this study was to determine the effects of feeding glycerol to lactating sows on sow and litter performance during heat stress conditions.

Procedures

Animals and Facilities

The experimental protocol used in this study was approved by the University of Minnesota Institutional Animal Care and Use Committee. The experiment was conducted at the University of Minnesota's, Southern Research and Outreach Center, Swine Research Facility, in Waseca, Minnesota. Three hundred forty five mixed-parity (range = 0 to 13) sows (English Belle, GAP genetics, Winnipeg, MB, Canada) with an initial body weight of 558 ± 52 lbs were used to study the effects of feeding crude glycerol to lactating sows on sow and litter performance during heat stress conditions. A portion of the sows (n=193) were housed in group pens equipped with electronic sow feeders during gestation. The remaining sows (n=152) were housed in individual stalls during pregnancy. The sows assigned to this experiment represented seven contemporary farrowing groups as part of the research center's normal production flow. Each farrowing group contained about 49 multi-parity sows. The experiment began on July 24, 2007 and ended on November 12, 2007. During this time the average farrowing room temperature ranged from 75.8 °F to 79.1 °F

Sows were washed, weighed, and their last rib backfat depth was recorded on day 109 of gestation when they were moved into farrowing rooms. Sows were placed in an individual farrowing stall (7 ft long x 3.18 ft high x 2.16 ft wide) with fully slatted floors. Each farrowing stall was equipped with a single feeder and a nipple waterer to provide *ad libitum* access to water. A heat mat and a heat lamp were available for newborn piglets. Dietary treatments were assigned to the sows when they moved into the farrowing rooms on day 109 of gestation.

Dietary Treatments

One lot of crude glycerol was obtained from SoyMor Biodiesel LLC in Albert Lea, MN and analyzed at a commercial laboratory prior to finalizing diet formulations (Table 1). Crude glycerol used in this experiment had a methanol content of less than 100 ppm which is below current FDA guidelines. Dietary treatments included four corn-soybean meal based diets with increasing inclusion rates of 0 %, 3%, 6%, and 9% crude glycerol (Table 2). All dietary treatments were formulated on a standardized ileal digestible (SID) amino acid basis, which means all diets were formulated to account for the availability of dietary amino acids to the pigs. Diets were formulated with metabolizable energy to SID lysine ratios equalized across experimental diets. Calcium to available phosphorus ratios were similar across experimental diets. Supplemental salt was adjusted in the 3, 6 and 9% crude glycerol diets to account for the salt content of the crude glycerol used. Diets were formulated using nutrient concentrations for feed ingredients listed in NRC (1998). Experimental diets were formulated to meet or exceed NRC (1998) nutrient recommendations for lactating sows with average pre-farrowing weight of 475 lb, expected litter size of 10, and expected average piglet daily gain of 0.6 lb. 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 75 °F, which was elevated from the normal thermostat setting of 70 °F. Daily temperature and relative humidity was recorded during afternoon feeding and used to calculate heat index. Sows were fed twice daily at 7:00 a.m and 2:30 p.m. Sows were fed 5 lbs of their respective dietary treatments from day 109 of gestation until farrowing (day 0 of lactation). At farrowing, amount of feed offered was gradually increased to allow for *ad libitum* intake from about day 5 after farrowing until weaning. Feed was added to each feeder twice daily at which time the amount given was weighed and recorded. The amount of feed offered was adjusted daily to avoid accumulation of feed in feeders. Uneaten feed was weighed and recorded at weaning.

Sows were weighed and their back fat depth was recorded within 24 hours after farrowing. Backfat depth of sows was determined ultrasonically at the last rib at both the right and left of the midline. Litter weights were measured and recorded at birth, after cross-fostering, and at weaning. Parity, farrowing date, litter size (total number born, total born alive, number after cross-fostering, and at weaning), mummies, stillborn, and pre-weaning deaths were also recorded. Litters were cross-fostered to adjust litter size to about 10 piglets per sow. Cross-fostering was complete within 48 h after farrowing and within dietary treatment.

Sow respiration rates were measured as an indication of heat stress 3 days before weaning at 4:00 p.m after the sows had settled down from their afternoon feeding. Respiration rates were measured by counting the sows' flank movements for 10 seconds. The number of flank movements observed during 10 seconds was multiplied by 6 to determine breaths per minute.

