Title: Utilizing Glycerol in Swine Diets: I. Feed Manufacturing Considerations and Nutritional Strategies to Reduce Dietary Costs **– NPB #07-151**

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Date Submitted February 13, 2009

Industry Summary

Biodiesel is an alternative to petroleum-based diesel fuel and according to the National Biodiesel Board, there are currently 105 biodiesel production facilities operating in the United States, and 77 facilities are in the planning or construction stage. If all of these facilities are realized, the estimated US biodiesel production capacity will exceed 9.5 billion liters. This level of production would yield nearly 1.2 million metric tons of crude glycerol, the primary co-product of the biodiesel production process. Crude glycerol has the potential to be used as a feed ingredient in animal diets. However, little is known about glycerol's nutritional value or how it impacts feed quality and feed production. Consequently, experiments sponsored by the National Pork Board, were carried-out to evaluate the effects of glycerol on feed characteristics, the pelleting process, and nursery pig growth performance.

The first experiment was designed to quantify the effects of added glycerol, soybean oil, or a 50:50 soy oil/glycerol blend on the flowability characteristics of ground corn or ground corn and 15 or 30% spray-dried whey. The experiment was conducted using corn ground by either a hammermill or a three-high roller mill. Feed flowability was determined by measuring the angle of repose four times for each sample. As was expected, roller mill ground grain had a lower angle of repose compared to grain ground with a hammermill, indicating less feed bridging would occur with roller mill ground grain. The addition of soy oil and spray-dried whey increased angle of repose, thus, decreasing flowability. Glycerol or a 50:50 soy oil/glycerol blend improved the flowability of the hammermill ground grain, but did not influence the flowability of the roller mill ground corn. Additionally, glycerol improved the flowability as spray-dried whey level increased. These data suggest that the addition of glycerol to a meal diet containing hammermill ground corn and spray-dried whey tends to improve flowability.

These research results were submitted in fulfillment of the Nutritional Efficiency Consortium research projects.
Contributing organizations for 2007 include: Arizona Pork Council, DPI Global, Eli Lilly/Elanco, Iowa Corn Growers Association, Iowa Pork Producers Association, Illinois Corn Marketing Board, Illinois Pork Producers Association, Kansas Corn Commission, Kansas Pork Association, Lucta USA, Minnesota Pork Board, Missouri Pork Producers Association, Monsanto, Mississippi Pork Producers Association, Montana Pork Producers Council, National Corn Growers Association, North Carolina Pork Council, Inc., National Pork Board, Nebraska Pork Producers Association, Inc., Ohio Pork Producers Council, Pioneer Hi-Bred International, Inc., Utah Pork Producers Association and the Wisconsin Pork Association.

This report is published directly as submitted by the projects principal investigator. This report has not been peer reviewed.

The second experiment was designed to evaluate how increasing levels of crude glycerol in diets effects pellet mill production efficiency. Diets were formulated to contain 0, 3, 6, 9, 12, and 15% crude glycerol. All diets were steam conditioned to 65.5°C and pelleted through a pellet mill equipped with a die that had an effective thickness of 31.8 mm and holes 3.96 mm in diameter. Increasing the level of crude glycerol in the diet up to 9% improved pellet quality. Additionally, glycerol tended to reduce the electrical energy consumption, thus improving pelleting efficiency. It was noted during the experiment that attempts to increase conditioning temperatures above 65.5°C resulted in slippage of the pellet mill rolls. Consequently, it appears that the inclusion of glycerol in a diet improves feed quality; however, glycerol inclusion levels may be limited due to a potential negative interaction with conditioning temperature. This observation needs to be investigated further.

A nursery pig growth performance trial was conducted to evaluate diets formulated with glycerol, soybean oil, or a blend of glycerol and soybean oil. A total of 182 pigs (initial BW, 11.0 ± 1.3 kg; 5 or 6 pigs/pen) were fed 1 of 7 corn-soybean meal-based diets with no added soy oil or crude glycerol (control), the control diet with 3 or 6% added soy oil, 3 or 6% added crude glycerol, and 6 or 12% addition of a 50:50 (wt/wt) soy oil/crude glycerol blend with 5 pens/diet. All diets were pelleted as described above, and pellet mill performance data was measured. The addition of crude glycerol lowered the temperature change across the pellet die, decreased pellet mill motor load, and improved production efficiency. The addition of crude glycerol also improved pellet durability compared with soybean oil and the soy oil/crude glycerol blend treatments. Pigs fed increasing levels crude glycerol had an increase in weight gain, but no differences were observed in the efficiency of gain. Both average daily gain and gain-to-feed tended to increase with increasing soy oil or the soy oil/crude glycerol blend. In summary, adding crude glycerol to the diet before pelleting increases pellet quality and improves feed mill production efficiency. The addition of 3 or 6% crude glycerol, soy oil, or a blend of soy oil and glycerol in nursery pig diets tended to increase weight gain. However, improved feed efficiency was only observed in the pigs fed soy oil or the soy oil/crude glycerol blend.

This study was designed to evaluate feasibility of replacing spray-dried whey with glycerol in nursery pig diets. A total of 350 weanling pigs 8-d after weaning (initial BW 6.3 ± 0.9 kg) were used in a 14-d growth assay. The pigs were fed one of ten diets that included 0, 3.6, or 7.2% lactose or 0, 3.6, or 7.2 % crude glycerol and fed in either meal or pelleted form. The changes in pellet temperature across the pellet die increased as lactose level increased, and decreased with the addition of glycerol. Pellet quality increased with the addition of both lactose and glycerol. Glycerol decreased the amount of energy required to pellet. Pigs fed the pelleted diets containing 7.2% glycerol had a decreased average daily gain to all of other treatments. Pigs fed the pelleted glycerol diets had a decreased average daily feed intake compared to pigs fed the pelleted lactose diets, and pigs fed diets containing either lactose of glycerol fed in meal form. Thus, based on these results, adding glycerol to diets prior to pelleting tends to improve pellet quality and decreases energy cost. However, it does not appear glycerol can replace lactose in weanling pig diets.

Scientific Abstract:

Experiments were conducted to: 1) determine the glycerol effects on diet flowability with different ingredients; and 2) evaluate glycerol effects on pellet mill production and pig performance. In the first series of experiments, the effects of added soybean oil, glycerol, or a 50:50 soybean oil/glycerol blend were examined in combination with ground corn or ground corn with spray-dried whey. Angle of repose was the criteria used to estimate flowability. There was a mill type × liquid source × percent liquid added interaction ($P < 0.05$) observed. Roller mill ground grain decreased angle of repose (AOR), improving flow ability compared with HM ground grain. Increasing soy oil increased AOR, decreasing flow ability. Increasing glycerol or the 50:50 soy oil/glycerol blend decreased AOR, improving flow ability when added to HM ground maize. There was a spray-dried whey level × percent liquid added × liquid source interaction ($P < 0.05$) observed. The addition of glycerol or the 50:50 soy oil/glycerol blend decreased AOR, improving flow ability. Increasing soy oil increased AOR regardless of spray-dried whey concentration. In the following studies, glycerol effects in diets on pellet mill production efficiency and nursery pig growth performance was evaluated. Diets were formulated to contain 0, 3, 6, 9, 12, and 15% glycerol. All diets were steam conditioned to 65.5°C and pelleted through a pellet mill equipped with a die that had an effective thickness of 31.8 mm and holes 3.96 mm in diameter. Increasing crude glycerol increased both the standard (linear and quadratic, $P < 0.01$) and modified (linear, $P < 0.01$; quadratic, $P \leq 0.02$) pellet durability indexes up to 9% with no further benefit thereafter. The addition of crude glycerol decreased (linear; $P < 0.01$) production rate (t/h) and production efficiency (kWh/t). A total of 182 pigs (initial BW, 11.0 ± 1.3 kg; 5 or 6 pigs/pen) were fed 1 of 7 corn-soybean meal-based diets with no added soy oil or crude glycerol (control), the control diet with 3 or 6% added soy oil, 3 or 6% added crude glycerol, and 6 or 12% addition of a 50:50 (wt/wt) soy oil/crude glycerol blend with 5 pens/diet. The addition of crude glycerol lowered ($P < 0.01$) delta temperature, amperage, motor load, and production efficiency. The addition of crude glycerol improved ($P < 0.01$) pellet durability compared with soy oil and the soy oil/crude glycerol blend treatments. Pigs fed increasing crude glycerol had increased (linear, $P = 0.03$) ADG. Average daily gain tended to increase with increasing soy oil (quadratic; $P = 0.07$) or the soy oil/crude glycerol blend (linear, $P = 0.06$). Adding crude glycerol to the diet did not affect G:F compared with the control. Gain:feed tended to increase with increasing soy oil (linear, $P < 0.01$; quadratic, $P = 0.06$) or the soy oil/crude glycerol blend (linear, $P < 0.01$; quadratic, $P = 0.09$). Nitrogen digestibility tended ($P = 0.07$) to decrease in pigs fed crude glycerol compared with pigs fed the soy oil treatments. Apparent digestibility of GE tended ($P = 0.08$) to be greater in the pigs fed soy oil compared with pigs fed the soy oil/crude glycerol blends. In conclusion, adding crude glycerol to the diet before pelleting increased pellet durability and improved feed mill production efficiency. The addition of 3 or 6% crude glycerol, soy oil, or a blend of soy oil and glycerol in diets for 11- to 27-kg pigs tended to increase ADG. For pigs fed crude glycerol, this was a result of increased ADFI, whereas, for pigs fed soy oil or the soy oil/crude glycerol, the response was a result of increased G:F.

Introduction

The Renewable Fuel Standards Program, which is part of the Energy Policy Act of 2005, mandates that a minimum level of renewable fuels be consumed in the United States each year. In 2006, the minimum biofuels consumption level was set at four billion gallons, with expectations of doubling by 2012. Biodiesel is the renewable alternative to petroleum-based diesel fuel. It consists of monoalkyl esters formed through an alcohol-based catalyzed reaction of triglycerides in oils and fats. According to the National Biodiesel Board, there are currently 105 biodiesel production facilities operating in the United States, and 77 facilities are in the planning or construction stage. If all of these facilities are realized, the estimated U.S. biodiesel production capacity will exceed 2.5 billon gallons (EPA, 2007). This level of production will yield nearly 1.3 million tons of glycerol, the primary co-product of the biodiesel production process.

Glycerol comprises approximately 10 to 11% of a typical triglyceride. Purification of crude glycerol to a chemically pure substance results in a valuable industrial chemical. However, it is costly and the glycerol market is already saturated, thus the price of glycerol continues to decline. This trend will likely continue as more biodiesel production facilities come online.

The declining price of glycerol has sparked much interest in utilizing crude glycerol as a feed ingredient in animal diets. However, little is known about glycerol's nutritional value or how it impacts feed quality and feed processing efficiency. Additionally, the majority of current glycerol studies have focused on using glycerol as an energy source for replacing cereal grains or fat in the diet. Glycerol could have potential as a replacement for other ingredients. Lactose is a simple carbohydrate included in weanling pig diets. Spray-dried whey is a popular lactose source, but with the variability in cost and ingredient quality from various suppliers, glycerol could be added to a nursery pig diet in place of a lactose source.

