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Evaluation of glycerol, a biodiesel co-product, in grow-finish pig diets to support growth and improve pork quality

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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. Two-hundred sixteen crossbred pigs (body weight = 69 ± 3.9 lb) were used to determine the effects of long-term (LT) and short-term (ST) feeding of glycerol on growth performance, carcass traits, and pork quality of grow-finish pigs. Pigs were blocked by initial body weight, and pens within blocks were assigned randomly to 1 of 3 dietary treatments in a 4-phase feeding program (24 pens; 9 pigs/pen). Dietary treatments were: Control – a corn-soybean meal based diet (CON); Long-term – CON + 8% glycerol fed throughout the entire experiment (LT); and Short-term – pigs were fed CON for the first 6 weeks followed by CON + 8% glycerol fed during the last 8 weeks of the experiment (ST). Pigs fed LT had higher ($P < 0.05$) ADG while pigs fed ST tended ($P = 0.07$) to grow faster than CON. Average daily feed intake was greater ($P < 0.05$) for pigs assigned to LT compared to CON, while ST-fed pigs had similar ADFI to CON. Gain:feed ratio (G:F) was greater ($P < 0.05$) for pigs fed ST compared to LT, but both were similar to CON fed pigs. Average daily water disappearance (ADWD) tended to be greater ($P = 0.06$) for LT-fed pigs compared to CON-fed pigs while ST were similar to both LT and CON-fed pigs. Hot carcass weight (HCW) was greater ($P < 0.05$) for LT-fed pigs compared to CON, while ST-fed pigs had HCW similar to both LT and CON-fed pigs. Dressing percentage of CON-fed pigs was similar to both LT and ST-fed pigs, but in LT-fed pigs it was higher ($P < 0.05$) than for ST-fed pigs. Tenth rib BF and loin eye area were not affected by dietary treatment, but there was a trend ($P = 0.08$) for LT-fed pigs to have lower fat-free lean percentage than CON fed pigs. Short-term glycerol feeding increased ($P < 0.05$) belly firmness compared to CON, and tended ($P = 0.09$) to increase belly firmness compared to LT-fed pigs. Dietary treatment had no effect on pork quality of loins based on our taste panel assessment. Grow-finish pigs fed diets containing 8% crude glycerol achieved growth performance similar to pigs fed a typical corn-soybean meal diet. Effects of crude glycerol on carcass traits appear to be limited to improvements in belly firmness with short-term feeding of glycerol.

Key words: Glycerol, Pigs, Pork Quality

Introduction

Crude glycerol is the by-product produced during the transesterification of animal fat or vegetable oil (usually soybean oil) and alcohol (usually methanol) to produce biodiesel. During biodiesel production, 100 lb of animal fat or vegetable oil is combined with 10 lb of alcohol to yield 100 lb of biodiesel and 10 lb of crude glycerol (National Biodiesel Board, 2008). In 2008, biodiesel production capacity was estimated to be 2.61 billion gallons from 176 plants (National Biodiesel Board, 2008). With this level of production capacity, there will be a large amount of crude glycerol produced. Additional uses for crude glycerol need to be identified to prevent the biodiesel industry from being inundated by this co-product.

Crude glycerol can be refined to pure glycerol which is an important industrial product in the food, pharmaceutical, and cosmetic industries (Thompson and He, 2006). However, with the recent expansion of biodiesel production, there is an increase in crude glycerol production, causing a surplus of crude glycerol that is not needed for further purification. Purifying crude glycerol is costly and not economically feasible for small-to-moderately-sized biodiesel production facilities (Thompson and He, 2006). The overflow of available crude glycerol has prompted researchers to look for new uses for the co-product. The production of biodiesel and other biofuels uses ingredients that would normally supply energy to swine diets, so a logical use for the co-products of biofuels is to supply energy in swine diets.

Limited research has been conducted on the use of crude glycerol in swine diets. 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 ± 4.54 kcal/lb which is 94% the metabolizable energy content of corn (Lammers et al., 2008a). This similarity indicates crude glycerol could be a good alternative energy source in swine diets.

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 (Coutts et al., 2002). The influence of glycerol on water balance may extend to muscle tissue after slaughter. A French research group reported dietary glycerol decreased drip loss of loin muscle (Mourot et al., 1994) while an Iowa State research group reported no differences in water-holding capacity of pork (Lammers et al. 2008b). Water-holding capacity of meat is important because added moisture weight adds value to a cut of meat and water-holding capacity affects the juiciness, texture, and flavor of meat (Offer and Knight, 1988).

In previous experiments, researchers have fed crude glycerol to pigs throughout the entire grow-finish period (Mourot et al., 1994) while human experiments have involved consumption of pure glycerol in water solutions only hours before endurance athletic performances (Coutts et al., 2002). Physiological effects of dietary crude glycerol may be different for long term (entire grow-finish period) verses short term (partial grow-finish period) feeding. Xu (2007a) reported that diet changes 3 to 9 weeks pre-slaughter linearly affected carcass characteristics, especially fat quality.