Piglets were weaned at approximately 18 $\pm$ 1 days of age. Litter weight was recorded at weaning. At weaning, sow weight and backfat depth were recorded to assess body condition. Sows were then returned to their respective gestation housing system. Sows were monitored for estrus using a mature boar daily through 10 days post-weaning.

Feed Sample Collection and Analysis

Feed samples were collected from every batch of experimental feed with two samples analyzed from each experimental diet. Samples for analysis were chosen randomly and sent to a commercial lab for analysis of dry matter, crude protein, amino acids, calcium, phosphorus, salt, and glycerol concentrations. One sample of each diet was randomly selected for particle size analysis at a commercial lab.

Water Disappearance, Body Temperature, Milk Composition, Plasma Glucose and Glycerol Concentration Measurements.

Eighty four randomly selected sows (initial body weight = 564 $\pm$ 52 lbs; 21 sows/treatment) were used for more 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 the select sows were equipped with a DLJ Single Jet Water Meter that was plumbed directly into the water supply line for the stall's nipple drinker. Water meter readings were recorded on day 109 of gestation, day 0, and day 10 of lactation, and at weaning to calculate average daily water disappearance. Body temperature was measured once during lactation 3 days before piglets were weaned. Body temperatures were measured rectally about 2 hours after the afternoon feeding using a digital thermometer. Milk samples were collected at weaning. Milk samples (volume $\geq$ 10 mL) were collected manually from all functional teats and analyzed at a commercial laboratory for ash, dry matter, crude fat, crude protein, and lactose concentrations.

Blood samples were collected 3 days before pigs were weaned about 3 hours after the morning feeding and analyzed for circulating glucose and glycerol concentrations. Plasma glucose was analyzed using a glucose assay kit (GAHK-20; Sigma-Aldrich, St. Louis, MO). Plasma glycerol was analyzed with the free glycerol determination kit (FG0100, Sigma-Aldrich, St. Louis, MO).

Statistical Analysis

Data were analyzed as a completely randomized design using the Mixed Procedure of SAS (SAS Inst. Inc, Cary, NC). The statistical model for sow and litter performance included the fixed effects of dietary treatment, gestation location, parity group, and the appropriate 2-way interactions with farrowing group as a random effect. To determine parity effects, sows were grouped into one of three parity groups based on parity on day 109 of gestation. The 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 lactation weight change of sows, backfat depth of sows at weaning, change in backfat depth, litter weight at weaning, and litter gain. 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. Due to differences in litter size after cross-fostering, litter size after cross-fostering was used as a covariate in the analysis of litter size at weaning, litter weight at weaning, and gain of litters during lactation.

The statistical model for analysis of milk composition data included the effects of dietary treatment, gestation location, and their interaction, with farrowing group as a random effect and lactation length as a covariate. The statistical model for respiration rate and body temperatures of selected sows included dietary treatment and gestation location as fixed effects, farrowing group as a random effect.

Orthogonal polynomial contrasts were used to determine linear, quadratic and cubic effects of dietary glycerol level. All reported means are least squares means. Means separation was achieved by the PDIFF option of SAS (SAS Inst. Inc, Cary, NC) with the Tukey-Kramer adjustment. Pooled standard error (PSE) was calculated by averaging the standard errors 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 the Mixed procedure of SAS. Variables that did not have homogeneous variances had their models fitted to their variance structure to minimize the Akaike's Information Criterion. The significance level was set at $P < 0.05$, with $0.05 < P < 0.10$ considered a trend.

Results and Discussion

Temperature and Relative Humidity

The average temperature and relative humidity for each farrowing group was recorded to monitor environmental conditions in the farrowing rooms. 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. Sow's have constant feed intake, body weight change, and piglet growth rate during lactation when farrowing room temperature ranges between 65°F to 70 °F, (Quiniou and Noblet, 1999; Rozeboom et al., 2000). Sow performance drastically decreases above 70 °F due to heat stress. Pigs sense heat based on temperature and relative humidity much like humans do (Rozeboom et al., 2000). Consequently, one must consider heat index, a measurement combining temperature and relative humidity, to assess the magnitude of heat stress experienced by the sows. All seven farrowing groups experienced room temperature and heat index temperatures above 75 °F and therefore experience heat stress conditions during their lactation period.

