JOURNAL OF ANIMAL SCIENCE
The Premier Journal and Leading Source of New Knowledge and Perspective in Animal Science

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

S. J. Schieck, G. C. Shurson, B. J. Kerr and L. J. Johnston

J Anim Sci published online Jul 23, 2010;

Evaluation of glycerol, a biodiesel co-product, in grow-finish pig diets to support growth and pork quality[1,2]

S. J. Schieck,[*] G. C. Shurson,[*] B. J. Kerr,[‡] and L. J. Johnston[†3]

[*]Department of Animal Science, University of Minnesota, St. Paul, MN; [‡]USDA-ARS, Ames, IA; and [†]West Central Research and Outreach Center, University of Minnesota, Morris, MN

---

[1]This project was supported financially by the Minnesota Pork Board (Mankato, MN), the Minnesota Agricultural Experiment Station, and SoyMor Biodiesel LLC (Albert Lea, MN).

[2]The authors thank the staff of the University of Minnesota West Central Research and Outreach Center Swine Unit for care of experimental animals and colleagues at the South Dakota State University Meat Laboratory for assistance in carcass data collection and for conducting pork quality evaluations. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Minnesota or the USDA and does not imply approval to the exclusion of other products that may be suitable.

[3]Corresponding author: johnstlj@morris.umn.edu

Published Online First on July 23, 2010 as doi:10.2527/jas.2010-2858

ABSTRACT: Crossbred pigs (n = 216; BW = 31.3 ± 1.8 kg) were used to determine the effects of long- and short-term feeding of crude glycerol on growth performance, carcass traits, and pork quality of grow-finish pigs. Pigs were blocked by initial BW, and pens within blocks were assigned randomly to 1 of 3 dietary treatments (24 pens; 9 pigs/pen). Dietary treatments were: control, a corn-soybean meal based diet (CON); long-term, CON + 8% glycerol fed throughout the experiment (LT); and short-term, pigs fed CON for the first 6 wk followed by CON + 8% glycerol fed during the last 8 wk of the experiment (ST). Pigs fed LT had higher ($P < 0.05$) ADG, while pigs fed ST tended ($P < 0.10$) to grow faster than CON (CON = 0.962 kg/d, LT = 0.996 kg/d, and ST = 0.992 kg/d; SE = 0.01). Pigs assigned to LT had greater ($P < 0.05$) ADFI compared to CON, while ST-fed pigs had similar ADFI to CON (CON = 2.78 kg/d, LT = 2.93 kg/d, and ST = 2.86 kg/d; SE = 0.03). Gain:feed tended ($P < 0.10$) to be greater for CON- and ST-fed pigs compared to LT-fed pigs (CON = 0.346, LT = 0.339, and ST = 0.346; SE = 0.002). Hot carcass weight 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 (CON = 94.8 kg, LT = 97.5 kg, and ST = 96.3 kg; SE = 0.90). Dressing percentage of CON-fed pigs was similar to both LT- and ST-fed pigs, but LT-fed pigs tended to have higher ($P = 0.06$) dressing percentage than ST-fed pigs (CON = 74.5%, LT = 74.9%, and ST = 74.3%; SE = 0.16). Tenth rib backfat and LM area were not affected by dietary treatment. There was a trend ($P < 0.10$) for LT-fed pigs to have lower fat-free lean percentage than CON fed pigs (CON = 53.1%, LT = 52.26%, and ST = 52.67%; SE = 0.25). Short-term glycerol feeding increased ($P < 0.05$) belly firmness compared to CON, and had similar belly firmness compared to LT-fed pigs (CON = 29.46°, LT = 35.16°, and ST = 42.08°; SE = 3.07). Dietary treatment had no effect on pork quality of loins based on taste panel assessments. Feeding pigs 8% crude glycerol throughout the grow-finish period resulted in a 3%

improvement in growth rate and a 2% depression in gain efficiency compared to control diets. Grow-finish pigs fed diets containing 8% crude glycerol during the last 8 wk before harvest achieved growth performance similar to pigs fed control diets. Effects of crude glycerol on carcass traits seem to be limited to improvements in belly firmness with short-term feeding of glycerol.