Objectives

The objectives of this study were to determine the effects of long-term (LT) and short-term (ST) feeding of crude glycerol on growth performance, carcass characteristics, and muscle and fat quality of grow-finish pigs.

Procedures

Animal 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 in the swine research unit at the University of Minnesota's West Central Research and Outreach Center in Morris, Minnesota. The experiment took place from November 20, 2007 through February 26, 2008. The pigs were terminal offspring of Yorkshire x Landrace sows sired by Duroc boars.

Two-hundred sixteen crossbred, mixed-sex pigs with initial body weight of 69 ± 3.9 lb were weighed and blocked by initial body weight. Within block, 9 pigs (5 gilts and 4 barrows) were grouped together in a pen. Pens within block were assigned randomly to 1 of 3 dietary treatments. Pigs were housed in an environmentally-controlled grow-finish facility with 24 pens (8 pens per treatment). Target room temperature was set at 20°C. Each pen (5.25 ft x 14.76 ft) was equipped with 1 nipple waterer, one 4-space self-feeder and totally-slatted floors. Pigs were allowed *ad libitum* access to feed and water throughout the experiment.

Dietary Treatments

Crude glycerol used in this study was obtained from SoyMor Biodiesel LLC (Albert Lea, MN). Crude glycerol was analyzed at a commercial laboratory for glycerol, sodium chloride, free fatty acid, and methanol content before use (Table 1). Two lots of crude glycerol were used to complete the experiment. Lot 1 was used during wk 1 to 12 while Lot 2 was included in diets during wk 13 and 14. Pigs received Lot 2 glycerol during the 2 weeks before harvest. The three dietary treatments (Table 2) were: Control - a typical corn-soybean meal based diet fed throughout the experiment (CON); Long-term - CON + 8% crude glycerol throughout the entire experiment (LT); or Short-term - CON for the first 6 weeks of the experiment followed by CON + 8% crude glycerol fed for the last 8 weeks of the experiment (ST). Dietary treatments followed a 4-phase feeding program based on average body weight of pigs in each pen. Body weights for phases 1 to 4 were: 50 to 100 lb, 101 to 150 lb, 151 to 200 lb, and 201 lb to market, respectively. 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 amino acids for pigs. Diets were formulated with metabolizable energy to SID lysine ratio equalized across experimental diets. Calcium to available phosphorus ratios were similar across experimental diets. Experimental diets were formulated to meet or exceed NRC (1998) nutrient requirement recommendations for mixed-sex grow-finish pigs with carcass lean tissue gain of 350 g/d. Supplemental salt was not added to the 8% crude glycerol diet to account for the salt supplied by the crude glycerol.

Growth Performance and Water Disappearance

Growth performance measurements were recorded throughout the experiment. Pigs were weighed individually on the day dietary treatments were imposed and bi-weekly or every week if a diet-phase change was needed during the experiment. The individual weights of the pigs within pens were used to calculate ADG on a pig and pen basis. On weigh days, feed disappearance was also measured to calculate average daily feed intake (ADFI) on a pen basis. Gain efficiency (G:F) was calculated using ADG and ADFI.

Water disappearance measurements were recorded for every pen. Each pen was equipped with a DLJ Single Jet Water Meter that was plumbed directly into the water line supplying each pen's water nipple. Water meter readings were recorded on weigh days and used to calculate average daily water disappearance (ADWD) on a pen basis.

Carcass Measurements

The growth performance portion of the experiment ended when pigs were marketed at a commercial processor. All pigs were marketed on the same day. Hot carcass weight (HCW) was measured on 200 carcasses immediately after slaughter. Twenty-four hours after chilling, backfat (BF) depth was measured at the 10th rib. Loins were retrieved from the left side of carcasses for measurement of loin eye area. Final live weight of pigs along with HCW was used to calculate dressing percentage. Fat-free lean percentage was calculated using 10th rib BF depth, loin eye area, and HCW measurements.

Pork Quality Measurements

A total of 48 pigs, (one barrow and one gilt from each pen) weighing closest to the mean weight of their pen were selected for pork quality measurements. The right belly was collected for belly firmness measurements. Belly length and thickness measurements were recorded as the belly lay flat on a table. The bellies were then draped individually over a smoke stick at 50% of belly length with skin side down. The distance between the 2 ends of the belly was measured as it lay over the smoke stick suspended above the table. The measurements were then used in the Belly Flop Test formula to determine firmness of the bellies. Belly firmness measurements were determined at an environmental temperature of 7.2°C. Minolta color measurements for lightness (L*), redness (a*), and yellowness (b*) were recorded for belly fat located at the flank end of the belly. A Minolta Colorimeter (CR-310 model, Minolta Corp., Ramsey, NJ) was used with calibration to the white setting with values of L* = 97.38, a* = 0.06, and b* = 1.82.