Sow and Litter Performance

Effect of Dietary Treatment

Each dietary treatment had sows of similar parities and lactation length was similar across dietary treatments (Table 4). Dietary treatments had no effect on sow weight at farrowing and weaning, sow weight change during lactation, sow backfat at farrowing and weaning, sow backfat change during lactation, and percentage of sows returning to estrus within 10 days post-weaning. Overall, there was a tendency ($P = 0.08$) for average daily feed intake (ADFI) to differ among dietary treatments. Sows fed 3% glycerol ate more feed ($P < 0.05$) than those assigned to 6% glycerol. Sows fed the control diet had similar ADFI compared with sows fed the 3%, 6%, and 9% glycerol diets. We have no explanation for the decrease in ADFI of sows fed the 6% glycerol diet relative to sows fed the other diets. In research with grow-finish pigs, feeding increasing levels of crude glycerol up to 15% did not influence ADFI of pigs (Kijora and Kupsch, 1996; Lammers et al., 2008b). The percent of sows returning to estrus within 10 d post-weaning was similar for all dietary treatments.

At farrowing, litters were cross-fostered to equalize initial litter size across dietary treatments. Litter size at weaning tended to decrease linearly ($P = 0.10$) as level of dietary glycerol increased (Table 5). Level of glycerol in the diet did not affect piglet pre-weaning mortality, weight of litters at birth (after cross-fostering), weight of litters at weaning, or ADG of piglets. Litter's of sows fed the 6% glycerol diet tended ($P = 0.07$) to gain less than litters of sows fed the control diet. This led to a negative linear response

($P < 0.05$) in litter gain as glycerol increased in the diet from 0 – 6%. Presumably, the depressed gain of litters nursing sows fed 6% glycerol could be partially attributed to the tendency for decreased ADFI of these sows.

There was no significant diet by gestation housing interaction. There was a treatment by parity interaction ($P < 0.05$) for backfat of sows at farrowing and at weaning, however, this interaction appears to be caused by the much greater backfat depth of gilts and parity 1 sows compared to sows of parity 2 or greater. Significant treatment by parity interactions were not evident for any other performance measure. It should be noted there was a significant ($P < 0.05$) parity by gestation location interaction for ADFI, which appeared because sows of parity 2 or greater, regardless of gestation location, consumed more feed on a daily basis compared to parity group 1 sows. There were no interactions between dietary treatment and parity for litter performance.

Lactation Water Disappearance

Water fulfills a number of physiological functions necessary for life (NRC, 1998). Many factors, including salt content of the diet, determine the water requirements of swine (NRC, 1998). Overall average daily water disappearance (ADWD) was not affected by dietary treatment (Table 6). We expected the increased salt content of the 6 and 9% glycerol would increase ADWD of sows compared to control and 3% glycerol fed sows. Daily water disappearance responses observed in this experiment are typical for lactating sows.

Respiration Rate and Core Body Temperature

Lactation is a very stressful time for a sow, especially in the summer when the temperature is high leading to heat stress conditions. Pigs feel heat based on air temperature and relative humidity just like humans do but sows are more sensitive because they do not sweat (Rozeboom et al., 2000). Sows are more sensitive to heat than pigs at other stages of development. Glycerol plays a role in water balance of the body. In endurance athletes, ingestion of glycerol enhances water retention (Coutts et al., 2002) resulting in decreased heart rate and rectal temperature while exercising in heat-stress conditions (Anderson et al., 2001). In the current experiment, respiration rates and rectal body temperature were used to measure heat stress of sows. As mentioned previously, all seven farrowing groups experienced heat index temperatures that were in the heat stress range for lactating sows. The elevated respiration rates of sows observed in this experiment indicate these females were heat stressed (Table 7). Rectal temperatures of sows were similar to normal rectal temperatures of pigs (102.5 °F; Merck, 2005). Level of crude glycerol in the diet did not affect respiration rate or rectal body temperature of the sows which suggests that dietary glycerol did not help alleviate heat stress of lactating sows.