Key words: glycerol, pigs, pork quality

INTRODUCTION

Crude glycerol is a by-product of biodiesel production. In 2008, biodiesel production capacity was estimated to be 9.88 billion liters from 176 plants (National Biodiesel Board, 2008). Crude glycerol can be refined to pure glycerol for use in the food, pharmaceutical, and cosmetic industries (Thompson and He, 2006). Recent expansion of biodiesel production has caused a surplus of crude glycerol that is not needed for further purification. The overflow of available crude glycerol has prompted researchers to look for new uses for this co-product. Lammers et al. (2008a) found that crude glycerol containing 86.95% glycerol has a ME content of 3,207 ± 10 kcal/kg, which is 94% of the ME content of corn (NRC, 1998). This observation is supported by Kerr et al. (2009) who indicated that crude glycerol may be a good alternative energy source in swine diets.

Glycerol plays a role in water balance of the body. Glycerol ingestion enhanced water retention of endurance athletes when administered hours before competition (Robergs and Griffin, 1998; Coutts et al., 2002). The influence of glycerol on water balance may extend to muscle tissue after slaughter. Mourot et al. (1994) reported that dietary glycerol decreased drip loss of pork loins when crude glycerol was fed to pigs during the entire growing-finishing period. Della Casa et al. (2009) reported that both concentration of dietary glycerol and duration of glycerol feeding affected moisture loss of pork. Physiological effects of dietary crude glycerol may be different for long term (entire grow-finish period) verses short term (partial grow-finish period) feeding.

We hypothesized that dietary crude glycerol would influence quality of pork and that duration of glycerol feeding may alter this response. Therefore, 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.

MATERIALS AND METHODS

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

Animal and Facilities

The experiment was conducted in the swine research unit at the University of Minnesota's West Central Research and Outreach Center in Morris. The experiment took place over a 14-wk period from November 20, 2007 through February 26, 2008. The pigs were terminal offspring of Yorkshire x Landrace sows sired by Duroc boars (Compart Boar Store, Nicollet, MN).

Two-hundred sixteen crossbred, mixed-sex pigs with initial BW of 31.3 ± 1.8 kg were weighed and blocked by initial BW. 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 (1.6 x 4.5 m) was equipped with 1 nipple drinker, 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 a commercial company (SoyMor Biodiesel LLC, Albert Lea, MN). Crude glycerol was analyzed before use for NaCl (969.10; AOAC, 2006) and free fatty acid (5a-40; AOCS, 1998). Content of methanol and glycerol content were both analyzed using HPLC with refractive index detection according to standard methods (991.46; AOAC, 2006) as modified (Minnesota Valley Testing Laboratories Inc., New Ulm, MN; 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 wk before harvest. Dietary treatments were: control, a corn-soybean meal based diet fed throughout the experiment (**CON**); long-term, CON + 8% crude glycerol fed throughout the entire experiment (**LT**); or short-term, CON for the first 6 wk of the experiment followed by CON + 8% crude glycerol fed for the last 8 wk of the experiment (**ST**; Table 2). Both lots of crude glycerol used were not pure (glycerol = 82.30 and 83.20%, respectively), so the treatment diets contained less than 8% glycerol according to the pure glycerol content in the crude glycerol. Liquid crude glycerol was added at the expense of corn when experimental diets were manufactured. Dietary treatments followed a 4-phase feeding program based on average BW of pigs in each pen. Body weights for phases 1 to 4 were: 23 to 45 kg, 45 to 68 kg, 68 to 91 kg, and 91 kg to harvest, respectively. All diets were formulated on a standardized ileal digestible (**SID**) amino acid basis with ME to SID Lys ratio equalized across experimental diets. Supplemental NaCl was eliminated in the 8% crude glycerol diet to account for the NaCl content of the crude glycerol. Diets were formulated using nutrient concentrations for feed ingredients listed in NRC (1998). Experimental diets were formulated to meet or exceed

NRC (1998) nutrient requirements for mixed-sex grow-finish pigs with carcass lean tissue gain of 350 g/d.

Feed samples were collected from every batch of experimental feed with 1 sample analyzed from each phase per experimental diet. Samples were selected randomly for analysis of DM by the vacuum oven method (934.01; AOAC, 2006); CP by the Kjeldahl method [984.13 (A to D); AOAC, 2006]; crude fat by ether extraction (920.39 (A); AOAC, 2006); and AA [982.30 E (a,b,c) chapter 45.3.05; AOAC, 2006] concentrations by HPLC. In addition, Ca, P, Na, and Cl were analyzed by inductively coupled plasma spectroscopic method [985.01 (A, B, D); AOAC 985.01 (A, B, D), 2006]; and glycerol was determined by GLC using the trimethylsilyl derivative method (Mattick and Rice, 1970). Particle size was determined for 1 sample from each diet selected randomly and analyzed using a Ro-Tap mechanical sieve shaker (Model RX-29; W. S. Tyler, Mentor, OH).