Loins from the right side of the carcass were collected from the packer and delivered to the South Dakota State University Meat Laboratory for evaluation. Drip loss (48 hour) was determined on one chop (1 inch thick) cut from each loin and trimmed of fat. Purge loss was measured on days 7 and 21. Percent purge loss for days 7 and 21 were added together to determine total purge loss.

Subjective scores for color, marbling, and firmness were determined for each loin. Subjective color scores were determined in accordance with National Pork Producers Council (NPPC) Fresh Pork Color Standards (NPPC, 2000). Color scores were based on a 6-point scale with a score of 1 equaling pale, pinkish gray to white pork and a score of 6 equaling dark purplish, red pork (NPPC, 2000). Firmness scores were based on a 3-point scale with 1 equaling soft pork and 3 equaling very firm pork (NPPC, 2000). Marbling scores were based on NPPC's 10-point marbling standards with a score of 1 equaling 1 % intramuscular fat, 2 equaling 2 % intramuscular fat and so on in 1 % increments (NPPC, 2000). Objective color measurements were recorded using a Minolta Colorimeter with calibration to the red setting with values of L* =

45.33, a* = 37.86, and b* = 16.69. Ultimate pH of the loins was measured by a ThermoOrion pH meter (model 330, Thermo Fisher Scientific Inc., Waltham, MA).

Taste panel assessment of cooked loins was assessed by a group of 8 trained panelists. Each loin was assessed for juiciness, tenderness, pork flavor intensity, off-flavor intensity, overall desirability, and off-flavors. The assessment took place over 4 sessions with loins from each of the three dietary treatments (CON, LT, and ST) equally represented in each session.

Statistical Analysis

Data were analyzed in a randomized complete block design using the Mixed Procedure of SAS (SAS Inst. Inc., Cary, NC). The statistical model for overall performance (ADG, ADFI, G:F, and ADWD) included dietary treatment as a fixed effect and block as a random effect. Repeated measures analysis was used to determine effects of dietary treatments on performance data collected across consecutive diet phases. Treatment and time were fixed effects and block was a random effect in the model. Pen was the experimental unit.

The statistical model to analyze carcass characteristics, characteristics of the belly, and pork quality of loins contained dietary treatment and sex as fixed effects and block as a random effect. Belly firmness was analyzed both with and without belly thickness as a covariate. Pen was the experimental unit for carcass characteristics with the sex effect determined by calculating the average carcass characteristics of barrows and gilts within pen. The experimental unit for belly characteristics and loin pork quality was individual carcass. The statistical model for taste panel data contained dietary treatment and sex as fixed effects and block and session as random effects. Chi-square analysis was used to analyze frequency of off-flavors indicated by panelists.

All reported means are least square means. Means separation was accomplished by the PDIFF option of SAS (SAS Inst. Inc, Cary, NC) with Tukey-Kramer adjustment. Pooled standard error was estimated 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 $0.05 < P < 0.10$ indicating a trend.

Results and Discussion

During the experiment, 6 pigs were removed for reasons unrelated to dietary treatments. Of the 6 pigs removed, 2 pigs died (CON and LT), 1 pig was euthanized due to a severe leg injury (CON), and 3 pigs were removed due to a leg injury (CON), severe prolapse (ST), and low body weight gain with no response to antimicrobial treatment (ST). When a pig had to be removed on a non-weigh day, the pen's ADFI and ADWD were adjusted to reflect the loss of the pig. Ten pigs (CON = 3, LT = 4) were excluded from collection of carcass data because they were too light to fit specifications of the packer/processor and could not be harvested on the same day as contemporary pigs.

Growth Performance

Initial body weight of pigs did not differ among treatments (Table 3). Final body weight tended to differ among treatments ($P = 0.09$), because pigs fed CON were lighter than glycerol-fed pigs. Consequently pigs fed CON had lower ADG compared to LT-fed pigs ($P < 0.05$) and tended to have lower ADG than pigs fed glycerol in late finisher ($P < 0.10$). Long-term glycerol-fed pigs and ST-fed pigs had similar ADG. Control-fed pigs had lower ADFI ($P < 0.05$) compared to LT-fed pigs, but similar to ST-fed pigs. Pigs fed glycerol short term had higher G:F than the LT-fed pigs ($P < 0.05$) and G:F similar to CON-fed pigs, while CON-fed pigs tended to have higher ($P = 0.07$) G:F than LT-fed pigs. Average daily water disappearance (ADWD) tended to be different ($P = 0.06$) among dietary treatments with LT-fed pigs using more water than CON-fed pigs, but similar to ST-fed pigs.

