Effect of crude glycerol on pellet mill production and nursery pig growth performance[1,2]

C. N. Groesbeck,* L. J. McKinney,† J. M. DeRouchey,* M. D. Tokach,* R. D. Goodband,*[3] S. S. Dritz,‡ J. L. Nelssen,* A. W. Duttlinger,* A. C. Fahrenholz,† and K. C. Behnke†

*Department of Animal Sciences and Industry; †Department of Grain Science and Industry; and ‡Food Animal Health and Management Center, College of Veterinary Medicine, Kansas State University, Manhattan 66506-5601

ABSTRACT: The objective of this study was to determine the effects of diets containing crude glycerol on pellet mill production efficiency and nursery pig growth performance. In a pilot study, increasing crude glycerol (0, 3, 6, 9, 12, and 15%) in a corn-soybean meal diet was evaluated for pellet mill production efficiency. 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. Each diet was replicated by manufacturing a new batch of feed 3 times. 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). In a 26-d growth assay, 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.

Key words: feed manufacturing, glycerol, pelleting, pig

J. Anim. Sci. 2008. 86:2228–2236
doi:10.2527/jas.2008-0880

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 15 billion liters, with expectations of doubling consumption by 2012. Biodiesel is an alternative to petroleum-based diesel fuel and consists of monoalkyl esters formed through an alcohol-based catalyzed reaction of triacylglycerides 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 US biodiesel production capacity will exceed 9.5 billion liters (USEPA, 2007). This

[1]Contribution No. 08-144-J from the Kansas Agric. Exp. Stn., Manhattan.

[2]Appreciation is expressed to the National Pork Board, Des Moines, IA, for financial support.

[3]Corresponding author: Goodband@ksu.edu

Received January 17, 2008.
Accepted April 23, 2008.

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

	Added crude glycerol, %					
Item	0	3	6	9	12	15
Ingredient, %						
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
CP, %	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 of ME	4.25	4.25	4.25	4.25	4.25	4.25

[1]Contained 90.7% glycerin and 136 mg/kg of methanol. Diets were formulated using nutrient values from NRC (1998) except for a ME value of 3,420 kcal/kg for crude 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 as $CuSO_4 \cdot 5H_2O$; 165.4 mg of Fe as $FeSO_4H_2O$; 39.7 mg of Mn as $MnSO_4 \cdot H_2O$; 0.30 mg of Se as Na_2SeO_3; 165.4 mg of Zn as ZnO; and 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$.

level of production will yield nearly 1.2 million metric tons of crude glycerol, the primary co-product of the biodiesel production process. Purification of crude glycerol to a chemically pure substance results in a valuable industrial chemical. However, purification is costly and the glycerol market is already saturated; thus, the price of crude glycerol continues to decline. This trend will continue as more biodiesel production facilities begin production. Consequently, there has been much interest in using crude glycerol as a feed ingredient in animal diets to reduce diet costs. Lammers et al. (2007) fed 10% crude glycerol to pigs with little to no adverse effects on ADG, carcass composition, or meat quality. However, little is known about crude glycerol's nutritional value or how it affects feed quality and feed processing efficiency. Therefore, the objective of these trials was to evaluate the effects of crude glycerol on pelleting efficiency, growth performance, and nutrient excretion in nursery pigs.

MATERIALS AND METHODS

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

Exp. 1

Experiment 1 included 6 treatments that were corn-soybean meal-based swine grower diets formulated to contain 0, 3, 6, 9, 12, and 15% crude glycerol (Table 1).

The crude glycerol used in this study and Exp. 2 contained 90.7% glycerol, 0.2% CP, 3.2% crude fat, and 5.53% ash. It had a peroxide value of 1.97 mEq of peroxide/kg of sample and 136 mg/kg of methanol. Diets were manufactured and pelleted, and data were 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 pellet mill (Master Model HD, Series 2000, California Pellet Mill, 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 (65.5°C). Samples of corn, soybean meal, diet mash (before conditioning), and pellets were collected for each experimental run. Mean particle size of corn and soybean meal used in the diets was determined to be 667 and 1,025 µm, respectively (Standard 319.1; ASAE, 1983).