Growth Performance and Water Disappearance

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. Individual weights of the pigs within pens were used to calculate ADG on a pig and pen basis. On weigh day, feed disappearance was measured to calculate ADFI of pigs on a pen basis. Gain efficiency was calculated using ADG and ADFI.

Water disappearance measurements were recorded for every pen. Each pen was equipped with a water meter (model DLJSJ50, Daniel L. Jerman Co., Hackensack, NJ) that was plumbed directly into the water line supplying the drinker in each pen. Water meter readings were recorded on weigh day and used to calculate average daily water disappearance (**ADWD**) on a pen basis.

Carcass and Pork Quality Measurements

All pigs were marketed on the same day. Hot carcass weight was measured on 200 carcasses immediately after slaughter. Twenty-four h after chilling, backfat (**BF**) measurements were recorded at the P2 location over the 10th rib approximately 60 mm left of the midline. Loins were retrieved from the left side of carcasses, cut at the 10th rib, and LM area was traced on tracing paper to be measured using a grid. Final live weight of pigs along with HCW was used to calculate dressing percentage using the following formula: Dressing % = (HCW/final live weight) x 100. Fat-free lean percentage was calculated for ribbed carcasses (NPPC, 2000).

Forty eight pigs, (1 barrow and 1 gilt from each pen) weighing closest to the mean weight of their pen were selected for pork quality measurements. The right belly with spareribs removed was collected for belly firmness measurements using procedures reported by Whitney et al. (2006). Belly firmness measurements were determined at a room temperature of 7°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 48 selected carcasses were collected for meat quality evaluation. Drip loss (48 h) and purge loss (7 and 21 d) were measured using procedures reported by Stein et al. (2006). Subjective scores for color, marbling, and firmness were determined for each loin (NPPC, 2000). Minolta color measurements for L*, a*, and b* were measured using a Minolta Colorimeter with calibration to the red setting with values of L* = 45.33, a* = 37.86, and b* = 16.69. A homogenization method was used to measure ultimate pH of the loins. A loin sample (10 g) was chopped and added to 90 mL of doubly distilled water.

The sample was then homogenized and pH was recorded by a pH meter (ThermoOrion, model 330; Thermo Fisher Scientific Inc., Waltham, MA).

Cooked loins were evaluated by a trained taste panel of 8 people. Loins were cut into 2.54 cm thick chops and cooked to an internal temperature of 71°C, then cut into 2.54 x 1.27 cm cubes for sampling. 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 3 dietary treatments (CON, LT, and ST) equally represented in each session. Panelists ranked the juiciness of each loin sample on an 8-point scale with 1 = extremely dry and 8 = extremely juicy. Tenderness was ranked on an 8-point scale with 1 = extremely tough and 8 = extremely tender. Pork flavor intensity was ranked on an 8-point scale with 1 = extremely bland and 8 = extremely intense. Off-flavor intensity was ranked on a 4-point scale with 1 = intense off-flavor and 4 = no off-flavor. Off-flavors detected were described as bitter, bloody, burnt, fishy, metallic, soapy, sour, or stale. Overall desirability was ranked on an 8-point scale with 1 = extremely undesirable and 8 = extremely desirable.

Statistical Analysis

Data were analyzed in a randomized complete block design using PROC MIXED 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 as a fixed effect 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. The experimental unit for belly characteristics and loin pork quality was pen. The statistical model for taste panel data contained dietary treatment as a fixed effect and block as a random effect. 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 with Tukey-Kramer adjustment. Pooled SE 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's Information Criterion (Littell et al., 2006). 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 ($\chi^2 = 1.03$; df = 2). Ten pigs (CON = 3, LT = 4, and ST = 3; $\chi^2 = 1.21$, df = 4) were excluded from collection of carcass data because they were too light to fit specifications of the processor and could not be harvested on the same day as contemporaries.

Growth Performance

Initial BW of pigs (31.3 ± 1.8 kg) did not differ among treatments (Table 3). Final BW 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 LT tended ($P < 0.10$) to have poorer gain efficiency than those assigned to CON and ST diets. Gain efficiency of CON- and ST-fed pigs was not different. Average daily water disappearance 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.