Addressing practical issues associated with handling and feeding glycerol, and providing a basis for comparing glycerol with other feed ingredients, will enable swine producers to better make production decisions to potentially improve feed quality and production efficiency, and cheapen diet costs. Therefore, the following experiments, which were sponsored by the National Pork Board, were directed at evaluating the effects of glycerol on feed characteristics, feed manufacturing, and nursery pig performance.

Objectives

1) To evaluate the effects of glycerol on feed characteristics and the pelleting process.

2) Evaluate the effects of glycerol or soy oil blends on pellet quality and pig performance.

3) Determine if glycerol can be a replacement for lactose in nursery diets and its effects on pig performance.

Materials and Methods

Objective 1 - To evaluate the effects of glycerol on feed characteristics and the pelleting process.

General

Experiments were conducted using maize ground by either a full circle, teardrop hammer mill (P-240D Pulverator, Jacobsen Machine Works, Minneapolis, MN) or a three high roller mil (Model TP 012, Roskamp Manufacturing, Cedar Falls, IA) at the Kansas State University Grain Science Feed Mill. Particle size and standard deviation were determined with a Ro-Tap tester (W. S. Tyler, Mentor, OH) with a stack of 13 screens, as outlined in the American Society of Agricultural Engineers (publication S319). Angle of repose was defined as the maximum angle measured in degrees at which a pile of grain retains its slope (Appel, 1994). An angle of repose tester was constructed from 4 pieces of poly vinyl chloride (PVC, Groesbeck et al., 2006). In brief the tester is 3” in diameter and 36” tall and attached to a 3” PVC floor mounting. A 3” diameter plate was mounted to the top of the machine, which allowed two 3” PVC couplers to slide up and down the long axis of the tester. To conduct the angle of repose test, a 500 g sample was placed inside the couplers at a specified height at the top of the tester. The base of the angle of repose tester was held stationary and the PVC couplers were lifted vertically, allowing the test ingredient to flow downward resulting in a pile on top of the plate. The height of the pile was measured, and angle of repose was calculated by the following equation, Angle of repose = $\tan^{-1}$ (the height of the pile divided by one half the diameter of the plate). A larger angle of repose represents a steeper slope and poorly flowing product; a low angle of repose would represent a freer flowing product.

Experiment 1

The objective of this study was to evaluate the effects of added soy oil, glycerol, or a 50:50 soy oil/glycerol blend on the flow ability of ground maize. Samples were ground through a RM (roller mill) or HM (hammermill). After processing, corn was dried for 12 h to equalize moisture content, resulting in a DM of 96%. The maize contained 101 g/kg CP and 30 g/kg fat on an as-fed basis. Particle size mean and standard deviations were 645 µm and 1.97 for maize ground through the roller mill and 674 µm and 2.31 for maize ground through the hammer mill. Soy oil, glycerol, or a 50:50 blend of soy oil/glycerol was added to the ground maize at 0, 20, 40, 60, or 80 g/kg for a total of 30 samples (2 mill types, 3 liquid sources, and 5 levels of added liquid). Angle of repose was measured, and replicated 4 times on each sample.

Experiment 2

The objective of this study was to evaluate the effects of added soy oil, glycerol, or a 50:50 soy oil/glycerol blend on the flow ability of a HM ground maize diet with either 150 or 300 g/kg spray-dried whey. The HM maize sample used in Exp.1 was the same sample used in Exp. 2. Soy oil, glycerol, or a 50:50 blend of soy oil/glycerol was added to the ground grain and spray-dried whey-based diet at 0, 40, or 80 g/kg for a total of 18 samples (1 HM sample, 2 levels of added whey, 3 liquid sources, and 3 levels of added liquid). Angle of repose was then measured, and replicated 4 times on each sample.

Experiment 3

The objective of this study was to evaluate the effects of humidity and temperature on the flow ability of HM ground maize with 0, 30 or 60 g/kg added glycerol. The maize contained 85.4 g/kg CP, 33 g/kg fat, and 12% moisture on an as-fed basis. Particle size mean and standard deviations of the HM ground maize were 1,081 μm and 2.52. This experiment was conducted at two temperature levels (25°C and 35°C) and two relative humidity levels (40 % and 70%). An environmentally controlled facility was used to minimize temperature and humidity fluctuations. All samples were placed into the humidity chamber for a minimum of 12 h before the experiment was conducted to allow for acclimation of the ingredients to the environmental conditions. Digital humidity and temperature readers (Traceable® Humidity, Fisher Scientific, Hampton, NH) were used to measure the minimum and maximum temperature and humidity. Angel of repose was then measured, and replicated 4 times on each.

Experiment 4

The objective of this study was to evaluate the effects of temperature and humidity on flow ability of HM ground grain with 0, 40, or 80 g/kg added glycerol and 0, 150, and 300 g/kg added whey permeate. The HM maize sample used in Exp. 3 was the same sample used in Exp. 4. This experiment was conducted at two temperature levels (25°C and 35°C) and two relative humidity levels (40 % and 70%). The environmental chamber was the same as in Exp. 3. Angle of repose was then measured, and replicated 4 times on each sample.

Statistical analysis.

All data was analyzed using PROC MIXED in SAS (SAS Institute, Cary, NC). Experiment 1 was analyzed as a 2 × 3 × 5 factorial (2 mill types, 3 liquid sources, and 5 levels of added liquid). Experiment 2 was analyzed as a 2 × 3 × 3 factorial (2 levels of added whey, 3 liquid sources, and 3 levels of added liquid). Experiment 3 was analyzed as a 3 × 2 × 2 factorial (3 levels of added glycerol, 2 temperatures, and 2 humidity levels). Experiment 4 was analyzed as a 3 × 2 × 2 × 2 factorial (3 levels of added glycerol, 2 temperatures, 2 humidity levels, and 2 whey permeate levels). All interactions were evaluated and non-significant interactions were removed from the model statement.

Objective 2 - Evaluate the effects of glycerol or soy oil blends on pellet quality and pig performance.

Experiment 1

Experiment 1 included six treatments that were corn-soybean meal-based swine grower diets formulated to contain 0, 3, 6, 9, 12, and 15% crude glycerol (Table 1). Diets were manufactured, pelleted, and data collected at the Kansas State University Grain Science Feed Mill. All diets were steam conditioned to 65.5°C by adjusting the steam flow rate and pelleted using a California Pellet Mill (Master Model HD, Series 2000 Crawfordsville, IN.) equipped with a die that had an effective thickness of 31.8 mm and holes 3.96 mm in diameter. Pellets were cooled using a double-pass perforated deck cooler (Wenger Manufacturing, Sabetha, KS). All experimental runs were performed using a warm die. Samples of corn, soybean meal (SBM), diet mash (before conditioning), and pellets were collected for each experimental run. Particle size was determined using the corn (667 μm) and SBM (1,025 μm) collected (ASAE Standard 319.1; 1983).

Pellet mill production data was collected on all diets, and each diet run was replicated by manufacturing a new batch of feed three times. Pellet mill electrical consumption, production rate, hot-pellet temperature, motor load, feeder rate, conditioning rate, and pellet durability were measured. Conditioning temperature was measured through a stiff thermocouple that was placed in the steam of the conditioned mash as it moved from the conditioner to the pellet die. To measure hot pellet temperature, pellets were collected in a foam insulated pail, and the temperature was taken using a stiff thermocouple after the temperature reading reached equilibrium. Conditioning temperature and production rate were held constant. Pelleting efficiency, expressed as kilowatthours per metric ton (kWh/t), was determined from voltage and amperage meter readings and production rate. Standard and modified pellet durability index (PDI) was evaluated for each experimental run using 500 g of cold pellets (ASAE Standard S269.3; 2003).

Experiment 2

The experimental protocol used in this study was approved by the Kansas State University Institutional Animal Care and Use Committee. A total of 182 weanling pigs (21 ± 3 d of age and initial BW 11.0 ± 1.3 kg) were used in a 26-d growth assay. Pigs were blocked by initial weight and randomly allotted to one of seven dietary treatments with five or six pigs/pen and five pens/treatment. Experimental diets included a control with no added soy oil or glycerol, the control diet with 3 or 6% added soy oil, the control diet with 3 or 6% added glycerol, and the control with 6 or 12% of a 50:50 soy oil glycerol blend (Table 2). All diets were formulated to the same lysine to ME ratio. Similar to Exp. 1, pellet mill production data was collected during diet manufacturing.

Pigs were housed in an environmentally controlled nursery at the Kansas State University Segregated Early-Weaning Facility. Each pen was 1.2 × 1.2-m and contained one self-feeder and one cup waterer to provide ad libitum access to feed and water. Pigs were weighed and feed disappearance was determined on d 0, 8, 19, and 26 to determine ADG, ADFI, and G:F. On d 14 pigs were fed their respective treatment diet, but with the addition of 0.5% Cr_2O_3, an indigestible marker. On d 19, grab samples of feces were collected from a minimum of two pigs/pen. Concentrations of Cr (Kimura and Miller, 1957; Williams et al., 1962), DM and N (AOAC, 1995; method 930.15 and 990.03) and GE using adiabatic bomb calorimetry (Parr Instruments, Moline, IL) in the feces and diet were determined to calculate apparent digestibility of DM, N, and GE.

Statistical Analysis

Statistical analysis was performed using MIXED procedures (SAS Inst. Inc., Cary, NC.). Data from Exp. 1 was analyzed as a completely randomized block design, with batch as the experimental unit. Contrasts for linear, quadratic, and cubic polynomial effects of glycerol were also included in the analysis. In Exp. 2, pellet mill production data was analyzed as completely randomized block, with batch as the experimental unit. Pig growth data was analyzed as `completely randomized block, with initial weight as the blocking factor. Pen was the experimental unit for growth and digestibility data analyses. Contrasts include linear and quadratic effects of soy oil, glycerol, and the blend of soy oil and glycerol. Contrasts between the mean of pigs fed soy oil, glycerol, and the soy oil/glycerol blend were conducted.

Objective 3 - Determine if glycerol can be a replacement for lactose in nursery diets and its effects on pig performance.

General

The experimental protocol used in this study was approved by the Kansas State University Institutional Animal Care and Use Committee. Prior to starting on trial pigs were fed standard SEW and transition diets (KSU Swine Nutrition Guide, 2007). Pigs were housed in an environmentally controlled nursery at the Kansas State University Segregated Early-Weaning Facility. Each pen was 1.2 × 1.2-m and contained one self-feeder and one cup waterer to provide ad libitum access to feed and water. Initial temperature of the nursery was maintained at 32°C for the first week and decreased approximately 2°C each week thereafter. All pigs used in these experiments were 21 ± 3 days of age at weaning and randomly allotted dietary treatments in a complete randomized design. All diets were formulated to meet or exceed NRC (1998) nutrient requirements, and diets were formulated using an ME value of 3,420 kcal/kg for glycerol, the same ME value used for corn (NRC, 1998). Pigs were fed a glycerol source obtained from a bio-diesel plant in Bruster, MN.