Milk Composition

Crude glycerol in sow lactation diets had no affect on crude protein content of the sows' milk (Table 8). As dietary crude glycerol increased from zero to 6%, there was a linear tendency for the dry matter ($P = 0.07$) and crude fat ($P = 0.09$) content of milk to increase. Milk lactose level 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 the sow uses dietary glycerol for milk lactose synthesis because milk lactose increased as dietary crude glycerol increased. We expected dietary crude glycerol to increase milk yield. However, dietary glycerol tended ($P = 0.07$) to decrease litter weight gain, and by inference milk yield, through a negative linear response ($P < 0.05$; Table 2.6) as dietary glycerol increased. This presumed decrease in milk yield may be related to litter size as milk yield increases when litter size increases due to a greater number of functional mammary glands (King et al., 2000). Ash content of the sows' milk was affected ($P < 0.05$) by dietary glycerol with sows fed 3% glycerol secreting more ash in their milk compared to sows fed 6% and 9% glycerol. Milk ash content of control fed sows was similar to that of sows fed 3% glycerol. The milk composition of sows in this experiment is comparable to the composition of a typical sow (Darragh and Moughan, 1998) indicating dietary crude glycerol does not negatively alter the composition of sows' milk.

Plasma Glycerol and Glucose Concentrations

Increased dietary crude glycerol elevated glycerol concentration in plasma linearly ($P < 0.0001$; Table 8). Glycerol levels in blood plasma of sows fed 6% crude glycerol were higher ($P < 0.05$) than control fed sows. Glycerol blood plasma levels of sows fed 9% crude glycerol were higher ($P < 0.05$) than sows fed the other three dietary treatments. Crude glycerol in sow lactation diets did not affect the plasma glucose concentrations. The linear increase of lactose in milk as dietary crude glycerol increased indicates the body metabolizes the extra glycerol in the blood stream to glucose via gluconeogenesis. The glucose is ultimately used in production of lactose by the mammary gland.

Summary

In conclusion, feeding up to 9% crude glycerol to lactating sows has no adverse effects on sow or litter performance. The increased dietary salt content resulting from the higher glycerol inclusion had no effect on the sow's daily water consumption. 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. Dietary crude glycerol does have an effect on milk composition as lactose increased linearly with increase in dietary glycerol. Increasing dietary glycerol up to 9 % increases plasma glycerol concentration without influencing plasma glucose concentrations.

Results from this study suggest that lactating sows fed diets containing up to 9% crude glycerol have acceptable performance compared to sows fed a standard corn-soybean meal diet. Based on the current results, we conclude up to 9% crude glycerol can be added to sow lactation diets as an alternative energy source to partially replace corn in the diet.

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Table 1. Analyzed composition of crude glycerol

Characteristic, %	As fed basis
Glycerol	86.1
Salt (NaCl)	6.01
Chloride	3.65
Sodium	2.36
Free fatty acids	0.20
Methanol	< 0.01

Table 2. Composition and analyzed nutrient content of experimental diets

Ingredient, % (As-fed)	Control	3% Glycerol	6% Glycerol	9% Glycerol
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 (NaCl)	0.35	0.17	0.00	0.00
Sow vit-min premix[1]	0.50	0.50	0.50	0.50
Biotin premix[2]	0.20	0.20	0.20	0.20
Total	100	100	100	100
Nutrient, (As-fed)				
Dry matter, %	87.43	87.57	87.60	87.46
Calculated ME, kcal/kg[3]	3384	3383	3383	3376
Crude protein, %	17.56	17.17	16.43	17.81
Glycerol, %	0.00	2.68	5.20	6.77
Total calcium, %	0.92	0.91	0.70	0.69
Total phosphorus,%	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, kcal/g: Total Lys[4]	349	364	345	318
Average particle size, micron	900.0 $\pm$ 2.63	1,061 $\pm$ 2.41	1,093 $\pm$ 2.42	1,230 $\pm$ 2.25

[1]Sow Vit-Min premix supplied the following per kg of diet: vitamin A, 11,013 IU; vitamin D, 2,753 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; niacin, 55.1 mg; pantothenic acid, 33 mg; riboflavin, 10 mg; vitamin B_{12}, 0.1 mg; choline, 495 mg; pyridoxine, 1.7 mg; folic acid, 1.7 mg; thiamine, 1 mg; Zn, 90.3 mg; Mn, 18 mg; Fe, 54 mg; Cu, 5.40 mg; Se, 0.3 mg; I, 2.2 mg.
[2]Biotin premix supplied 0.51 mg of biotin per kg of diet.
[3]Calculated ME from corn, soybean meal, choice white grease (NRC, 1998) and crude glycerol (Lammers et al., 2008a).
[4]Calculated ME:Lysine from corn, soybean meal, choice white grease (NRC, 1998), crude glycerol (Lammers et al., 2008a) and lysine (analyzed value).