The ramifications of crude glycerol use in swine diets is not fully understood as indicated by inconsistent results 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%. Grow-finish pigs fed corn-soybean meal diets containing 5, 10, or 15% crude glycerol showed quadratically increased ADG when crude glycerol inclusion increased from 0 to 10%, but ADG decreased at 15% dietary glycerol (Stevens et al., 2008). Similarly, in a nursery pig study with pigs fed 0, 3, 6, 9, 12, or 15% crude glycerol in corn-soybean meal diets, ADG linearly increased as inclusion of crude glycerol increased (Groesbeck et al., 2008). In another nursery pig study where pigs were fed wheat-based diets with 0, 4, and 8% crude glycerol, glycerol increased overall growth performance, increased ADFI quadratically, and did not affect feed efficiency (Zijlstra et al., 2009). Pigs fed crude glycerol in diets based on corn and soybean meal (2.5, 5, and 10% crude glycerol; Duttlinger et al., 2008; Lammers et al., 2008b), barley-soybean meal (5, 10, 20, and 30% crude glycerol; Kijora et al., 1995; Kijora and Kupsch, 1996), and wheat-soybean meal (5% crude glycerol; Mourot et al., 1994) demonstrated no difference in ADG compared to their control diets. The inconsistency in ADG responses reported by different researchers is unclear. However, the energy value of the crude glycerol sources may have been over- or underestimated relative to the composition of crude glycerin (Kerr et al., 2009), leading to differences in performance among the different studies (Zijlstra et al., 2009).

The ADFI observed in this experiment is similar to that reported in a previous study, in which dietary glycerol had a positive linear effect on ADFI (Stevens et al., 2008). This response could be due to the slight reduction in 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 marginally lower. Metabolizable energy of crude glycerol depends mostly on its glycerol content (Kerr et al., 2009). Hansen et al. (2009) studied growing-finishing gilts and reported a linear decline in ADFI during the first week of feeding up to 16% crude glycerol in barley-wheat-lupin based diets. However, by the second week and over the entire 9-wk experiment, dietary crude glycerol had no statistically significant effect on ADFI of gilts.

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 NaCl because the crude glycerol used contained on average 5.91% NaCl (Table 1), which supplied the diets with more NaCl than the CON diet. Our measure of ADWD should be viewed with caution as we did not quantify water wastage in this experiment.

Carcass and Pork Quality Characteristics

Hot carcass weight was affected by dietary treatment ($P < 0.05$; Table 4). Because HCW was influenced by dietary treatment, tenth rib BF, LM area, and fat-free lean percentage were also analyzed using HCW as a covariate. Because the HCW covariate did not explain a significant portion of the variation in BF depth and LEA, unadjusted results are presented in 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 tended to have greater dressing percentage ($P = 0.06$) compared to ST-fed pigs, while CON-fed pigs were similar to both LT and

ST-fed pigs. These results conflict with previous studies, in which feeding glycerol long term at levels up to 30% of the diet had no effect on HCW or dressing percentage (Kijora et al., 1995; Lammers et al., 2008b). Tenth rib BF and LEA were not affected by dietary treatment. Lammers et al. (2008b) also reported dietary glycerol did not affect 10th rib BF or LEA. Similarly, Hansen et al. (2009) reported no effect of dietary crude glycerol on BF depth of gilts. However, Stevens et al. (2008) found that dietary glycerol levels up to 15% linearly increased 10th rib BF depth and decreased fat-free lean percentage. In contrast, Lammers et al. (2008b) reported no change in fat-free lean percentage with feeding up to 10% dietary glycerol. Control pigs tended to have a higher percentage of fat-free lean than pigs fed glycerol long-term.

Belly firmness is an important characteristic that indicates fat quality (Lea and Swoboda, 1970; Nishioka and Irie, 2006) and contributes to ease of processing, meat appearance, shelf life, and taste (Irie, 1999; NPPC, 2000; Nishioka and Irie, 2006). A higher belly firmness measurement indicates a firmer belly fat. Belly firmness data were analyzed with and without belly thickness as a covariate, and dietary treatment affected belly firmness regardless of belly thickness ($P < 0.05$; Table 5). Pigs fed glycerol in late finisher had firmer bellies ($P < 0.05$) compared to pigs fed CON, and were similar to pigs fed glycerol throughout the experiment. 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). Unsaturation index and fat firmness are related inversely (Lea and Swoboda, 1970; Wood, 1984). According to Xu et al. (2009), a diet change that occurs as little as 3 wk pre-slaughter can affect the profile of fatty acids in fat. Belly thickness was not affected by dietary treatment. Fat color is an important aspect of pork quality that influences the appearance and attractiveness of meat to consumers (Schinckel et al., 2002; Maw et al., 2003). Color of belly fat expressed as Minolta L*, a*, and b* was not affected by dietary treatment.