Experiment 1

A total of 350 weanling pigs (8 d post weaning, initial BW 6.3 ± 0.9 kg) were used in a 14-d growth assay. Pigs were weighed and pens were allotted completely random to one of ten dietary treatments with five pigs/pen and seven pens/treatment. Experimental diets included ten treatments that were corn-soybean meal-based swine grower diets formulated to contain 0, 3.6, or 7.2% lactose or 0, 3.6, or 7.2 % crude glycerol and fed in either meal or pelleted form (Table 1). Diets were manufactured, pelleted, and pellet mill production data collected at the Kansas State University Grain Science Feed Mill. All diets were steam conditioned to 65.5°C by adjusting the steam flow rate and pelleted using a California Pellet Mill (Master Model HD, Series 2000 Crawfordsville, IN.) equipped with a die that had an effective thickness of 31.8 mm and holes 3.96 mm in diameter. Pellets were cooled using a double-pass perforated deck cooler (Wenger Manufacturing, Sabetha, KS). All experimental runs were preformed using a warm die. Samples of corn, soybean meal (SBM), diet mash (before conditioning), and pellets were collected for each experimental run. Particle size and standard deviation was determined using the corn (786 µm, 2.20) and SBM (1,045 µm, 1.66) collected (ASAE Standard 319.1; 1983).
Pellet mill production data was collected on all diets, and each diet run was replicated by manufacturing a new batch of feed three times. Pellet mill electrical consumption, production rate, hot-pellet temperature, motor load, feeder rate, conditioning rate, and pellet durability index (PDI) were measured. Conditioning temperature was measured through a stiff thermocouple that was placed in the steam of the conditioned mash as it moved from the conditioner to the pellet die. To measure hot pellet temperature, pellets were collected in a foam insulated pail, and the temperature was taken using a stiff thermocouple after the temperature reading reached equilibrium. Conditioning temperature and production rate were held constant. Pelleting efficiency, expressed as kilowatthours per metric ton (kWh/t), was determined from voltage and amperage meter readings and production rate. Standard and modified PDI was evaluated for each experimental run using 500 g of cold pellets (ASAE Standard S269.3; 2003).
Pigs were weighed and feed disappearance was determined on d 0, 7, and 14 to determine ADG, ADFI, and G:F. All diets included 0.4% Cr_2O_3, an indigestible marker. On d 12, grab samples of feces were collected from a minimum of two pigs/pen. Concentrations of Cr (Kimura and Miller, 1957; Williams et al., 1962), DM and N (AOAC, 1995; method 930.15 and 990.03) and GE using adiabatic bomb calorimetry (Parr Instruments, Moline, IL) in the feces and diet were determined to calculate apparent digestibility of DM, N, and GE.

Experiment 2

A total of 375 weanling pigs (7-d post weaning, initial BW 6.7 ± 1.1 kg) were used in a 14-d growth assay. Prior to starting on trial, pigs were fed standard SEW and transition diets. Pigs were allotted completely random to one of 14 dietary treatments with five pigs/pen and five or six pens/treatment. Experimental diets included fourteen treatments that were corn-soybean meal-based swine grower diets formulated to contain 0, 3.6, 7.2, or 10.8% lactose or 0, 3.6, 7.2, or 10.8 % crude glycerol and fed in either meal or pelleted form (Table 2). Seven diets were manufactured at the Kansas State University Animal Science Feed Mill, and one half of each batch was pelleted at the Kansas State University Grain Science Feed Mill as in Exp. 1. Pellet mill production data was not collected on these diets. Pigs were weighed and feed disappearance was determined on d 0, 7, and 14 to determine ADG, ADFI, and G:F. All diets included 0.4% Cr_2O_3, an indigestible marker. On d 12, grab samples of feces were collected and analyzed same as Exp. 1.

Statistical Analysis

Statistical analysis was performed using MIXED procedures (SAS Inst. Inc., Cary, NC.). In Exp. 1, pellet mill production data was analyzed as completely randomized block, with batch as the experimental unit. Contrasts included linear and quadratic effects lactose and glycerol. Pig growth and data from Exp. 1 and 2 was analyzed with pen as the experimental unit. Interactions between diet form (meal or pellet), inclusion level (0, 3.6, 7.2, and 10.8%), and ingredient source (lactose or glycerol) were evaluated. Contrasts were used to evaluate differences between meal and pelleted treatments, as well as, linear and quadratic effects of lactose and glycerol.

VII. Results

Objective 1 - To evaluate the effects of glycerol on feed characteristics and the pelleting process.

Experiment 1

In Exp. 1, a mill type × liquid source × percent liquid added interaction (Figure 1, $P < 0.05$) was observed. Roller mill ground grain decreased angle of repose, improving flow ability compared to HM ground grain. The addition of soy oil increased angle of repose, decreasing flow ability. The addition of glycerol or a 50:50 soy oil/glycerol blend decreased angle of repose, improving flow ability when added to the diet containing HM ground maize. Adding glycerol or the 50:50 soy oil/glycerol blend to the diet containing RM ground maize did not influence angle of repose.

Experiment 2

In Exp. 2, a spray-dried whey level × liquid source × percent liquid added interaction (Figure 2, ($P < 0.05$) observed. The addition of glycerol or the 50:50 soy oil/glycerol blend decreased angle of repose, improving flow ability. The addition of glycerol decreased angle of repose greater in the 150 g/kg spray-dried whey sample compared to the 300 g/kg spray-dried whey sample. The addition of soy oil increased angle of repose regardless of spray-dried whey concentration.

Experiment 3

In Exp. 3, a percent added glycerol × humidity × temperature interaction (Figure 3, $P < 0.05$) was observed. Increasing glycerol decreased angle of repose, improving flow ability under all temperature and humidity conditions. At 25°C, increasing humidity from 40 to 70% increased angle of repose in the 0 g/kg added glycerol sample. At 35°C, samples with 0 and 30 g/kg added glycerol had similar flow ability; however, the 60 g/kg added glycerol at the 70% humidity had similar flow ability as the 60 g/kg added glycerol at 25°C and 70% humidity. As temperature increased flow ability decreased; however, flow ability improved as humidity increased.

Experiment 4

In Exp. 4, a percent glycerol × percent whey permeate × humidity interaction (Figure 4, $P < 0.03$) was observed. Adding whey or glycerol or increasing humidity decreased angle of repose, improving flow ability. In the maize diet without added glycerol and 300 g/kg whey diet angle of repose increased as humidity increase; however, the 300 g/kg whey diet with 40 g/kg or 80 g/kg added glycerol resulted in similar flow ability. At 70% humidity, the diets containing 150 or 300 g/kg had similar flow ability to the diet containing 40 g/kg glycerol and no added whey.

Objective 2 - Evaluate the effects of glycerol or soy oil blends on pellet quality and pig performance.

Experiment 1

There was no difference ($P > 0.11$) in conditioning temperature, indicating that conditioning temperature was indeed held constant between treatments (Table 3). Hot pellet temperature decreased (linear; $P < 0.03$) with increasing glycerol levels. Delta temp also decreased (linear; $P < 0.02$) with increasing glycerol levels. Delta temp should follow a similar pattern to hot pellet temperature as delta temp is calculated using hot pellet temperature and conditioning temperature. There was no difference ($P > 0.84$) in voltage (volts) with increasing glycerol. Amperage (Amps) decreased (linear; $P < 0.01$) with the addition of glycerol. The greatest decreases occurred with the addition of 3% glycerol and again at the 12% glycerol additions; however; all diets with glycerol had lower amps than the control. Motor load also decreased (linear; $P < 0.01$) with the addition of glycerol. Voltage, amps, and motor load are measures of energy usage by the pellet mill. Amperage and motor load values follow similar trends. Amperage measures the electrical current pulled from the pellet mill, and motor load energy needed to rotate the pellet die. Motor load will increase with increased friction in the die, and decrease as friction is decreased in the die. The decrease in motor load when glycerol is added to the diet indicates a decrease pellet die friction.

Pellet durability index also increased (quadratic; $P < 0.01$) through 9% added glycerol for both the standard and modified PDI, resulting in a 2 to 6% improvement in PDI compared to the control. These results differ from previous research reporting broiler diets pelleted with 10% glycerol had visibly poorer pellet quality; however, pellet durability index was not measured (Cerrate et al., 2006). The addition of glycerol decreased (linear; $P > 0.01$) production rate (t/h). The production energy (kWh/t) decreased (linear; $P < 0.01$). A reduction or improvement in production efficiency (kWh/t) will result in a direct economical savings for the feed mill by reducing total energy usage of the pellet mill.

Experiment 2

Similar to Exp. 1, a conditioning temperature of 65.5 °C was targeted for pelleting. There was a tendency ($P < 0.08$) for the 3% soy oil, 3% glycerol, and the 6% blend treatments to have a higher conditioning temperature of 66.3 °C compared to all other treatments at 65.8 °C (Table 4). Although statistically significant, this small difference is of little practical importance. Hot pellet temperature and delta temperature were decreased (linear; $P < 0.01$) with the addition of soy oil, and decreased (quadratic; $P < 0.03$) with the addition of glycerol or the soy oil/glycerol blend. A lower delta temperature is an indication of a reduced die friction. As die friction increases, delta temperature would be expected to increase. The greatest improvement occurred with the initial liquid addition of glycerol or the soy oil/glycerol blend, only slightly decreasing further with the addition of either the 6% glycerol or the 12% blend addition. Hot pellet temperature and delta temperature was reduced ($P < 0.01$) for the soy oil/glycerol blend when compared to soy oil and glycerol additions. The soy oil/glycerol blend at 6% still had a greater decrease in hot pellet temperature then either the 6% addition of soy oil or glycerol, indicating that glycerol and soy oil combined can further reduce the die friction then either ingredient added to the diet individually. There was no difference ($P > 0.10$) between hot pellet temperature and delta temperature between the soy oil and glycerol treatments, indicating that glycerol has a similar lubrication effect on the pellet die as soy oil.

There was no difference ($P > 0.11$) in voltage between any of the treatments. Amperage and motor load decreased (linear; $P < 0.01$) with the addition of soy oil, and the soy oil/glycerol blend. Adding glycerol decreased (quadratic; $P < 0.05$) amperage and motor load with the greatest decrease occurring with the 3% addition of glycerol to the diet, with little to no additional improvement with the 6% glycerol addition. The addition of the soy oil/glycerol blend had the greatest decrease in motor load (linear; $P < 0.01$) and amperage (quadratic; $P < 0.03$), with the greatest decrease occurring with 12% soy oil/glycerol blend. The addition of soy oil and glycerol resulted in increased ($P < 0.01$) amperage and motor load compared to the blend, indicating that the soy oil/glycerol blend had greatest reduction in pellet die friction.

Pellet quality was not affected ($P > 0.26$) with the addition glycerol; however, the 6% added glycerol had the greatest PDI compared to all other treatments. Soybean oil is typically added to nursery diets to aid in pelleting and reduces diet friction; however, the addition of soy oil results in poor quality pellets (Briggs et al., 1999). As expected the addition of soy oil decreased (quadratic; $P < 0.01$) PDI. The soy oil/glycerol blend decreased (linear; $P < 0.01$) PDI, however, PDI of the blend was greater ($P < 0.01$) than the PDI of soybean oil alone. The addition of the 6% and 12%, soy oil/glycerol blends resulted in a 5 to 37% improvement in PDI compared to the addition of 3 or 6% soy oil alone. Similar to Exp. 1 the addition of glycerol improved PDI. The addition of glycerol improved ($P < 0.01$) PDI an average of 15% when compared to the soy oil/glycerol blends and an average of 40% when compared to the soy oil treatments. These data indicate that glycerol added to a diet before pelleting with or without added soy oil will result in an improved PDI.