Inconsistent results have been reported for ADG, ADFI, and G:F in different studies when crude glycerol was added to grow-finish pig diets at levels ranging from 2.5 to 30%. The inconsistencies in ADG responses reported by different researchers is unclear.

The ADFI results of the current experiment are similar to those in a previous study in which dietary glycerol had a positive linear relationship to ADFI (Stevens et al., 2008). This response could be due to the slight reduction in metabolizable energy (ME) of crude glycerol compared to corn (Lammers et al., 2008a) because when crude glycerol partially replaces corn, the lower ME of crude glycerol causes the ME of the overall diet to be lower. The lower ME of the diet causes the pig to eat more to satisfy daily energy needs. Metabolizable energy of crude glycerol depends mostly on its glycerol content.

No studies have been published in which water disappearance of pigs fed crude glycerol was monitored. The diets containing crude glycerol in this study did not contain supplemental salt because the crude glycerol used contained about 5.91% salt (Table 1), which supplied the diets with more salt than the CON diet.

Performance data were analyzed across growth phases. There was no treatment by phase affect for ADG, ADFI, or G:F. We observed a diet by phase interaction ($P < 0.05$) for average daily water disappearance (Figure 1). It appears short term glycerol-fed pigs had an increase in water use during phase 3 and 4 compared to phase 1 and 2 while CON and LT pigs displayed more consistent water use. Short-term glycerol-fed pigs were switched from the control diet to the 8% glycerol diet at the beginning of phase 3, indicating the increase in water use in phase 3 and 4 may be a result of the higher salt content of the 8% glycerol diet compared to the control diet.

Carcass Characteristics

Hot carcass weight and dressing percentage were affected by dietary treatment and sex ($P < 0.05$, Table 4). Pigs fed glycerol long term had higher HCW than pigs fed CON ($P < 0.05$), but similar to short-term glycerol-fed pigs. Long-term pigs had greater dressing percentage ($P < 0.05$) compared to ST-fed pigs, while CON-fed pigs were similar to both LT and ST-fed pigs. Tenth rib BF and LEA were not affected by dietary treatment, but were influenced by sex. Fat-free lean percentage was affected by sex ($P < 0.05$) and tended to be affected by dietary treatment ($P = 0.08$). Control pigs tended to have a higher percentage of fat-free lean than pigs fed glycerol long-term. The long-term glycerol fed pigs ate more and were less efficient, suggesting that pigs that are less efficient tend to have more carcass fat then pigs with higher G:F. Our results for sex effects on carcass characteristics are consistent with previous findings in which barrows have more BF depth and less fat-free lean percentage in their carcasses than gilts harvested at similar body weights (Wiseman et al., 2007). There were no treatment by sex interactions for any carcass characteristics ($P > 0.10$).

Pork Quality Measurements

Belly firmness is an important characteristic indicating fat quality and contributes to ease of processing, meat appearance, shelf life, and taste (Nishioka and Irie, 2006). In the present study, belly firmness was measured to evaluate the effect of dietary treatment on belly fat quality. A higher belly firmness measurement indicates firmer belly fat. Belly firmness data were analyzed with and without belly thickness as a covariate. With and without belly thickness taken into account, dietary treatment and sex affected belly firmness ($P < 0.05$; Table 5). Pigs fed glycerol in late finisher had firmer bellies ($P < 0.05$) compared to pigs fed CON, and were similar ($P > 0.05$) to pigs fed glycerol long term. When belly thickness was used as a covariate in the statistical model, there was a trend for pigs fed glycerol short term to have firmer bellies than pigs fed glycerol long term ($P = 0.09$). Without knowing fatty acid composition of belly fat, it is difficult to speculate why pigs fed glycerol in late finisher had firmer bellies than longer term glycerol-fed or control-fed pigs. Previous research results indicate that dietary glycerol affects the distribution of saturated and unsaturated fatty acids as indicated by a decrease in the unsaturation index (Mourot, 1994; Lammers et al., 2008b). According to Xu (2007a) a diet change can occur as little as 3 wks pre-slaughter for profile of fatty acids to be affected. Belly thickness was not affected by dietary treatment ($P > 0.10$) but barrows had thicker ($P < 0.001$) bellies than gilts. Previous research results have shown that gilts are leaner than barrows which leads to lower belly thickness than barrows (Correa et al., 2008).

Fat color is an important aspect of pork quality that influences the appearance and attractiveness of meat to consumers (Maw et al., 2003). Color of belly fat expressed as Minolta L*, a*, and b* were not affected by dietary treatment or sex (Table 5).