Visual pork quality is an important characteristic that influences consumers' decision to purchase pork. Muscle pH is often measured because it is correlated strongly to the color, water holding capacity, and tenderness of meat. Ultimate pH of pork loins was not influenced by dietary treatment (Table 6). These observations are consistent with previous experiments (Mourot et al., 1994; Kijora and Kupsch, 1996; Lammers et al., 2008b; Hansen et al., 2009). Even when pure glycerol was fed to pigs at 5 and 10%, ultimate pH was not affected by diet (Della Casa et al., 2009). When measuring loin color with a Minolta colorimeter, Minolta L*, a*, and b* were not affected by dietary treatment, which is in agreement with previous studies (Lammers et al., 2008b; Della Casa et al, 2009; Hansen et al., 2009). Similarly, subjective color score was not influenced by dietary treatment. Subjective color results from this study are in agreement with previous studies involving glycerol feeding (Kijora and Kupsch, 1996; Della Casa et al., 2009). Similar to Lammers et al. (2008b), marbling of loins in this study was not affected by dietary treatment. However, Della Casa et al. (2009) reported higher marbling scores of chops for the pigs fed 5 to 10% glycerol during the late finishing phase of growth. Firmness of loins was not affected by dietary treatment.

Water-holding capacity is of great importance in regards to meat quality because meat is marketed on a weight basis (Offer et al., 1984; Offer and Knight, 1988). Water holding capacity as measured by 48 h drip loss, purge losses at d 7 and 21, and total purge loss was not affected by dietary treatment, which is consistent with the work of others (Lammers et al., 2008b; Hansen et al., 2009). 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 and Airhart et al. (2002) noticed a tendency for lower drip loss compared with pigs not receiving glycerol. 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). Another reason could be the variation in NaCl content of crude glycerol used, but Mourot et al. (1994), Airhart et al. (2002), Della Casa et al. (2009) or Hansen et al. (2009) reported the NaCl content of the glycerol used in their experiments. Addition of NaCl post-mortem increases water-holding capacity of meat because of swelling of the myofibrils, which are the site of water uptake in meat (Offer and Trinick, 1983; Voyle et al., 1984). Dietary crude glycerol could influence drip loss because of its NaCl content. If the crude glycerol contains a substantial amount of NaCl and researchers do not account for this in diet formulations, the higher NaCl content could affect the ionic strength of the muscle causing the myofibrils to swell with more water. Alternatively, glycerol has osmotic properties allowing for greater fluid retention. If the crude glycerol has 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 (Table 6). 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). Della Casa et al. (2009) reported loins from pigs fed a diet containing 5% glycerol for only the finisher phase were less tender than control, 5 and 10% pure glycerol fed throughout the grow-finish phase, and for pigs fed a 10% glycerol diet only during the finishing phase. In the present experiment, length of glycerol feeding did not affect tenderness. Frequency of off-flavors such as bitter, metallic, soapy, sour, and other were not affected by dietary treatment (Figure 1).

In summary, feeding crude glycerol both throughout the entire grow-finish period and for only 8 wk before 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 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 but pigs fed glycerol long term and CON pigs had bellies of similar firmness. Dietary crude glycerol and duration of feeding did not have an effect on pork quality and no differences in sensory characteristics were detected during taste panel assessment. Inclusion of crude glycerol in the diet of grow-finish pigs for either the entire grow-finish phase or just 8 wk prior to marketing, results in satisfactory pork quality. Belly firmness may be improved if crude glycerol is included in diets during the late finishing period. This finding may have important implications for practical application of glycerol feeding. Short-term feeding of crude glycerol in the late finishing period may have utility in reducing the documented negative effects of some ethanol co-products on pork fat quality (Stein and Shurson, 2009). 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.

LITERATURE CITED

Airhart, J. C., T. D. Bidner, and L. L. Southern. 2002. Effect of oral glycerol administration with and without betaine on carcass composition and meat quality of late-finishing barrows. J. Anim. Sci. 80(Suppl. 2):71. (Abstr.)

AOAC. 2006. Official Methods of Analysis. 18th ed. Assoc. Off. Anal. Chem., Arlington, VA.

AOCS. 1998. Official Methods and Recommended Practices. 5th ed. Am. Oil Chem. Soc., Champaign, Ill.

Coutts, A., P. Reaburn, K. Mummery, and M. Holmes. 2002. The effect of glycerol hyperhydration on Olympic distance triathlon performance in high ambient temperatures. Int. J. Sports Nutr. Exerc. Metab. 12:105-119.