Soy oil had an increased ($P > 0.01$) production rate compared to glycerol. Production rate (t/h) was not different between glycerol and the soy oil/glycerol blend or the control, and the soy oil/glycerol blend was not different from any of the other treatments. Production efficiency (kWh/t) decreased (quadratic; $P < 0.01$) with the addition of soy oil, glycerol, and the soy oil/glycerol blend, with the greatest benefit occurring with the initial addition of any of the liquid sources. The control diet had the greatest ($P < 0.01$) production efficiency (kWh/t) while the soy oil/glycerol blend the lowest. Glycerol had an increased ($P < 0.01$) production efficiency (kWh/t) compared to soy oil, but was intermediate to the control and the soy oil/glycerol blend. The potential energy savings by the feed mill with a decrease in production efficiency (kWh/t) demonstrated the importance of liquid addition to meal diets before pelleting.
Several international studies have evaluated the use of glycerol in swine and poultry diets (Bernal et al., 1978; Kijora et al., 1995; Simon et al., 1996). However the majority of these studies used a glycerol by-product of bio-diesel production from rapeseed oil. In our study pigs were fed a glycerol source that contained 90.7% glycerol and 136 ppm methanol, from a bio-diesel plant in Bruster, MN.

From d 0 to 26, pigs fed diets containing soy oil had a tendency for increased (quadratic, $P < 0.07$) ADG with the greatest improvement occurring with the addition of 3% with no additional improvement observed at 6% (Table 5). Pigs fed diets with increasing glycerol had increased (linear, $P < 0.03$) ADG. In addition, pigs fed increasing levels of the soy oil/glycerol blend had a tendency for increased (linear, $P < 0.06$) ADG. Pigs fed increasing soy oil had increased ($P < 0.03$) ADFI compared to pigs fed the soy oil/glycerol blend treatments. The pigs fed the diets with increasing glycerol had a tendency for increased ($P < 0.08$) ADFI compared with pigs fed diets containing soy oil. Pigs fed diets with increasing soy oil had increased (linear, $P < 0.01$) G:F, with the greatest improvement with the 3% added soy oil, with no additional improvement at 6%. Increasing added glycerol had no effect on G:F, while pigs fed the soy oil/glycerol blend had increased (linear, $P < 0.01$) G:F. Pigs fed the diets containing soy oil had greater ($P < 0.03$) G:F compared with pigs fed diets containing glycerol. The pigs fed the soy oil/glycerol blends had improved ($P < 0.03$) G:F compared to pigs fed the soy oil treatments. Pigs fed diets with increasing soy oil had a tendency for increased (quadratic, $P < 0.07$) final BW. Pigs fed increasing glycerol had increased (linear, $P < 0.03$) final BW and The pigs fed the soy oil/glycerol blend had a tendency for increased (linear, $P < 0.06$) final BW. Overall there was little difference in final BW between the pigs fed soy oil, glycerol, or the soy oil/glycerol blend, but all three treatments resulted in a greater final BW compared to the pigs fed the control diets.

Fecal excretion of DM tended ($P < 0.07$) to increase in the pigs fed glycerol compare to the pigs fed soy oil or pigs fed the soy oil/glycerol blends (Table 3). Nitrogen digestibility tended ($P < 0.07$) to decrease in the pigs fed diets containing glycerol compared to pigs fed diets containing soy oil. Previous research by Simon et al., (1997) showed that N retention in broilers increased as glycerol inclusion increased up to 20%. However, in subsequent work reported no effect of N retention when glycerol is increased in a diet. Gross energy intake tended ($P < 0.10$) to decrease in the pigs fed the soy oil/glycerol blends compared to the pigs fed glycerol. This was expected as the pigs fed the soy oil/glycerol blend had decreased ADFI compared to the pigs fed glycerol. Gross energy fecal excretion also tended ($P < 0.10$) to decrease in soy oil/glycerol blend fed pigs compared with the glycerol fed pigs. Gross energy digestion tended ($P < 0.08$) to increase in the pigs fed soy oil compared to pigs fed the soy oil/glycerol blends. Pigs fed the added soy oil treatments tended ($P < 0.07$) to have increased percentage GE digestion compared with pigs fed glycerol.

Previous research conducted by Lammers et al. (2007a) supports the addition of glycerol to swine diets, without altering growth performance. Our data differs slightly from these previous data in that glycerol tended to increase ADFI, and decrease G:F. Lammers et al. (2007a) demonstrated no difference in ADG, ADFI, G:F, or carcass composition in pigs fed glycerol at 5 or 10% inclusions. Additional research also supports the use of glycerol as a feed ingredient without altering growth performance criteria in both swine and poultry (Bernal et al., 1978; Kijora et al., 1995; Simon et al., 1996). All of these studies focused on using glycerol as an energy source for replacing cereal grains in the diet. Lammers (2007b) estimated that the apparent DE of crude glycerol for nursery pig diet is 3386 ± 149 kcal/kg. However, our data indicates that glycerol can replace cereal grains at an energy value greater then corn. The increase in G:F would indicate the glycerol energy value used in formulation was underestimated. However, additional research is needed to further evaluate glycerol in swine diets, storage and oxidation, product variability, storage of feed manufactured with glycerol, and the interaction between glycerol and conditioning temperature.

Adding glycerol to a corn-soybean meal diet prior to pelleting appears to be a management strategy to enhance the overall pellet process, by decreasing production efficiency (kWh/t) and improving pellet quality, without compromising growth performance. These data indicating that glycerol can be included in a diet up to 6% or in a soy oil/glycerol blend up to 12%, resulting in similar final BW between soy oil, glycerol, and the soy oil/glycerol blend.

Objective 3 - Determine if glycerol can be a replacement for lactose in nursery diets and its effects on pig performance.

Experiment 1

There was no difference ($P > 0.12$) in conditioning temperature, indicating that conditioning temperature was indeed held constant between treatments (Table 3). Hot pellet temperature and delta temperature increased (linear; $P < 0.01$) with increasing lactose level. Hot pellet temperature and delta temperature decreased (linear; $P < 0.01$) with increasing glycerol level. Delta temperature should follow a similar pattern to hot pellet temperature as delta temperature is calculated using hot pellet temperature and conditioning temperature. There was no difference ($P > 0.19$) in voltage (volts) with increasing lactose or glycerol. Amperage (Amps) increased (linear; $P < 0.01$) with increasing lactose, and decreased (linear; $P < 0.01$) with increasing glycerol. Motor load also increased (linear; $P < 0.01$) with the addition of lactose and decreased (linear; $P < 0.01$) with the addition of glycerol. Voltage, amps, and motor load are measures of energy usage by the pellet mill. Amperage and motor load values follow similar trends. Amperage measures the electrical current pulled from the pellet mill, and motor load energy needed to rotate the pellet die. Motor load will increase with increased friction in the die, and decrease as friction is decreased in the die. The decrease in motor load when glycerol is added to the diet indicates a decrease pellet die friction.

Pellet durability index increased (linear; $P < 0.01$) with the addition of both lactose and glycerol for both the standard and modified PDI, with both the glycerol treatments having the greatest PDI. The addition of lactose increased (linear; $P > 0.01$) production rate (t/h), while the addition of glycerol had no effect on production rate compared to the control. The addition of lactose had no effect on production energy (kWh/t) compared to the control, while the addition of glycerol decreased (linear; $P < 0.01$) production energy (kWh/t). A reduction or improvement in production efficiency (kWh/t) will result in a direct economical savings for the feed mill by reducing total energy usage of the pellet mill.

From d 0 to 14, there was a tendency ($P < 0.06$) for an inclusion level × diet form (meal or pellet) interaction observed for ADG (Table 4 and 5). Pigs fed the pelleted diets containing the 7.2% glycerol inclusion level had decreased ADG compared to all other treatments. There was also an inclusion level × diet form and diet form × source (lactose or glycerol) interaction ($P < 0.03$) observed for ADFI. Pigs fed the pelleted diets containing the 7.2% glycerol inclusion level had decreased ADFI compared to all other treatments. Pigs fed the pelleted glycerol diets had decreased ADFI (338 g) compared to pigs fed the pelleted lactose (397 g) diets and pigs fed diets containing either lactose (395 g) or glycerol (391 g) fed in meal form. All of these interactions are due to the decreased performance of the pigs fed the pelleted diet with 7.2% glycerol. There was no effect ($P < 0.15$) of diet form, inclusion level or source (lactose or glycerol) on G:F.

Apparent digestibility demonstrated a diet form (meal vs pellet) × source interaction ($P < 0.04$) for DM intake (Table 6 and 7). Pigs fed diets containing glycerol had decreased DM intake and pigs fed pelleted diets with glycerol had lower DM intakes compared to pigs fed glycerol in meal form. This response is primarily a result of the decreased ADFI of the pigs fed 7.2% glycerol in pelleted form. There was an inclusion level × source (lactose vs glycerol) interaction (P < 0.04) observed for fecal excretion of DM. Pigs fed diets with increasing glycerol had decreased fecal excretion of DM compared to pigs fed increasing lactose, and both pigs fed the diets containing lactose and glycerol had decreased fecal excretion of DM compared to the control pigs. There was a diet form × source, and inclusion level × source ($P < 0.05$) interaction observed for DM retention (g/d). Pigs fed the diets containing lactose in pellet form had increased DM retention compared to the pigs fed diets containing lactose in meal form. Pigs fed the diets containing glycerol in meal form had increased DM retention compared to the pigs fed the diets with glycerol in pelleted form, and increasing glycerol in pelleted diets decrease DM retention. Overall, DM digestion was greatest ($P < 0.02$) in the pigs fed the diets containing lactose in pelleted form compared to the pigs fed diets with glycerol, and increasing glycerol increased percent DM retained.

Nitrogen intake (g/d) was greater ($P < 0.04$) for the pigs fed the lactose diets compared to the pigs fed the glycerol diets. There was a inclusion level × source × diet form interaction ($P< 0.03$) observed for N fecal excretion (g/d). Pigs fed the diets with increasing lactose in meal form had increased N fecal excretion, while pigs fed lactose in pelleted form had decreased N fecal excretion. Pigs fed diets with increasing glycerol had decreased N fecal excretion. Overall, N digestibility increased ($P < 0.01$) in pigs fed pelleted diets. Nitrogen digestion also increased ($P < 0.04$) in pigs fed diets containing lactose compared to pigs fed diets containing glycerol.

Gross energy intake increased ($P < 0.02$) for pigs fed pelleted diets compared to pigs fed meal diets and GE was also increased ($P < 0.04$) in pigs fed diets containing lactose compared to pigs fed diets with glycerol. Fecal excretion decreased ($P < 0.01$) in pigs fed pelleted diets compared to pigs fed meal diets. Overall, there was an inclusion level × source interaction ($P < 0.02$) observed for GE digestion. Gross energy digestion increased as fed were fed increasing glycerol, but pigs fed diets containing lactose had an increased GE digestion compared to pigs fed the diets containing glycerol.