Visual pork quality is probably one of the most important aspects that influence consumers when purchasing pork. Muscle pH is often measured because it is strongly correlated to the color, water holding capacity, and tenderness of meat. Ultimate pH of pork loins was not affected by dietary treatment or sex (Table 6). Minolta L*, a*, and b* of loins were not affected by dietary treatment or sex, which is in agreement with previous studies (Lammers et al., 2008b; Della Casa et al, 2009). Minolta L* values are most indicative of pork quality while a* and b* vary within a small range (NPPC, 2000). Dietary treatment did not affect subjective color score. However, barrows had darker ($P < 0.05$) loin muscle than gilts. Most consumers prefer a bright, reddish-pink color in fresh pork (NPPC, 2000). A score of 3 equals reddish pink color. The pork produced from this study was in the color range preferred by most consumers. Marbling of loins was not affected by dietary treatment or sex. Marbling scores indicated that loins contained 2 to 3 % intramuscular fat. Firmness of loins was not affected by dietary treatment or sex.

Water-holding capacity is of great importance in regards to meat quality because meat is marketed on a weight basis (Offer and Knight, 1988). Water holding capacity as measured by 48 hour drip loss, purge losses at days 7 and 21, and total purge loss was not affected by dietary treatment or sex. Lammers et al. (2008b) also reported that dietary glycerol had no affect on loin drip loss. When feeding pure glycerol, Della Casa et al. (2009) noticed a trend for higher drip loss in glycerol-fed pigs. In contrast, Mourot et al. (1994) reported pigs fed glycerol had significantly lower drip loss than pigs not receiving glycerol. Similarly, Airhart et al. (2002)

reported oral administration of glycerol tended to decrease drip loss. The inconsistent response of drip loss to glycerol feeding is puzzling. Differences in feed withdrawal prior to slaughter may explain some of the inconsistencies (Lammers et al., 2008b). One explanation for the effects dietary glycerol has on drip loss could depend on the salt content of the crude glycerol. If the crude glycerol contains a significant amount of salt and diet formulators do not account for this during diet formulations, the higher salt content could affect the ionic strength of the muscle causing the myofibrils of muscle to swell with more water. A second explanation could be related to the pure glycerol content of the crude glycerol. Glycerol has osmotic properties allowing for greater fluid retention. If the crude glycerol has a high pure glycerol content, the osmotic properties of the glycerol could lead to greater water-holding capacity.

Taste Panel Evaluation

Loin sensory tests for juiciness, tenderness, pork flavor intensity, off-flavor intensity, and overall desirability were not affected by dietary treatment or sex (Table 7). With the exception of tenderness, the results from this experiment are in agreement with previous studies (Lammers et al., 2008b; Della Casa et al., 2009). In the present experiment, length of glycerol feeding did not affect tenderness.

Summary

Feeding crude glycerol both throughout the entire grow-finish period and for only 8 weeks prior to slaughter had no adverse effects on growth performance. Although fat-free lean percentage tended to be greater in pigs fed the control diets than pigs fed glycerol long term and HCW of LT-fed pigs was greater than CON pigs, other carcass measurements such as dressing percentage, 10th rib BF, LEA, belly thickness, and Minolta L*, a*, and b* color scores were not different than CON-fed pigs. Duration of crude glycerol feeding did have an effect on belly firmness, such that pigs fed glycerol during the finisher period (ST) had firmer bellies than pigs fed CON and tended to have firmer bellies than pigs fed glycerol long-term. Dietary crude glycerol and duration of feeding did not have an effect on pork quality and no difference was detected during loin taste panel assessment. Inclusion of crude glycerol in the diet of grow-finish pigs for either the entire grow-finish phase or just 8 weeks prior to marketing results in satisfactory growth performance, pork quality, and taste panel assessments. With the exception of belly firmness, carcass characteristics were also not affected by glycerol feeding. Based on the current results, we conclude that 8% crude glycerol can be added to the diet and used as an effective alternative energy source to partially replace corn.

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Table 1. Analyzed composition of crude glycerol used in experimental diets

Composition, % (Lot 1)	**As fed basis**
Glycerol	82.30
Salt (NaCl)	5.97
Sodium	2.35
Chloride	3.62
Free fatty acids	0.10
Methanol	< 0.01 (< 100 ppm)

Composition, % (Lot 2)	**As fed basis**
Glycerol	83.20
Salt (NaCl)	5.85
Free fatty acids	0.25
Methanol	0.10 (1,000 ppm)