Della Casa, G. D. Bochicchio, V. Faeti, G. Marchetto, E. Poletti, A. Garavaldi, A. Panciroli, and N. Brogna. 2009. Use of pure glycerol in fattening heavy pigs. Meat Sci. 81:238-244.

Duttlinger, W., M. D. Tokach, S. S. Dritz, J. M. DeRouchey, J. L. Nelssen, R. D.Goodband, and K. J. Prusa. 2008. Effects of increasing dietary glycerol and dried distillers grains with solubles on growth performance of finishing pigs. J. Anim. Sci. 86(E-Suppl. 2):607. (Abstr.)

Groesbeck, C. N., L. J. McKinney, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, S.S. Dritz, J. L. Nelssen, A. W. Duttlinger, A. C. Fahrenholz, and K. C. Behnke. 2008. Effect of crude glycerol on pellet mill production and nursery pig growth performance. J. Anim. Sci. 86:2228-2236.

Hansen, C. F., A. Hernandez, B. P. Mullan, K. Moore, M. Trezona-Murray, R. H. King, and J. R. Pluske. 2009. A chemical analysis of samples of crude glycerol from the production of biodiesel in Australia, and the effects of feeding crude glycerol to growing-finishing pigs on performance, plasma metabolites and meat quality at slaughter. Anim. Prod. Sci. 49:154-161.

Irie, M. 1999. Evaluation of porcine fat with fiber-optic spectroscopy. J. Anim. Sci.77:2680-2684.

Kerr, B. J., T. E. Weber, W. A. Dozier, III, and M. T. Kidd. 2009. Digestible and metabolizable energy content of crude glycerin originating from different sources in nursery pigs. J. Anim. Sci. 87:4042-4049.

Kijora, C., H. Bergner, R. D. Kupsch, and L. Hagemann. 1995. Glycerin as a feed component in diets of fattening pigs. Arch. Anim. Nutr. 47:345-360.

Kijora, C., and R.-D. Kupsch. 1996. Evaluation of technical glycerols from "Biodiesel"production as a feed component in fattening pigs. Fett/Lipid. 98:240-245.

Lammers, P. J., B. J. Kerr, T. E. Weber, W. A. Dozier III, M. T. Kidd, K. Bregendahl, and M. S. Honeyman. 2008a. Digestible and metabolizable energy of crude glycerol for growing pigs. J. Anim. Sci. 86:602-608.

Lammers, P. J., B. J. Kerr, T. E. Weber, K. Bregendahl, S. M. Lonergan, K. J. Prusa, D.U. Ahn, W. C. Stoffregen, W. A. Dozier III, and M. S. Honeyman. 2008b. Growth performance, carcass characteristics, meat quality, and tissue histology of growing pigs fed crude glycerin-supplemented diets. J. Anim. Sci. 86:2962-2970.

Lea, C. H., and P. A. T. Swoboda. 1970. A chemical study of soft fat in cross-bred pigs. J. Agric. Sci. 74:279-289.

Littell, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Schabenberger. 2006. SAS for Mixed Models. 2nd ed. SAS Inst. Inc., Cary, NC.

Maw, S. J., V. R. Fowler, M. Hamilton, and A. M. Petchey. 2003. Physical characteristics of pig fat and their relation to fatty acid composition. Meat Sci. 63:185-190.

Mattick, L. R., and A. C. Rice. 1970. Quantitative determination of lactic acid and glycerol in wines by gas chromatography. Am. J. Enol. Vitic. 21:205-212.

Mourot, J., A. Aumaitre, A. Mounier, P. Peiniau, and A. C. Francois. 1994. Nutritional and physiological effects of dietary glycerol in the growing pig. Consequences on fatty tissues and post mortem muscular parameters. Livest. Prod. Sci. 38:237-244.

National Biodiesel Board. 2008. http://www.biodiesel.org Accessed May 7, 2008.

Nishioka, T., and M. Irie. 2006. Fluctuation and criteria of porcine fat firmness. Anim. Sci. 82:929-935.

NPPC. 2000. Pork composition & quality assessment procedures. National Pork Producers Council, Des Moines, IA.

NRC, 1998. Nutrient Requirements of Swine. 10th rev. ed. Natl. Acad. Press, Washington, DC.

Offer, G., and P. Knight. 1988. The structural basis of water-holding in meat. Part 1: General principles and water uptake in meat processing. Pages 63-171 in Developments in Meat Science. R. Lawrie, ed. Elsevier Science Publishing Co., Inc. New York, NY.