Experiment 2

From d 0 to 14 there was no effect ($P < 0.27$) of diet form (meal or pellet), inclusion level (0, 3.6, 7.2, or 10.8%), or source (lactose or glycerol) on ADG or ADFI. The was a tendency ($P < 0.06$) for an inclusion level × diet form × source interaction for G:F. Pigs fed the meal and pelleted diets with increasing lactose had decreased G:F compared to the control, the meal diet with 3.2% lactose had the greatest decrease in G:F. The pigs fed the meal diet with increasing glycerol had decreased G:F through 10.8% glycerol, and the pigs fed the pelleted diet with increasing glycerol had decreased G:F through 7.2% glycerol, with the 10.8% having the greatest G:F.

Discussion

Adding dietary fat and decreasing particle size in swine diets has been shown to improve feed efficiency (Smith et al., 1999; De La Llata et al., 2001a), but has also been shown to decreased flow ability (Groesbeck et al., 2006). The decreased flow ability is speculated to result in an increase feed handling issues. Decreasing particle size and adding fat further decreased flow ability. Increasing biofuel production has lead to an increase in biofuel by-products available for use as a feed ingredient. Glycerol, a by-product of soy oil biodiesel production is an energy source that can be added to swine diets (Lammers et al., 2007) potentially in place of, maize, soy oil or choice white grease. With the increase use of glycerol in swine diets, it is important to understand its implication on feed handling.

These data suggest that the addition of glycerol to a meal diet will improve flow ability and therefore feed handling. Hammermill and roller mill grinding are both methods used by the swine industry in particle size reduction. Previous work has demonstrated that RM ground grain with 60g/kg added fat will result in similar flow ability to HM ground grain with no added fat (Groesbeck et al., 2006). In Exp. 1, the addition of glycerol to a HM ground grain diet improved flow ability, while adding glycerol to the RM ground grain had no further improvement in flow ability. This response could be due to the increased particle size standard deviation seen in HM ground grain compared to RM ground grain (Groesbeck et al., 2006). The glycerol could be encapsulating the smaller particles reducing friction between particles, improving flow ability. These data, similar to Groesbeck et al. (2006) indicate that RM ground grain will flow better than HM ground grain, but these data indicate the addition of glycerol to HM ground grain can improve flow ability.

Soy oil and other fat sources are often added to diets to help control dust. It is not clear if glycerol would reduce dustiness, but these data show that glycerol can be added to swine diets in a blend with soy oil, resulting in improved flow ability compared to the addition of soy oil alone. Fat is also added to nursery diets to reduce dust, but may adversely affect flow ability when mixed with specialty protein ingredients (Carney et al. 2005, 2007). Lactose has been shown to improve flow ability (Carney et al., 2005); however, lactose was not evaluated in the presence of added fat. Similar to Carney et al. (2005) Experiment 2 and 4 also suggest that lactose added to maize-based diets will result in an improved feed handling. When lactose is incorporated in a diet with added glycerol, flow ability still improves.

Temperature and humidity are factors that negatively effect protein quality of complex nursery pig diets (Mavromichalis and Baker 2000), and may be a contributing factor in feed bridging or feed flow problems (Carney et al., 2007). Carney et al. (2007) demonstrated that as humidity level increased from 34 to 64% flow ability of ground grain with added specialty protein ingredient decreases flow ability. It was expected that an increase in humidity would cause an increase in water absorption by the ingredients and a decrease in flow ability. In Exp. 3 and 4 and increase in humidity resulted in improved flow ability. As glycerol was added to the diets and humidity was increased flow ability improved further. It appears that glycerol added to ground maize diets may flow better at higher humidity levels. In Exp. 3 a lower temperature and increased humidity resulted in the greatest improvement in flow ability. This indicates that increasing temperature will affect feed handling negatively, but the addition of glycerol could improve flow ability under high temperature and humidity conditions.

Our experiments suggest that flow ability of feed will be improved by the addition of glycerol, especially when added to meal diets containing maize ground through a hammer mill. These data also confirm previous research that the addition of lactose to a diet improved flow ability. Adding glycerol to diets with lactose will further improve flow ability, but 150 g/kg or 300g/kg added lactose will result in similar flow ability to a maize diet containing 40 g/kg added glycerol and 0 g/kg added whey. Temperature and humidity will also impact feed handling, but adding glycerol to diets the experience high temperature or humidity will improve flow ability.

Similar to previous studies conducted by Groesbeck et al. (2007) the addition of glycerol to a corn-soybean meal diet prior to pelleting appears to be a management strategy to enhance the overall pellet process, by decreasing production efficiency (kWh/t) and improving pellet durability index. It appears that the addition of glycerol helps reduce the friction created in the pelleting process resulting in a reduction in energy usage for the pellet mill. However, the use of glycerol in swine diets will depend on its impact on the growth performance of the pigs.

Previous research conducted by Lammers et al. (2007a) supports the addition of glycerol to swine diets, without altering growth performance. Lammers et al. (2007a) demonstrated no difference in ADG, ADFI, G:F or carcass composition in pigs fed glycerol at 5 or 10% inclusions. Lammers (2007b) estimated that the apparent

DE of crude glycerol for nursery pig diet is 3,386 ± 149 kcal/kg. Additional research also supports the use of glycerol as a feed ingredient without altering growth performance criteria in both swine and poultry (Bernal et al., 1978; Kijora et al., 1995; Simon et al., 1996). Groesbeck et al. (2007) also demonstrated that glycerol can replace cereal grains or fat at an energy value greater then corn. All of these studies focused on using glycerol as an energy source for replacing cereal grains in the diet, and have not evaluated if glycerol could replace other ingredients such as lactose.

Lactose is an energy source for the weanling pig. Studies have consistently demonstrated that the addition of lactose results in increased feed intake and growth in early-weaned pigs (Tokach et al., 1989; Nessmith et al 1997), and a study conducted across several universities indicated that the inclusion of up to 7.5% lactose in a late nursery diets results in increased feed intake and growth (Cromwell et al., 2007). In both Exp. 1 and 2 there was no benefit to added lactose or glycerol in the diet on growth performance. A growth performance lactose response was expected, and the lack of response seen in these trials is difficult to explain. However apparent digestibility results from the study are a strong indication that lactose improved digestibility and nutrient retention. Mahan et al. (2004) indicated that as weanling pigs mature, the positive response to lactose decreases. The pigs on Exp. 1 and 2 were weaned onto complex SEW and transition diets, by the time the pigs were placed on test (d 7 post weaning) the response to lactose may have already started to diminish and although it was evident in apparent digestibility, the improvements did not result in increased gain.

Adding glycerol to a corn-soybean meal based diet prior to pelleting is beneficial to pelleting, improving pellet durability index, and decreasing energy cost. The lack of lactose repose seen in these trials is confusing; therefore, further research is needed to justify the inclusion of glycerol as a supplement for lactose in weanling pig diet. Glycerol can be added to a swine diet; however, the digestibility data is an initial indication that it will replace lactose in weanling pig diets.

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Figures and Tables

Objective 1 - To evaluate the effects of glycerol on feed characteristics

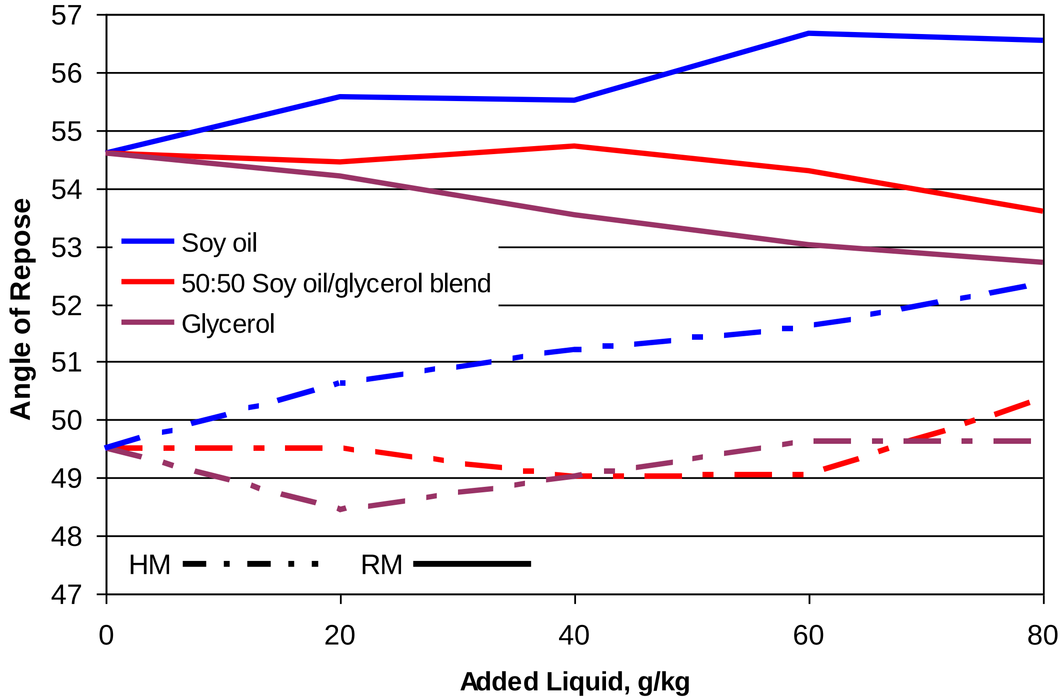

Figure 1. Influence of maize ground through a hammer (HM) or roller (RM) mill, liquid source, and liquid level on angle of repose

A mill type × liquid source × percent liquid added interaction (Figure 1, $P < 0.05$) was observed. Roller mill ground grain decreased angle of repose, improving flow ability compared to HM ground grain. The addition of soy oil increased angle of repose, decreasing flow ability. The addition of glycerol or a 50:50 soy oil/glycerol blend decreased angle of repose, improving flow ability when added to the diet containing HM ground maize.

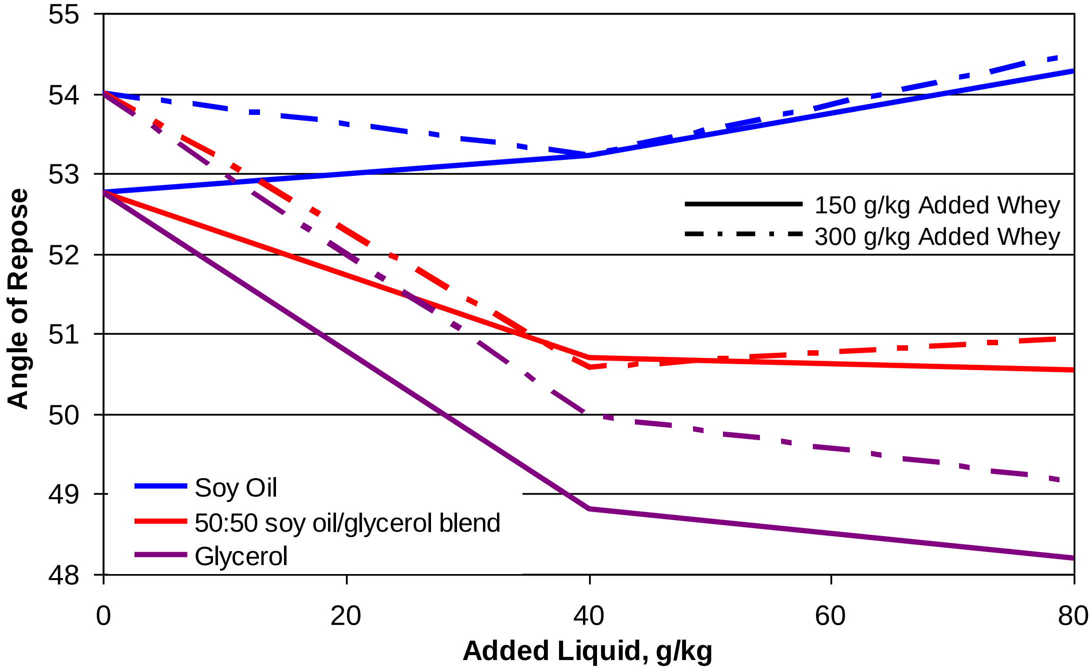

Figure 2. Influence of spray dried whey level, liquid source, and percent liquid added on angle of repose. A spray-dried whey level × liquid source × percent liquid added interaction (Figure 2, ($P < 0.05$) observed. The addition of glycerol or the 50:50 soy oil/glycerol blend decreased angle of repose, improving flow ability. The addition of glycerol decreased angle of repose greater in the 150 g/kg spray-dried whey sample compared to the 300 g/kg spray-dried whey sample.