Table 2. Composition and analyzed nutrient content of experimental diets

	Phase 1		Phase 2		Phase 3		Phase 4	
Ingredient, % (As-fed basis)	**CON[1]**	**GLY8[1]**	**CON**	**GLY8**	**CON**	**GLY8**	**CON**	**GLY8**
Corn	68.92	58.04	76.49	67.30	81.52	72.31	86.18	77.30
Soybean meal, 46% CP	28.55	31.765	21.21	22.70	16.29	17.80	11.69	12.885
Crude glycerol	0.00	8.00	0.00	8.00	0.00	8.00	0.00	8.00
Limestone	1.03	1.04	0.95	0.95	0.92	0.915	0.91	0.885
Monocalcium phosphate	0.80	0.79	0.65	0.65	0.57	0.575	0.52	0.53
Salt (NaCl)	0.30	0.00	0.30	0.00	0.30	0.00	0.30	0.00
VTM premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-lysine HCl	0.15	0.115	0.15	0.15	0.15	0.15	0.15	0.15
Total	100	100	100	100	100	100	100	100
Nutrient, % (Analyzed, as-fed basis)								
Dry matter, %	86.67	86.62	86.27	86.73	85.36	86.51	85.59	85.86
Calculated ME, kcal/kg[3]	3265	3252	3290	3280	3306	3296	3319	3310
Crude protein, %	18.84	21.62	15.77	16.49	14.36	14.81	12.12	12.65
Crude fat, %	2.12	2.24	2.39	2.47	2.19	2.33	2.35	2.44
Glycerol, %	0.00	4.60	0.00	5.28	0.00	5.26	0.00	4.91
Total calcium, %	0.66	0.68	0.48	0.51	0.53	0.40	0.46	0.45
Total phosphorus,%	0.50	0.55	0.41	0.43	0.39	0.38	0.36	0.40
Salt,%	0.40	0.50	0.36	0.54	0.44	0.60	0.40	0.62
Total Lys, %	1.15	1.32	0.94	1.04	0.85	0.86	0.69	0.73
Total Met + Cys,%	0.60	0.64	0.53	0.52	0.48	0.45	0.44	0.40
Total Thr, %	0.76	0.85	0.59	0.69	0.58	0.56	0.50	0.50
Total Trp, %	0.23	0.29	0.19	0.22	0.17	0.19	0.14	0.16
Calculated ME, kcal/g: Total Lys[4]	284	246	350	315	389	383	481	453
Average particle size, micron	643 ± 3.13	837 ± 2.56	708 ± 3.06	606 ± 2.93	799 ± 3.06	597 ± 3.14	618 ± 3.20	736 ± 2.91

[1] CON = corn soybean meal control based diet, GLY8 = diet containing 8% crude glycerol.

[2] Premix supplied the following per kg of diet: vitamin A, 8,820 IU; vitamin D_3, 1,653.75 IU; vitamin E, 33.08 IU; vitamin K, 4.41 mg; riboflavin, 6.62 mg; niacin, 38.89 mg; pantothenic acid, 22.05 mg; vitamin B_{12}, 0.04 mg; iodine, 1.10 mg; selenium, 0.30 mg; zinc, 60.64 mg; iron, 36.38 mg; manganese, 12.13 mg; copper, 3.64 mg.

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

[4] Calculated ME:Lysine from corn, soybean meal (NRC, 1998), crude glycerol (Lammers et al., 2008a) and lysine (analyzed value).

Table 3. Effect of dietary crude glycerol on growth performance (least square means)

	Dietary Treatment			Pooled	
	CON[1]	LT[1]	ST[1]	SE	P-Value
Pens	8	8	8	---	---
Initial wt, lb	69.4	69.1	68.4	1.43	0.15
Final wt, lb	279.3	284.5	284.3	2.92	0.09
ADG, lb	2.12^{ax}	2.20^{b}	2.19^{aby}	0.02	0.03
ADFI, lb	6.14^{a}	6.47^{b}	6.31^{ab}	0.07	0.01
G:F	0.346^{abx}	0.339^{ay}	0.346^{b}	0.002	0.04
ADWD, gal	1.92^{x}	2.20^{y}	2.15^{xy}	0.11	0.06

[1] CON = corn-soybean meal based diet; LT = CON+8% crude glycerol fed throughout experiment; ST = CON fed first 6 weeks, CON+8% crude glycerol fed last 8 wks of experiment.