Offer, G., D. Restall, and J. Trinick. 1984. Water-holding in meat. Pages 71-86 in Recent Adv. Chem. Meat 1 Proc. Sym., ARC Meat Research Institute, Langford, Bristol.

Offer, G., and J. Trinick. 1983. On the mechanism of water holding in meat: the swelling and shrinking of myofibrils. Meat Sci. 8:245-281.

Robergs, R. A., and S. E. Griffin. 1998. Glycerol: biochemistry, pharmacokinetics and clinical and practical applications. Sports Med. 26:145-167.

Schinkel, A. P., S. E. Mills, T. E. Weber, and J. M. Eggert. 2002. A review of genetic and nutritional factors affecting fat quality and belly firmness. Proc. Natl. Swine Imp. Fed. Conf. Nashville, TN. www.nsif.com/Conferences/2002/reviewgeneticnutritionalfactors.htm Accessed January 16, 2009.

Stein, H. H., A. K. R. Everts, K. K. Sweeter, D. N. Peters, R. J. Maddock, D. M. Wulf, and C. Pedersen. 2006. The influence of dietary field peas (Pisum sativum L.) on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 84:3110-3117.

Stein, H. H. and G. C. Shurson. 2009. Board invited review: The use and application of distillers dried grains with solubles (DDGS) in swine diets. J. Anim. Sci. 87:1292-1303.

Stevens, J., A. Schinckel, M. Latour, D. Kelly, D. Sholly, B. Legan, and B. Richert. 2008. Effects of feeding increasing levels of glycerol with or without distillers dried grains with solubles in the diet on grow-finish pig growth performance and carcass quality. J. Anim. Sci. 86(E-Suppl. 2):606. (Abstr.)

Thompson, J. C., and B. B. He. 2006. Characterization of crude glycerol from biodiesel production from multiple feedstocks. App. Eng. Agric. 22:261-265.

Voyle, C. A., P. D. Jolley, and G. W. Offer. 1984. The effect of salt and pyrophosphate on the structure of meat. Food Microstructure 3:113-126.

Whitney, M. H., G. C. Shurson, L. J. Johnston, D. M. Wulf, and B. C. Shanks. 2006. Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern Midwestern ethanol plant. J. Anim. Sci. 84:3356-3363.

Wood, J. D. 1984. Fat deposition and the quality of fat tissue in meat. Pages 407-436 in Fat in Animal Nutrition. Wiseman, J., ed. Butterworths, London.

Xu, G. S. K. Baidoo, L. J. Johnston, D. Bibus, J. E. Cannon, and G. C. Shurson. 2009. The effects of feeding diets containing corn distillers dried grains with solubles (DDGS), and DDGS withdrawal period, on growth performance and pork quality in grower-finisher pigs. J. Anim. Sci. 88:1388-1397.

Zijlstra, R. T., K. Menjivar, E. Lawrence, and E. Beltranena. 2009. The effect of feeding crude glycerol on growth performance and nutrient digestibility in weaned pigs. Can. J. Anim. Sci. 89:85-89.

Table 1. Analyzed composition of crude glycerol used in experimental diets (as-fed %)

Item	Lot 1	Lot 2
Glycerol	82.30	83.20
NaCl	5.97	5.85
Free fatty acids	0.10	0.25
Methanol	< 0.01	0.10

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

	Phase 1		Phase 2		Phase 3		Phase 4	
Item	CON[1]	GLY8[1]	CON	GLY8	CON	GLY8	CON	GLY8
Ingredient, %								
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
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	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition, %								
DM, %	86.67	86.62	86.27	86.73	85.36	86.51	85.59	85.86
Calculated ME,[3] kcal/kg	3,265	3,252	3,290	3,280	3,306	3,296	3,319	3,310
CP, %	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 Ca, %	0.66	0.68	0.48	0.51	0.53	0.40	0.46	0.45
Total P,%	0.50	0.55	0.41	0.43	0.39	0.38	0.36	0.40
NaCl,%	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:SID Lys[4]	337	325	406	400	479	464	572	552
Average particle size, µ	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]Vitamin and trace mineral premix supplied the following per kg of diet: vitamin A, 8,820 IU; vitamin D_3, 1,654 IU; vitamin E, 33 IU; vitamin K, 4.4 mg; riboflavin, 6.6 mg; niacin, 39 mg; pantothenic acid, 22 mg; vitamin B_{12}, 0.04 mg; iodine as ethylenediamine dihydriodide, 1.10 mg; selenium as sodium selenite, 0.30 mg; zinc as polysaccharide complex of zinc, 61 mg; iron as polysaccharide complex of iron, 36 mg; manganese as polysaccharide complex of manganese, 12 mg; and copper as polysaccharide complex of copper, 3.6 mg.