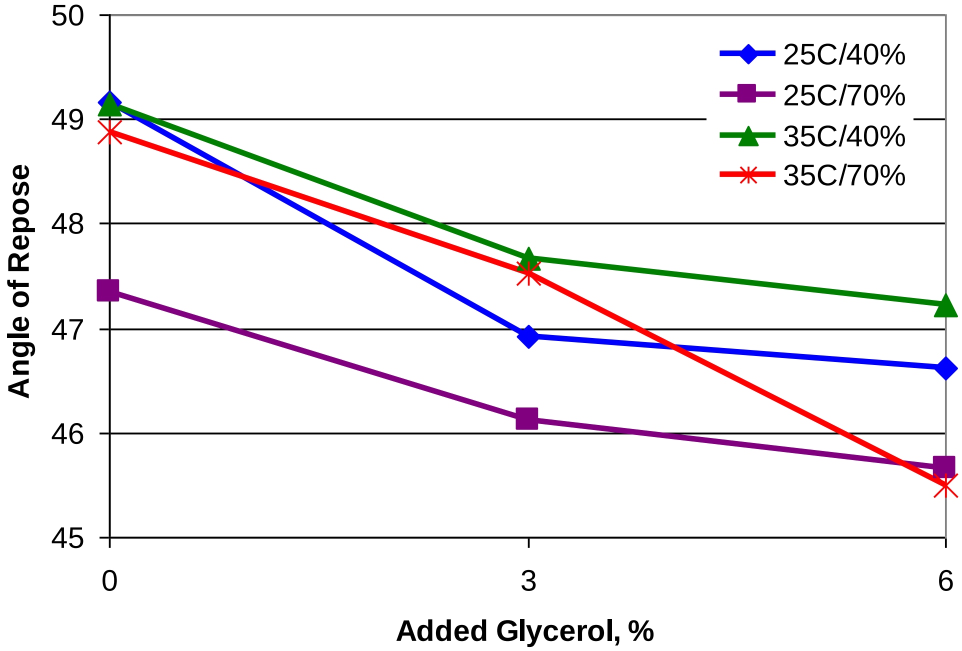

Figure 2. Influence of temperature and humidity on flow ability of HM ground maize with 0, 30, or 60 g/kg added glycerol.

A percent added glycerol × humidity × temperature interaction (Figure 3, $P < 0.05$) was observed. Increasing glycerol decreased angle of repose, improving flow ability under all temperature and humidity conditions. At 25°C, increasing humidity from 40 to 70% increased angle of repose in the 0 g/kg added glycerol sample. At 35°C, samples with 0 and 30 g/kg added glycerol had similar flow ability; however, the 60 g/kg added glycerol at the 70% humidity had similar flow ability as the 60 g/kg added glycerol at 25°C and 70% humidity.

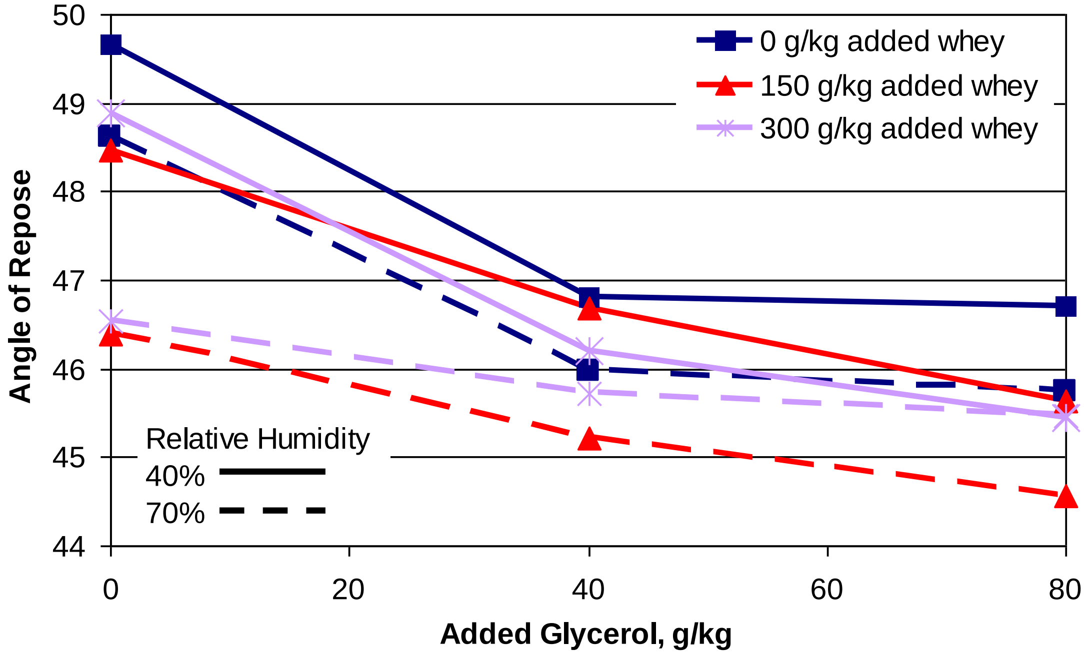

Figure 3. Influence of temperature and humidity on flow ability of HM ground maize with 0, 40, or 80 g/kg added glycerol and 0, 150, and 300 g/kg added whey permeate.

A percent glycerol × percent whey permeate × humidity interaction (Figure 4, $P < 0.03$) was observed. Adding whey or glycerol or increasing humidity decreased angle of repose, improving flow ability. In the maize diet without added glycerol and 300 g/kg whey diet angle of repose increased as humidity increase; however, the 300 g/kg whey diet with 40 g/kg or 80 g/kg added glycerol resulted in similar flow ability. At 70% humidity, the diets containing 150 or 300 g/kg had similar flow ability to the diet containing 40 g/kg glycerol and no added whey.

Objective 2 - Evaluate the effects of glycerol or soy oil blends on pellet quality and pig performance.

Table 1. Composition of diets (Exp. 1; as-fed basis)

	Added glycerol, %					
Item	0	3	6	9	12	15
Corn	63.54	60.30	57.06	53.82	50.57	47.33
Soybean meal, 46.5% CP	32.57	32.81	33.06	33.30	33.54	33.78
Crude glycerol[1]	---	3.00	6.00	9.00	12.00	15.00
Monocalcium phosphate, 21% P	1.65	1.65	1.65	1.65	1.65	1.65
Limestone	0.95	0.95	0.95	0.95	0.95	0.95
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[2]	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix[2]	0.15	0.15	0.15	0.15	0.15	0.15
L-lysine HCl	0.30	0.30	0.30	0.30	0.30	0.30
DL-methionine	0.12	0.12	0.12	0.12	0.12	0.12
L-threonine	0.12	0.12	0.12	0.12	0.12	0.12
Total	100.0	100.0	100.0	100.00	100.0	100.0
Calculated analysis						
Total lysine, %	1.38	1.38	1.38	1.38	1.38	1.38
ME, kcal/kg	3,299	3,299	3,299	3,299	3,299	3,299
Protein, %	21.0	20.8	20.7	20.5	20.3	20.2
Ca, %	0.80	0.80	0.80	0.80	0.80	0.80
P, %	0.75	0.74	0.73	0.73	0.72	0.71
Available P, %	0.42	0.42	0.42	0.42	0.42	0.42
Lysine:calorie ratio, g/Mcal	3.79	3.79	3.79	3.79	3.79	3.79

[1]Contained 90.7% glycerin and 136 ppm methanol Diets were formulated using an ME value of 3,420 kcal/kg for glycerol.

[2]Provided (per kilogram of complete diet): 11,025 IU of vitamin A; 1,654 IU of vitamin D; 44 IU of vitamin E; 4.4 mg of vitamin K (as menadione dimethylpyrimidinol bisulfate); 55.1 mg of niacin; 33.1 mg of pantothenic acid (as d-calcium pantothenate); 9.9 mg of riboflavin; 0.044 mg of vitamin B_{12}; 16.5 mg of Cu; 165.4 mg of Fe; 39.7 mg of Mn; 0.30 mg of Se; 165.4 mg of Zn; and 0.30 mg of I.

Table 2. Composition of diets (Exp. 2; as-fed basis)

		Soy oil, %		Glycerol, %		Blend, %[1]	
Item	Control	3	6	3	6	6	12
Corn	53.71	47.92	42.55	50.44	47.18	44.67	35.91
Soybean meal, 46.5% CP	41.98	44.62	46.86	42.23	42.47	44.86	47.54
Crude glycerol[2]	---	---	---	3.00	6.00	3.00	6.00
Soybean oil	---	3.00	6.00	---	---	3.00	6.00
Monocalcium phosphate, 21% P	1.60	1.71	1.81	1.61	1.61	1.71	1.77
Limestone	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
L-lysine HCl	0.30	0.30	0.30	0.30	0.30	0.30	0.30
DL-methionine	0.11	0.13	0.15	0.12	0.13	0.14	0.16
L-threonine	0.10	0.12	0.13	0.11	0.11	0.12	0.13
Antibiotic[4]	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis							
Total lysine, %	1.38	1.45	1.50	1.38	1.38	1.45	1.51
ME, kcal/kg	3,283	3,429	3,574	3,283	3,283	3,429	3,574
Protein, %	20.9	21.7	22.3	20.8	20.6	21.6	22.1
Analyzed protein, %[5]	19.5	21.7	22.2	20.5	19.8	20.4	21.7
Ca, %	0.79	0.81	0.84	0.79	0.79	0.81	0.83
P, %	0.74	0.76	0.78	0.73	0.72	0.76	0.76
Available P, %	0.41	0.44	0.46	0.41	0.41	0.44	0.45
Lysine:calorie ratio, g/Mcal	3.81	3.82	3.81	3.81	3.81	3.82	3.82

[1]Contained a 50:50 blend of soy oil and glycerol.
[2]Provided 90.7 % glycerin and contained 136 ppm methanol. Diets were formulated using an ME value of 3,420 kcal/kg for glycerol.
[3]Provided (per kilogram of complete diet): 11,025 IU of vitamin A; 1,654 IU of vitamin D; 44 IU of vitamin E; 4.4 mg of vitamin K (as menadione dimethylpyrimidinol bisulfate); 55.1 mg of niacin; 33.1 mg of pantothenic acid (as d-calcium pantothenate); 9.9 mg of riboflavin; 0.044 mg of vitamin B_{12}; 16.5 mg of Cu; 165.4 mg of Fe; 39.7 mg of Mn; 0.30 mg of Se; 165.4 mg of Zn; and 0.30 mg of I.
[4]Provided 140 g of Neomycin sulfate and 140 g Oxytetracycline HCl per ton of complete feed.
[5]Analyzed CP content (AOAC, 1995; method 990.03).