Pellet mill production data were collected on all diets. Each diet run was replicated by manufacturing a new batch of feed 3 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 placed in the stream 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

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

		Crude glycerol, %		Soy oil, %		Blend,[1] %	
Item	Control	3	6	3	6	6	12
Ingredient, %							
Corn	53.71	50.44	47.18	47.92	42.55	44.67	35.91
Soybean meal, 46.5% CP	41.98	42.23	42.47	44.62	46.86	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	1.61	1.61	1.71	1.81	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	0.12	0.13	0.13	0.15	0.14	0.16
L-Threonine	0.10	0.11	0.11	0.12	0.13	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	1.38	1.38	1.45	1.50	1.45	1.51
ME, kcal/kg	3,283	3,283	3,283	3,429	3,574	3,429	3,574
CP, %	20.9	20.8	20.6	21.7	22.3	21.6	22.1
Analyzed CP,[5] %	19.5	20.5	19.8	21.7	22.2	20.4	21.7
Ca, %	0.79	0.79	0.79	0.81	0.84	0.81	0.83
P, %	0.74	0.73	0.72	0.76	0.78	0.76	0.76
Available P, %	0.41	0.41	0.41	0.44	0.46	0.44	0.45
Lysine:calorie ratio, g/Mcal of ME	4.18	4.18	4.18	4.18	4.18	4.18	4.18

[1]Contained a 50:50 blend of soy oil and crude glycerol.

[2]Provided 90.7% glycerin and contained 136 mg/kg of methanol. Diets were formulated using a ME value of 3,420 kcal/kg for crude 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 as $CuSO_4 \cdot 5H_2O$; 165.4 mg of Fe as $FeSO_4H_2O$; 39.7 mg of Mn as $MnSO_4 \cdot H_2O$; 0.30 mg of Se as Na_2SeO_3; 165.4 mg of Zn as ZnO; and 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$.

[4]Provided 140 g of neomycin sulfate and 140 g of oxytetracycline HCl per ton of complete feed.

[5]Analyzed by the AOAC method 990.03 (AOAC, 1995).

pail, and the temperature was measured using a stiff thermocouple after the temperature reading reached equilibrium. Conditioning temperature and production rate were held constant. Pellet production efficiency, expressed as kilowatt-hours per metric ton (kWh/t), was determined from changes in voltage and amperage meter readings. Standard and modified pellet durability index (**PDI**) was evaluated for each experimental run using 500 g of cold pellets (Standard S269.3; ASAE, 2003).

Exp. 2

Before beginning the experiment, pigs were fed standard early weaning and transition diets (DeRouchey et al., 2007). A total of 182 nursery pigs (approximately 14 d after weaning and initial BW of 11.0 ± 1.3 kg) were used in a 26-d growth assay. Pigs were blocked by initial BW and randomly allotted to 1 of 7 dietary treatments with 5 or 6 pigs/pen and 5 pens/treatment. Experimental diets included a control with no added soy oil or crude glycerol, the control diet with 3 or 6% added soy oil, the control diet with 3 or 6% added crude glycerol, and the control diet with 6 or 12% of a 50:50 (wt/wt) soy oil/crude glycerol blend (Table 2). The same batch of crude glycerol from Exp. 1 was used in Exp. 2. All diets were formulated to the same total Lys:ME ratio. Chemical composition of all ingredients except crude glycerol was derived from NRC (1998). All diets were formulated using the ME value of corn (3,420 kcal/kg) as the ME value for crude glycerol. Similar to Exp. 1, pellet mill production data were collected during diet manufacturing.

Pigs were housed in an environmentally controlled nursery at the Kansas State University Segregated Early-Weaning Facility. Each pen measured 1.2 × 1.2 m and contained 1 self-feeder and 1 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. From d 14 to 21, an indigestible marker (Cr_2O_3) was added at 0.5% to all treatment diets. On d 19, grab samples of feces were collected from a minimum of 2 pigs/pen. Concentrations of Cr (Kimura and Miller, 1957; Williams et al., 1962), DM and N (AOAC, 1995), and GE (adiabatic bomb calorimetry, Parr Instruments, Moline, IL) in the feces and diet were determined to calculate apparent digestibility of DM, N, and GE.