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

[4]Calculated ME:standardized ileal digestible (SID) Lys from corn, soybean meal (NRC, 1998), and crude glycerol (Lammers et al., 2008a).

Table 3. Effect of dietary crude glycerol on growth performance

	Dietary treatment[1]			Pooled	
	CON	LT	ST	SE	*P*-value
N	8	8	8	-	-
Initial BW, kg	31.47	31.33	31.03	0.65	0.15
Final BW, kg	126.66	128.95	128.92	1.32	0.09
ADG, kg	0.962[ax]	0.996[b]	0.992[aby]	0.01	0.03
ADFI, kg	2.78[a]	2.93[b]	2.86[ab]	0.03	0.01
G:F	0.346[x]	0.339[y]	0.346[x]	0.002	0.04
ADWD[2], L	7.29[x]	8.33[y]	8.13[xy]	0.39	0.06

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

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

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

[2]ADWD = average daily water disappearance.

Table 4. Effects of dietary crude glycerol on carcass characteristics

Item	Dietary Treatment[1]			Pooled SE	*P*-value
	CON	LT	ST		
Pens	8	8	8	-	-
No. of carcasses	66	67	67	-	-
HCW, kg	94.84[a]	97.46[b]	96.30[ab]	0.90	0.02
Dressing percent	74.49[xy]	74.90[x]	74.32[y]	0.16	0.06
10th rib backfat, mm	22.55	23.69	23.01	0.48	0.26
LM area, cm^2	53.12	51.91	51.88	0.70	0.17
Fat-free lean, %	53.10[x]	52.26[y]	52.67[xy]	0.25	0.09

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

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

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

Table 5. Effects of dietary crude glycerol on belly characteristics

	Dietary treatments[1]				
Item	CON	LT	ST	Pooled SE	*P*-values
Pens	7	8	8	-	-
No. of bellies	13	16	15	-	-
Belly firmness, degrees[2]	29.17[a]	36.17[ab]	41.41[b]	3.10	0.03
Belly thickness, cm	3.15	3.28	3.12	0.11	0.53
Adjusted belly firmness,[2,3] degrees	29.46[a]	35.16[ab]	42.08[b]	3.07	0.01
Belly fat:					
Minolta L*	82.60	82.10	82.41	0.45	0.67
Minolta a*	6.48	6.59	6.38	0.26	0.79
Minolta b*[4]	5.93	5.73	5.62	0.26	0.21

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

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

[2]Belly firmness = 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 an elevated stick.

[3]Belly firmness score adjusted for belly thickness.

[4]Model fitted to variance structure.

Table 6. Effects of dietary crude glycerol on loin characteristics

	Dietary treatments[1]				
Item	CON	LT	ST	Pooled SE	*P*-values
Loins	16	15	15	-	-
Ultimate pH	5.46	5.50	5.46	0.04	0.70
Minolta L*	55.35	54.70	55.34	0.67	0.57
Minolta a*	16.38	16.59	16.26	0.24	0.58
Minolta b*	9.22	9.12	8.90	0.28	0.67
Subjective color[2]	3.84	3.88	3.72	0.15	0.60
Marbling[3]	2.47	2.62	2.41	0.22	0.74
Firmness[4]	2.31	2.69	2.25	0.19	0.21
48 h drip loss,[5] %	1.94	1.33	1.20	0.23	0.12
7 d purge loss,[5] %	1.22	1.35	1.13	0.33	0.91
21 d purge loss, %	1.92	1.71	1.42	0.33	0.31
Total purge loss, %	3.18	3.06	3.55	0.50	0.78
Juiciness[6]	5.13	5.27	5.06	0.19	0.74
Tenderness[7]	5.68	5.77	5.73	0.19	0.94
Pork flavor intensity[8]	5.34	5.31	5.20	0.11	0.64
Off-flavor intensity[9]	3.78	3.76	3.80	0.05	0.87
Overall desirability[10]	5.27	5.15	5.15	0.25	0.81

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

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

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

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

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

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

Figure 1. Number of off-flavor comments by category. Bitter: $\chi^2 = 5.50$, df = 4; Metallic: $\chi^2 = 2.74$, df = 4; Soapy: $\chi^2 = 11.86$, df = 6; Sour: $\chi^2 = 9.44$, df = 6; Other: $\chi^2 = 6.67$, df = 4; and Total: $\chi^2 = 10.87$, df = 10; *P*-value for all off-flavors is > 0.10.