Table 3. Effects of added glycerol on production efficiency, Exp 1[1,2]

	Added glycerol, %							Contrast, $P <$	
Item	0	3	6	9	12	15	SE	Linear	Quadratic
Conditioning temp, °C	65.4	65.6	65.7	65.7	65.4	65.5	0.20	0.97	0.16
Hot pellet temp, °C	76.1	75.4	74.5	76.6	72.2	72.8	1.20	0.03	0.50
Delta temp, °C	10.5	9.6	8.6	10.6	6.4	7.0	1.14	0.02	0.60
Voltage, volts	250.4	250.0	248.9	252.3	250.1	250.3	1.94	0.84	0.95
Amperage, amps	29.3	25.2	23.6	22.9	19.5	18.1	0.85	0.01	0.45
Motor load, %	54.7	45.7	41.7	41.0	33.3	30.3	2.00	0.01	0.42
Pellet durability									
Standard, %	90.1	92.1	93.5	95.7	94.9	94.7	0.73	0.01	0.01
Modified, %	87.5	89.4	91.2	93.9	92.3	91.6	1.14	0.01	0.02
Production rate, t/hr	1.20	1.15	1.13	1.00	0.99	1.00	0.04	0.01	0.25
Total energy, kWh/t	8.41	7.51	7.12	7.81	6.72	6.12	0.28	0.01	0.63

[1]All diets were corn-soybean meal-based swine grower diets.

[2]Each experimental diet was replicated by manufacturing a new batch of feed three times.

Table 4. Effects of added soy oil and glycerol on production efficiency, Exp 2[1,2]

		Soy oil,%		Glycerol, %		Blend[3], %			Contrasts, $P <$[4]					
									Soy oil		Glycerol		Blend	
Item	Control	3	6	3	6	6	12	SE	L	Q	L	Q	L	Q
Conditioning temp, °C	65.8	66.3	65.9	66.3	65.9	66.2	65.8	0.20	0.71	0.07	0.82	0.06	0.94	0.07
Hot pellet temp, °C[5,6]	77.3	74.2	71.6	74.1	73.4	71.1	69.3	0.72	0.01	0.71	0.01	0.11	0.01	0.01
Delta temp, °C[5,6]	11.3	7.7	5.5	7.6	7.3	4.7	3.3	0.71	0.01	0.33	0.01	0.03	0.01	0.01
Voltage, volts	247.7	249.9	245.8	248.4	250.1	249.4	249.3	1.53	0.40	0.11	0.28	0.82	0.45	0.62
Amperage, amps[5,6]	28.3	23.0	19.6	23.7	22.8	20.9	16.0	0.52	0.01	0.10	0.01	0.01	0.01	0.03
Motor load, %[5,6]	53.6	45.9	34.6	42.9	41.6	36.3	26.9	2.22	0.01	0.41	0.01	0.05	0.01	0.09
Pellet durability														
Standard, %[5,6,7]	92.6	81.6	58.3	94.7	95.5	85.4	80.3	1.84	0.01	0.01	0.26	0.79	0.01	0.52
Modified, %[5,6,7]	89.9	74.7	40.0	91.9	92.2	78.3	65.8	1.80	0.01	0.01	0.39	0.69	0.01	0.82
Production rate, t/hr[7]	1.25	1.28	1.27	1.23	1.25	1.27	1.24	0.02	0.29	0.19	0.95	0.16	0.44	0.16
Total energy, kWh/t[5,6,7]	8.36	6.71	5.69	7.17	6.81	6.01	4.89	0.16	0.01	0.04	0.01	0.01	0.01	0.01

[1]All diets were formulated to the same lysine to ME ratio.
[2]Each experimental diet was replicated by manufacturing a new batch of feed three times; each run consisted of 340 kg batches.
[3]Addition of 50% soy oil and 50% glycerol.
[4]Linear (L) and quadratic (Q) contrasts.
[5]Contrast soy oil vs. blend, $P < 0.01$.
[6]Contrast glycerol vs. blend, $P < 0.01$.
[7]Contrast soy oil vs. glycerol, $P < 0.01$.

Table 5. Effects of soy oil and glycerol on growth performance of nursery pigs[1]

		Soy oil, %		Glycerol, %		Blend, %[2]			Contrasts, P <					
									Soy oil		Glycerol		Blend	
Item	Control	3	6	3	6	6	12	SE	Linear	Quad	Linear	Quad	Linear	Quad
D 0 to 26														
Initial wt, kg	11.0	11.0	11.0	11.0	11.0	11.0	11.0	0.60	1.00	0.56	0.32	0.56	1.00	0.25
ADG, g	528	571	554	568	570	555	564	18.2	0.18	0.07	0.03	0.23	0.06	0.58
ADFI, g[3,4]	782	782	761	809	814	757	762	33.9	0.52	0.72	0.32	0.69	0.55	0.60
G:F[4,5]	0.68	0.73	0.73	0.70	0.70	0.73	0.74	0.01	0.01	0.06	0.12	0.31	0.01	0.09
Final wt, kg	24.7	25.8	25.4	25.8	25.8	25.4	25.7	0.97	0.17	0.07	0.03	0.23	0.06	0.61

[1]A total of 182 pigs (initial BW 11.0 ± 1.3 kg) were used in a 26 d growth assay. Pigs were blocked by initial weight and randomly allotted to one of seven dietary treatments with five or six pigs/pen and five pens/treatment.
[2]Contained a 50:50 blend of soy oil and glycerol.
[3]Contrast soy oil vs glycerol, *P* < 0.08.
[4]Contrast glycerol vs blend , *P* < 0.03.
[5]Contrast soy oil vs glycerol, *P* < 0.03

Table 6. Effects of soy oil and glycerol on apparent digestibility in nursery pigs[1]

		Soy oil, %		Glycerol, %		Blend, %[2]			Contrasts, P <					
									Soy oil		Glycerol		Blend	
Item	Control	3	6	3	6	6	12	SE	Linear	Quad	Linear	Quad	Linear	Quad
DM intake, g/d	689	700	677	711	709	670	671	30.0	0.78	0.63	0.62	0.74	0.69	0.79
Fecal excretion of DM, g/d[3,4]	102	100	98	110	110	93	101	6.09	0.68	1.00	0.30	0.63	0.91	0.31
DM retention, g/d	586	600	580	601	600	576	572	25.4	0.86	0.59	0.71	0.78	0.69	0.93
DM digestibility, %	85.1	85.7	85.5	84.4	84.4	86.0	85.0	0.46	0.50	0.41	0.35	0.58	0.99	0.12
N intake, g/d	26.8	28.3	26.6	27.3	27.4	25.2	27.3	1.43	0.92	0.36	0.76	0.89	0.79	0.31
Fecal excretion of N, g/d	4.8	4.6	4.2	4.8	5.0	3.8	4.6	0.47	0.35	0.82	0.79	0.88	0.79	0.13
N retention, g/d	22.0	23.9	22.4	22.5	22.4	21.4	22.6	1.04	0.81	0.21	0.81	0.83	0.71	0.48
N digestibility, %[4]	82.2	84.0	84.5	82.8	82.2	84.5	83.0	0.93	0.10	0.60	0.97	0.64	0.56	0.11
GE intake, mcal/d[5]	2.85	2.97	2.96	2.98	2.98	2.76	2.77	0.12	0.58	0.66	0.51	0.69	0.64	0.72
Fecal excretion of GE, mcal/d[5]	0.42	0.42	0.40	0.45	0.45	0.39	0.42	0.03	0.66	0.80	0.39	0.62	1.00	0.35
GE retention, mcal/d[6]	2.44	2.56	2.56	2.52	2.53	2.37	2.36	0.11	0.44	0.67	0.55	0.74	0.58	0.86
GE digestibility, %[4]	85.3	86.0	86.5	85.0	85.0	86.0	85.0	0.56	0.16	0.83	0.71	0.81	0.64	0.21

[1]Fecal collections occurred on d 19 and minimum of two pigs/pen were collected for apparent digestibility assays.
[2]Contained a 50:50 blend of soy oil and glycerol.
[3]Contrast glycerol vs blend, *P* < 0.05.
[4]Contrast soy oil vs glycerol, *P* < 0.07.
[5]Contrast glycerol vs blend, *P* < 0.10.
[6]Contrast soy oil vs blend, *P* < 0.08.

Objective 3 - Determine if glycerol can be a replacement for lactose in nursery diets and its effects

Table 1. Composition of diets (Exp. 1; as fed basis)

		Lactose, %		Glycerol, %	
Item	Control	3.6	7.2	3.6	7.2
Corn	63.25	59.36	55.47	59.36	55.47
Soybean meal, 46.5% CP	26.87	27.16	27.45	27.16	27.45
Fish meal	4.50	4.50	4.50	4.50	4.50
Lactose	---	3.60	7.20	---	---
Crude glycerol[1]	---	---	---	3.60	7.20
Soybean oil	1.40	1.40	1.40	1.40	1.40
Monocalcium Phosphate, 21% P	0.70	0.70	0.70	0.70	0.70
Limestone	0.35	0.35	0.35	0.35	0.35
Salt	0.25	0.25	0.25	0.25	0.25
Zinc oxide	0.25	0.25	0.25	0.25	0.25
Vitamin premix[2]	0.15	0.15	0.15	0.15	0.15
Trace mineral premix[2]	0.30	0.30	0.30	0.30	0.30
Lysine HCl	0.14	0.14	0.14	0.14	0.14
DL-Methionine	0.14	0.14	0.14	0.14	0.14
L-Threonine	0.70	0.70	0.70	0.70	0.70
Antibiotic[3]	1.00	1.00	1.00	1.00	1.00
TOTAL					
Calculated analysis					
Total lysine, %	1.43	1.43	1.43	1.43	1.43
ME, kcal/kg	3,333	3,333	3,333	3,333	3,333
Protein, %	21.2	21.0	20.8	21.0	20.8
Ca, %	0.87	0.87	0.87	0.87	0.87
P, %	0.79	0.78	0.78	0.78	0.78
Available P, %	0.49	0.49	0.49	0.49	0.49
Lysine:calorie ratio, g/Mcal	3.90	3.90	3.90	3.90	3.90

[1]Contained 90.7% glycerin and 136 ppm methanol. Diets were formulated using an ME value of 3,420 kcal/kg for glycerol.

[2]Provided (per kilogram of complete diet): 11,025 IU of vitamin A; 1,654 IU of vitamin D; 44 IU of vitamin E; 4.4 mg of vitamin K (as menadione dimethylpyrimidinol bisulfate); 55.1 mg of niacin; 33.1 mg of pantothenic acid (as d-calcium pantothenate); 9.9 mg of riboflavin; 0.044 mg of vitamin B_{12}; 16.5 mg of Cu; 165.4 mg of Fe; 39.7 mg of Mn; 0.30 mg of Se; 165.4 mg of Zn; and 0.30 mg of I.