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

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

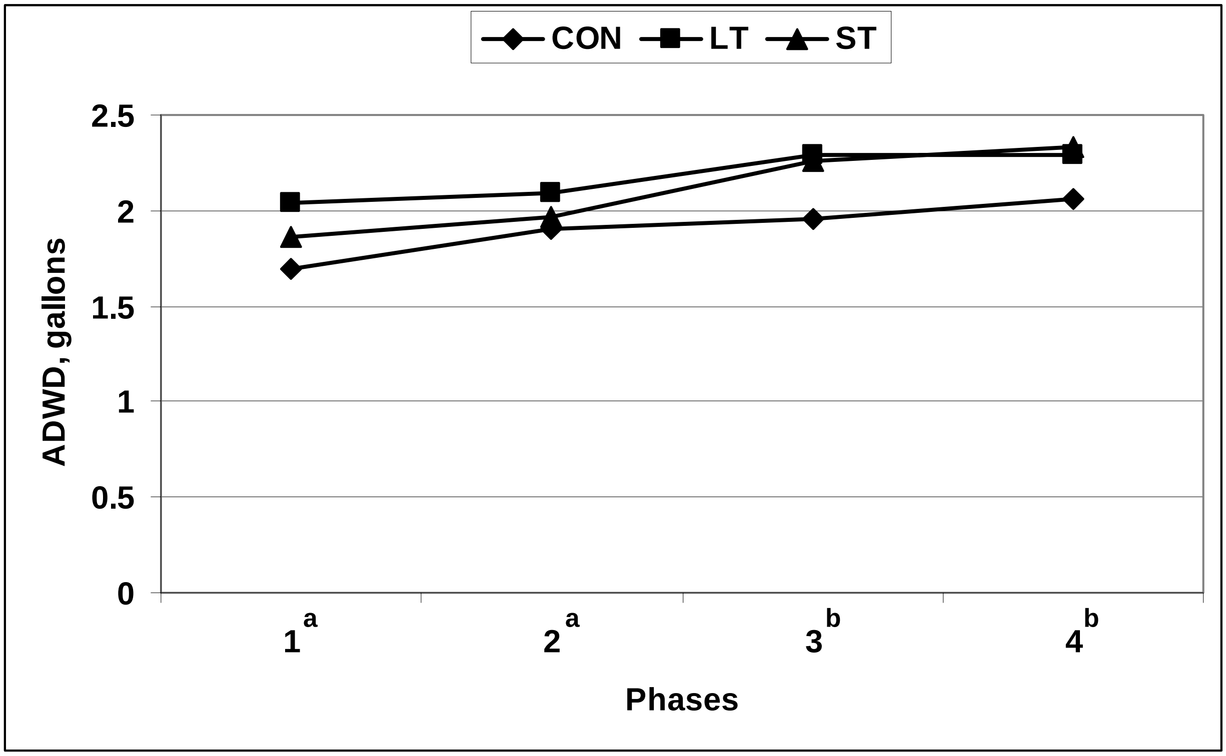

Figure 1. Effect of crude glycerol on average daily water disappearance at different phases (least square means) [ab]Means across phases differ ($P < 0.05$). PSE = 0.13; Treatment by phase p-value < 0.05.

Table 4. Effects of dietary crude glycerol and sex on carcass characteristics (least square means)

	Dietary Treatment (T)			Sex(S)		Pooled	P-Values		
Variables	**CON[1]**	**LT[1]**	**ST[1]**	**Barrows**	**Gilts**	**SE**	**T**	**S**	**TxS**
Hot carcass wt, lb	208.91^{a}	214.76^{b}	213.07^{ab}	217.38	207.11	2.59	0.02	< 0.01	0.88
Dressing percent[2]	74.48^{ab}	74.90^{a}	74.32^{b}	74.87	74.27	0.22	0.03	< 0.01	0.20
10th rib backfat, in	0.89	0.93	0.91	0.98	0.84	0.04	0.48	< 0.01	0.27
Loin eye area, in^2	8.29	8.03	8.04	7.90	8.34	0.15	0.15	< 0.01	0.33
Fat-free lean, %[3]	53.32^{x}	52.25^{y}	52.55^{xy}	51.56	53.85	0.48	0.08	<0.01	0.77

[1] CON = corn-soybean meal based diet; LT = CON+8% crude glycerol fed throughout experiment; ST = CON fed first 6 weeks, CON+8% crude glycerol fed last 8 wks of experiment.

[2] Dressing % = (HCW / final live weight) x 100

[3] Percentage of fat-free lean = Lbs. of fat-free lean / HCW x 100; Pounds of fat-free lean = 8.588 – 21.896 x 10th rib BF (inches) + 3.005 x 10th rib LEA (inches^2) + 0.465 x HCW (lbs.); (NPPC, 2000).

^{a,b}Means within a row differ ($P < 0.05$).

^{x,y}Means within a row tend to differ ($P < 0.10$).

Table 5. Effects of dietary crude glycerol and sex on belly characteristics (least square means)

	Dietary Treatments(T)			Sex(S)		Pooled	P-Values		
Variables	**CON[1]**	**LT[1]**	**ST[1]**	**Barrows**	**Gilts**	**SE**	**T**	**S**	**T*S**
Observations	13	16	15	22	22	---	---	---	---
Belly firmness, degrees[2]	30.25[a]	36.17[ab]	41.34[b]	42.34	29.49	4.10	0.02	< 0.01	0.19
Belly thickness, in	1.25	1.29	1.23	1.37	1.14	0.07	0.66	< 0.01	0.67
Adjusted belly firmness, degrees[2,3]	30.27[a]	35.30[abx]	42.26[by]	39.21	32.67	3.91	< 0.01	0.05	0.25
Belly fat									
Minolta L*	82.50	82.10	82.36	82.38	82.26	0.56	0.74	0.77	0.55
Minolta a*	6.56	6.59	6.40	6.50	6.53	0.36	0.82	0.92	0.48
Minolta b*[4]	5.95	5.73	5.60	5.73	5.80	0.32	0.31	0.79	0.57

[1] CON = corn-soybean meal based diet; LT = CON+8% crude glycerol fed throughout experiment; ST = CON fed first 6 weeks, CON+8% crude glycerol fed last 8 wks of experiment.