Table 3. Average farrowing room temperature and humidity across contemporary farrowing groups (least square means)

Variable	Dates farrowing groups							PSE	P-value
	Jul. 24 – Aug. 19	Aug. 7 – Sept. 2	Aug. 21 – Sept. 16	Sept. 5 – Sept. 30	Sept. 18 – Oct. 14	Oct. 2 – Oct. 28	Oct. 16 – Nov. 11		
Temperature of farrowing room, °F[1]	79.1	77.7	76.5	77.8	77.8	76.5	75.8	0.28	< 0.0001
Relative humidity of farrowing room, %[1]	68.5	69.1	61.0	58.3	61.4	57.5	49.4	0.40	< 0.0001
Heat Index, °F[2]	81.4	79.6	78.4	79.4	79.6	78.4	77.9	0.31	< 0.0001

[1]Recorded once daily during afternoon feeding.

[2]Heat index (°F) = $-42.379 + (2.04901523 \times T_F) + (10.14333127 \times RH) - (0.22475541 \times T_F \times RH) - (6.83783 \times 10^{-3} \times T_F^2) - (5.481717 \times 10^{-2} \times RH^2) + (1.22874 \times 10^{-3} \times T_F^2 \times RH) + (8.5282 \times 10^{-4} \times T_F \times RH^2) - (1.99 \times 10^{-6} \times T_F^2 \times RH^2$; where T_F = temperature in Fahrenheit and RH = relative humidity expressed as a whole number.

Table 4. Effect of crude glycerol level in lactation diets on sow performance (least square means)

	Crude glycerol inclusion, %					P-value			
Variable	**0**	**3**	**6**	**9**	**PSE**	**Trt[1]**	**Linear**	**Quadratic**	**Cubic**
No. of sows	90	89	85	81	---	---	---	---	---
Parity	4.51	4.36	4.22	4.22	0.15	0.47	0.13	0.63	0.34
Lactation length, day	18.51	18.35	18.22	18.23	0.24	0.47	0.14	0.57	0.35
ADFI, lb	13.33[ab]	13.69[a]	12.54[b]	13.23[ab]	0.39	0.08	0.21	0.62	0.37
Sow weight at d 0, lb	525.6	529.5	522.1	530.3	6.12	0.74	0.92	0.71	0.38
Sow weight at weaning, lb	522.9	524.8	516.9	523.8	6.23	0.80	0.76	0.69	0.63
Sow weight change, lb[2]	-2.26	-4.37	-5.86	-4.50	2.89	0.85	0.53	0.55	0.75
Sow backfat at d 0, mm	16.3	16.1	16.5	16.6	0.43	0.81	0.45	0.69	0.89
Sow backfat at weaning, mm[3]	14.9	14.6	15.3	15.2	0.41	0.60	0.36	0.79	0.88
Sow backfat change, mm[3,4]	-1.4	-1.5	-1.2	-1.4	0.25	0.77	0.68	0.76	0.63
Wean-to-estrus interval[4,5]	7.09	5.66	5.56	7.72	0.73	0.08	0.68	0.01	0.63
Wean-to-estrus interval before 11 d	5.29	5.22	5.40	5.06	0.16	0.19	0.43	0.22	0.07
Sows returning to estrus before 11 d, %	93	96	96	91	---	0.49	---	---	---

[1]Overall effect of dietary crude glycerol treatment.
[2]Lactation length, average farrowing room temperature and humidity used as covariates in statistical model.
[3]Lactation length used as covariate in statistical model.
[4]Statistical model was fitted to variance structure.
[5]Results reflect removal of outliers (2 sows from 3% glycerol treatment).
[a,b]Means within a row with different superscripts differ ($P < 0.05$).