[3]Provided 140 g of Neomycin sulfate and 140 g Oxytetracycline HCl per ton of complete feed.

Table 2. Composition of diets (Exp. 2; as fed basis)[1]

		Lactose, %			Glycerol, %		
Item	Control	3.6	7.2	10.8	3.6	7.2	10.8
Corn	62.46	58.83	55.21	51.57	58.83	55.21	51.57
Soybean meal, 46.5% CP	27.75	27.75	27.74	27.74	27.75	27.74	27.74
Fish meal	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Lactose	---	3.60	7.20	10.80	---	---	---
Crude glycerol[2]	---	---	---	---	3.60	7.20	10.80
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Monocalcium Phosphate, 21% P	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Limestone	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Lysine HCl	0.27	0.28	0.29	0.30	0.28	0.29	0.30
DL-Methionine	0.11	0.12	0.13	0.15	0.12	0.13	0.15
L-Threonine	0.11	0.12	0.13	0.14	0.12	0.13	0.14
Antibiotic[4]	0.70	0.70	0.70	0.70	0.70	0.70	0.70
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis							
Total lysine, %	1.43	1.43	1.43	1.42	1.43	1.43	1.42
ME, kcal/kg	3,332	3,333	3,333	3,333	3,332	3,333	3,333
Protein, %	21.4	21.2	20.9	20.6	21.2	20.9	20.6
Ca, %	0.87	0.87	0.87	0.87	0.87	0.87	0.87
P, %	0.80	0.79	0.78	0.77	0.79	0.78	0.77
Available P, %	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Lysine:calorie ratio, g/Mcal	3.90	3.90	3.90	3.90	3.90	3.90	3.90

[1]One half of each batch of feed was pelleted to result in the 14 treatments.

[2]Diets were formulated using an ME value of 3,420 kcal/kg for glycerol.

[3]Provided (per kilogram of complete diet): 11,025 IU of vitamin A; 1,654 IU of vitamin D; 44 IU of vitamin E; 4.4 mg of vitamin K (as menadione dimethylpyrimidinol bisulfate); 55.1 mg of niacin; 33.1 mg of pantothenic acid (as d-calcium pantothenate); 9.9 mg of riboflavin; 0.044 mg of vitamin B_{12}; 16.5 mg of Cu; 165.4 mg of Fe; 39.7 mg of Mn; 0.30 mg of Se; 165.4 mg of Zn; and 0.30 mg of I.

[4]Provided 140 g of Neomycin sulfate and 140 g Oxytetracycline HCl per ton of complete feed.

Table 3. Effects of added glycerol on production efficiency[1]

		Lactose, %		Glycerol, %			Contrasts, P <			
							Lactose		Glycerol	
Item	Control	3.6	7.2	3.6	7.2	SE	Linear	Quadratic	Linear	Quadratic
Conditioning temp, °C	65.7	65.6	65.7	65.4	65.7	0.15	1.00	0.64	0.93	0.12
Hot pellet temp, °C	74.9	75.7	77.4	73.6	70.2	0.56	0.01	0.56	0.01	0.17
Delta temp, °C	9.2	10.1	11.6	8.2	4.5	0.52	0.01	0.63	0.01	0.06
Volts	252.2	251.9	248.0	251.7	252.3	2.10	0.19	0.51	0.97	0.82
Amps	21.6	22.2	23.0	19.3	17.2	0.34	0.01	0.79	0.01	0.64
Motor Load, %	33.8	37.1	38.4	30.1	27.1	1.32	0.01	0.40	0.01	0.78
Pellet durability										
Standard, %	86.1	88.5	90.1	89.9	91.8	1.15	0.01	0.75	0.01	0.39
Modified, %	87.0	89.2	90.8	89.8	92.0	1.17	0.01	0.81	0.01	0.80
Production rate, t/hr	0.89	0.93	0.93	0.90	0.88	0.01	0.01	0.04	0.19	0.10
KWH/ton	8.95	8.86	9.04	7.93	7.29	0.20	0.65	0.42	0.01	0.28

[1]Each experimental diet was replicated by manufacturing a new batch of feed three times.

Table 4. Effects of glycerol on growth performance of nursery pigs, Exp.1[1,2]

	Meal					Pellet					SE
		Lactose, %		Glycerol, %			Lactose, %		Glycerol, %		
Item	0	3.6	7.2	3.6	7.2	0	3.6	7.2	3.6	7.2	
D 0 to 14											
ADG, g	281	271	296	262	269	253	281	254	248	212	23.5
ADFI, g	409	383	408	390	392	367	417	377	359	316	23.8
G:F	0.68	0.71	0.72	0.67	0.68	0.68	0.67	0.67	0.69	0.66	0.02

[1]P-values are listed in Table 5.

[2]A total of 350 weanling pigs (8 d post weaning, initial BW 6.3 ± 0.9 kg) were used in a 14-d growth assay. Pigs were weighed and pens were allotted completely random to one of seven dietary treatments with five pigs/pen and seven pens/treatment.

Table 5. Effects of glycerol on growth performance of nursery pigs, Exp. 1 P-values

	Contrast, P <										
	Lactose		Glycerol								
Item	Linear	Quadratic	Linear	Quadratic	Level	Meal vs Pellet	Lactose vs glycerol	Level × Source	Level x diet form	Diet form x source	Level x source x diet form
D 0 to 14											
ADG, g	0.64	0.72	0.13	0.93	0.52	0.02	0.02	0.59	0.06	0.42	0.86
ADFI, g	0.80	0.81	0.05	0.01	0.24	0.79	0.01	0.60	0.02	0.03	0.65
G:F	0.63	0.99	0.70	0.93	0.93	0.28	0.32	0.81	0.41	0.15	0.63

Table 6. Effects of lactose and glycerol on apparent digestibility in nursery pigs, Exp. 1[1,2]

	Meal					Pellet					
		Lactose, %		Glycerol, %			Lactose, %		Glycerol, %		SE
Item	0	3.6	7.2	3.6	7.2	0	3.6	7.2	3.6	7.2	
DM intake, g/d	376	347	371	360	351	339	384	342	324	290	17.9
Fecal excretion of DM, g/d	106	72	78	88	71	59	65	58	62	51	4.32
DM retention, g/d	270	275	293	272	279	280	320	284	262	238	14.9
DM retention, %	71.6	79.6	78.8	75.4	80	82.3	83.1	83.2	81.1	82.6	0.87
N intake, g/d	13.0	11.7	13.0	12.3	11.0	11.7	13.6	11.7	10.4	9.1	1.20
Fecal excretion of N, g/d	5.2	3.9	4.5	4.5	3.2	3.9	4.5	1.9	3.9	3.2	0.63
N retention, g/d	7.8	8.4	9.7	8.4	9.1	9.1	10.4	9.7	9.1	7.1	0.94
N retention, %	61.8	72.3	74.2	69.5	73.2	75.6	76.0	76.6	72.2	74.3	1.63
GE intake, Mcal/d	3.58	3.30	3.50	3.42	3.33	3.19	3.57	3.18	3.02	2.71	0.18
Fecal excretion of GE, Mcal/d	1.07	0.73	0.78	0.89	0.70	0.57	0.60	0.52	0.58	0.48	0.05
GE retention, Mcal/d	2.51	2.56	2.73	2.52	2.63	2.62	2.98	2.66	2.45	2.24	0.15
GE retention, %	70.0	78.0	77.8	73.7	79.1	82.0	83.2	83.6	81.0	82.4	1.00

[1]P-values are listed in Table 7.
[2]Fecal collections occurred on d 12 and minimum of two pigs/pen were collected for apparent digestibility assays.

Table 7. Effects of lactose and glycerol on apparent digestibility in nursery pigs, Exp. 1 P-values

	Contrast, P <										
	Lactose		Glycerol								
Item	Linear	Quadratic	Linear	Quadratic	Level	Meal vs Pellet	Lactose vs glycerol	Level x Source	Level x diet form	Diet form x source	Level x source x diet form
DM intake, g/d	0.96	0.58	0.04	0.84	0.23	0.03	0.02	0.61	0.07	0.04	0.41
Fecal excretion of DM, g/d	0.01	0.08	0.01	0.41	0.02	0.01	0.99	0.04	0.60	0.11	0.12
DM retention, g/d	0.36	0.23	0.28	0.98	0.44	0.93	0.01	0.96	0.05	0.04	0.59
DM retention, %	0.01	0.01	0.01	0.24	0.03	0.01	0.02	0.01	0.35	0.88	0.11
N intake, g/d	0.99	0.76	0.06	0.88	0.34	0.24	0.04	0.57	0.34	0.19	0.34
Fecal excretion of N, g/d	0.04	0.55	0.04	0.55	0.03	0.05	0.99	0.99	0.14	0.47	0.03
N retention, g/d	0.17	0.69	0.73	0.55	0.80	0.52	0.09	0.47	0.09	0.23	0.80
N retention, %	0.01	0.14	0.03	0.77	0.07	0.01	0.04	0.46	0.55	0.62	0.94
GE intake, Mcal/d	0.81	0.65	0.05	0.91	0.27	0.02	0.04	0.68	0.12	0.07	0.47
Fecal excretion of GE, Mcal/d	0.01	0.11	0.01	0.48	0.03	0.01	0.88	0.07	0.90	0.28	0.13
GE retention, Mcal/d	0.38	0.29	0.39	0.90	0.56	0.98	0.01	0.90	0.07	0.05	0.69
GE retention, %	0.01	0.01	0.01	0.23	0.01	0.01	0.03	0.02	0.24	0.87	0.10

Table 8. Effects of glycerol on growth performance of nursery pigs, Exp. 2[1]

	Meal							Pellet							
		Lactose, %			Glycerol, %				Lactose, %			Glycerol, %			SE
Item	0	3.6	7.2	10.8	3.6	7.2	10.8	0	3.6	7.2	10.8	3.6	7.2	10.8	
D 0 to 14															
ADG, g	342	296	337	320	323	332	317	335	312	318	325	322	318	331	18.8
ADFI, g	437	416	436	429	425	441	431	427	408	425	450	420	417	413	19.0
G:F	0.78	0.71	0.77	0.75	0.76	0.75	0.73	0.79	0.76	0.75	0.73	0.77	0.76	0.80	0.03

[1]P-vlaues are listed in Table 9.

[2]A total of 375 weanling pigs (7-d post weaning, initial BW 6.7 ± 1.1 kg) were used in a 14-d growth assay. Pigs were allotted completely random to one of 14 dietary treatments with five pigs/pen and five or 5 or 6 pens/treatment.

Table 9. Effects glycerol on growth performance of nursery pigs, Exp. 2 P-values[1]

	Contrast, P <										
	Lactose		Glycerol								
Item	Linear	Quadratic	Linear	Quadratic	Level	Meal vs Pellet	Lactose vs glycerol	Level × Source	Level × diet form	Diet form × source	Level × source × diet form
D 0 to 14											
ADG, g	0.35	0.50	0.35	0.92	0.62	0.92	0.56	0.52	0.52	0.85	0.73
ADFI, g	0.75	0.27	0.58	0.94	0.55	0.42	0.79	0.47	0.76	0.37	0.78
G:F	0.03	0.43	0.35	0.23	0.89	0.17	0.15	0.41	0.46	0.30	0.06