[2] Flop Angle = Degrees (Cos^{-1} $[(0.5\,(L^2) - D^2) / (0.5\,(L^2))]$), where L = the length of the belly and D = distance between the two ends of the belly while it was draped over the smoke stick

[3] Belly firmness score adjusted for belly thickness.

[4] Model fitted to variance structure.

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

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

Table 6. Effects of dietary crude glycerol and sex on loin characteristics (least square means)

	Dietary Treatments(T)			Sex(S)		Pooled	P-Values		
Variables	**CON[1]**	**LT[1]**	**ST[1]**	**Barrows**	**Gilts**	**SE**	**T**	**S**	**T*S**
Loins	16	15	15	23	23	---	---	---	---
Ultimate pH	5.46	5.48	5.46	5.49	5.44	0.05	0.93	0.21	0.89
Minolta L*	55.35	54.88	55.22	54.99	55.31	0.97	0.87	0.67	0.91
Minolta a*	16.38	16.57	16.29	16.35	16.48	0.33	0.67	0.60	0.70
Minolta b*	9.22	9.22	8.87	9.05	9.15	0.42	0.63	0.77	0.72
Subjective color[2]	3.84	3.80	3.77	3.97	3.64	0.18	0.91	0.02	0.70
Marbling[3]	2.47	2.57	2.51	2.61	2.42	0.29	0.93	0.43	0.78
Firmness[4]	2.31	2.66	2.26	2.42	2.40	0.26	0.22	0.91	0.83
48 h drip loss, %[5]	1.94	1.36	1.22	1.31	1.70	0.38	0.29	0.23	0.47
7 d purge loss, %[5]	1.22	1.46	1.14	1.12	1.42	0.45	0.82	0.44	0.33
21 d purge loss, %	1.96	1.75	2.48	2.16	1.96	0.41	0.20	0.53	0.28
Total purge loss, %	3.18	3.22	3.60	3.28	3.39	0.66	0.78	0.83	0.22

[1] CON = corn-soybean meal based diet; LT = CON+8% crude glycerol fed throughout experiment; ST = CON fed first 6 weeks, CON+8% crude glycerol fed last 8 wks of experiment.

[2] Color score using 6 point scale with 1 = pale pinkish gray to white and 6 = dark purplish red.

[3] Marbling score using 10 point scale with 1 = 1% intramuscular fat and 10 = 10% intramuscular fat.

[4] Firmness score using 3 point scale with 1 = soft pork and 3 = very firm.

[5] Model fitted to variance structure.

Table 7. Effect of dietary glycerol and sex on loin taste characteristics (least square means)

	Dietary Treatments(T)			**Sex(S)**		**Pooled**	**P-Values**		
Variables	**CON[1]**	**LT[1]**	**ST[1]**	**Barrows**	**Gilts**	**SE**	**T**	**S**	**T*S**
Juiciness[2]	5.12	5.24	5.03	5.08	5.18	0.26	0.73	0.65	0.65
Tenderness[3]	5.68	5.72	5.72	5.64	5.76	0.25	0.98	0.57	0.79
Pork flavor intensity[4]	5.33	5.28	5.17	5.20	5.33	0.13	0.38	0.19	0.06
Off-flavor intensity[5]	3.78	3.78	3.77	3.72	3.82	0.08	0.98	0.06	0.06
Overall desirability[6]	5.26	5.11	5.12	5.10	5.24	0.21	0.70	0.39	0.88

[1] CON = corn-soybean meal based diet; LT = CON+8% crude glycerol fed throughout experiment; ST = CON fed first 6 weeks, CON+8% crude glycerol fed last 8 wks of experiment.

[2] Juiciness measurements using 8 point scale with 1 = extremely dry and 8 = extremely juicy.

[3] Tenderness measurements using 8 point scale with 1 = extremely tough and 8 = extremely tender.

[4] Pork flavor intensity measurements using 8 point scale with 1 = extremely bland and 8 = extremely intense.

[5] Off-flavor intensity measurements using 4 point scale with 1 = intense and 4 = none.

[6] Overall desirability measurements using 8 point scale with 1 = extremely undesirable and 8 = extremely desirable.