Table 5. Effect of crude glycerol level in lactation diets on litter performance (least square means)

	Crude glycerol inclusion, %					P-value			
Variable	0	3	6	9	PSE	Trt[1]	Linear	Quadratic	Cubic
No. of sows	90	89	85	81	---	---	---	---	---
Litter size[2,3]	9.86	9.70	9.70	9.65	0.13	0.42	0.20	0.63	0.19
Litter size at weaning[4]	9.50	9.60	9.36	9.39	0.08	0.10	0.10	0.67	0.96
Piglet pre-weaning mortality, %[3,5]	8.53	7.56	8.05	9.49	1.38	0.83	0.61	0.39	0.76
Litter weight at birth, lb[2]	36.06	35.09	34.90	35.75	0.68	0.84	0.59	0.55	0.47
Litter weight at weaning, lb[6]	134.16	132.59	127.67	131.32	1.88	0.16	0.12	0.22	0.91
Litter weight gain, lb[6]	98.73[x]	97.24[xy]	92.45[y]	94.47[xy]	2.21	0.07	0.03	0.34	0.53
Piglet ADG, lb	0.57	0.56	0.55	0.56	0.01	0.36	0.31	0.21	0.96

[1]Overall effect of dietary crude glycerol treatment

[2] After cross-fostering.

[3]Statistical model was fitted to variance structure.

[4] Litter size after cross-fostering used as covariates in statistical model.

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

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

[x,y]Means within a row with different superscripts tend to differ ($P < 0.10$)

Table 6. Effect of crude glycerol level in lactation diets on water disappearance (least square means)

	Crude glycerol inclusion, %					P-value			
Variable	0	3	6	9	PSE	Trt[1]	Linear	Quadratic	Cubic
No. of sows	21	21	21	21	---	---	---	---	---
Parity	4.58	4.58	4.38	4.31	0.26	0.80	0.34	0.88	0.66
Overall ADWD, gal[2]	9.62	9.08	9.10	10.92	1.00	0.52	0.41	0.24	0.41

[1]Overall effect of dietary glycerol treatment.

[2]ADWD = average daily water disappearance.

Table 7. Effect of crude glycerol level in lactation diets on indicators resulting from heat stress (least square means)

	Crude glycerol inclusion, %					P-value			
Variable	0	3	6	9	PSE	Trt[1]	Linear	Quadratic	Cubic
No. of sows	90	88	85	81	---	---	---	---	---
Parity	4.51	4.36	4.22	4.22	0.15	0.47	0.13	0.63	0.34
Respiration rates, bpm[2,3]	56.05	57.30	56.62	56.90	3.47	0.96	0.85	0.79	0.67
No. of Sows	21	21	21	21	---	---	---	---	---
Parity	4.58	4.58	4.38	4.31	0.26	0.80	0.34	0.88	0.66
Rectal body temperature, °F	102.34	102.74	102.58	102.63	0.20	0.47	0.48	0.34	0.21

[1]Overall effect of dietary crude glycerol treatment.
[2]Statistical model was fitted to variance structure.
[3]bpm = breaths per minute.

Table 8. Effect of crude glycerol level in lactation diets on milk and blood plasma composition (least square means)

	Crude glycerol inclusion, %					P-value			
Variable	0	3	6	9	PSE	Trt[1]	Linear	Quadratic	Cubic
No. of sows	21	21	21	21	---	---	---	---	---
Parity	4.58	4.58	4.38	4.31	0.26	0.80	0.34	0.88	0.66
Milk Composition									
Dry matter, %[2,3]	17.84	18.43	18.98	18.48	0.34	0.24	0.07	0.13	0.47
Crude protein, %[2]	4.94	5.01	5.22	5.01	0.10	0.16	0.23	0.13	0.77
Crude fat, %[2,3]	4.78	4.91	5.50	5.24	0.30	0.40	0.09	0.55	0.70
Lactose, %[2,3]	5.16	5.30	5.43	5.46	0.10	0.23	0.04	0.59	0.19
Ash, %[2,3]	0.77[xy]	0.79[x]	0.74[y]	0.74[y]	0.02	0.05	0.09	0.65	0.98
Blood plasma composition									
Glycerol, µM[3]	1.21[a]	1.69[ab]	7.21[b]	29.04[c]	1.58	< 0.01	< 0.0001	< 0.0001	< 0.0001
Glucose, mg/mL	0.73	0.74	0.75	0.72	0.03	0.81	0.98	0.38	0.75

[1]Overall effect of dietary crude glycerol treatment.
[2]Lactation length was used as covariate in statistical model.
[3]Statistical model was fitted to variance structure.
[x,y]Means within a row with different superscripts tend to differ ($P < 0.10$).
[a,b]Means within a row with different superscripts differ ($P < 0.05$).