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

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

[a–d]Means in the same row with different superscripts differ, $P < 0.05$.
[1]All diets were corn-soybean meal-based swine grower diets.
[2]Each experimental diet was replicated by manufacturing a new batch of feed 3 times.

Statistical Analysis

Statistical analysis was performed using the MIXED procedure (SAS Inst. Inc., Cary, NC). Data from Exp. 1 were analyzed as a completely randomized block design with batch (n = 3) as the experimental unit. Contrasts were used to test for linear and quadratic effects of crude glycerol. In Exp. 2, pellet mill production data were analyzed as a completely randomized block design with batch (n = 3) as the experimental unit. Contrasts were used to test for linear and quadratic effects of soy oil, crude glycerol, and the blend of soy oil and crude glycerol. All possible pairwise comparisons were used to test among soy oil, crude glycerol, and the soy oil/crude glycerol blend production data. Pig growth data were analyzed as a completely randomized block with block based on initial BW. The pen was the experimental unit for growth and digestibility data analyses. Contrasts used included linear and quadratic effects of soy oil, crude glycerol, and the blend of soy oil and crude glycerol. In addition, all possible pair-wise comparisons were used to separate the means of pigs fed soy oil, crude glycerol, and the soy oil/crude glycerol blend.

RESULTS AND DISCUSSION

Exp. 1

There was no effect of crude glycerol on conditioning temperature, indicating that conditioning temperature was indeed held constant at 65.5°C (Table 3). Hot pellet temperature and delta temperature decreased (linear, $P = 0.03$ and 0.02, respectively) with increasing crude glycerol. Delta temperature should follow a similar pattern to hot pellet temperature, as delta temperature is calculated as the difference between hot pellet temperature and conditioning temperature. There was no difference in voltage (**V**) with increasing crude glycerol content. Amperage (**Amps**) decreased (linear, $P < 0.01$) with the addition of crude glycerol. The greatest decreases in Amps occurred with the addition of 3% crude glycerol and again at the 12% crude glycerol additions; however, all diets with crude glycerol had lower Amps than the control. Motor load also decreased (linear, $P < 0.01$) with the addition of crude glycerol. Voltage, Amps, and motor load are measures of energy usage by the pellet mill. Amperage values followed a similar trend as motor load values. Amperage measures the electrical current demanded by the pellet mill, and motor load measures energy required by the pellet mill to rotate the pellet die. Motor load will increase with increased friction in the die and decrease as friction is decreased. The decrease in motor load when crude glycerol was added to the diet indicated a decrease in pellet die friction.

Pellet durability index also increased up to 9% added crude glycerol for both the standard (linear and quadratic, $P < 0.01$) and modified (linear, $P < 0.01$; quadratic, $P = 0.02$) PDI, resulting in a 2 to 6% improvement in PDI compared with the control. These results differ from previous research reporting that broiler diets pelleted with 10% crude glycerol had visibly poorer pellet quality; however, PDI was not measured in that study (Cerrate et al., 2006). The addition of crude glycerol decreased (linear, $P < 0.01$) production rate despite the attempt to hold production rate constant. Due to the lack of information available with crude glycerol on pellet quality, adjustments were continuously made to steam pressure to hold the conditioning temperature constant. These slight adjustments may have caused a decrease in production rate. The production efficiency also decreased (linear, $P < 0.01$) with added crude glycerol. A reduction or improvement in production efficiency will result in a direct economical savings for the feed mill by reducing total energy usage of the pellet mill.

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

		Crude glycerol, %		Soy oil,%		Blend,[3] %			P-value[4]					
									Crude glycerol		Soy oil		Blend	
Item	Control	3	6	3	6	6	12	SE	L	Q	L	Q	L	Q
Conditioning temperature, °C	65.8	66.3	65.9	66.3	65.9	66.2	65.8	0.20	0.82	0.06	0.71	0.07	0.94	0.07
Hot pellet temperature, [5,6] °C	77.3	74.1	73.4	74.2	71.6	71.1	69.3	0.72	<0.01	0.11	<0.01	0.71	<0.01	<0.01
Delta temperature,[5,6] °C	11.3	7.6	7.3	7.7	5.5	4.7	3.3	0.71	<0.01	0.03	<0.01	0.33	0.01	<0.01
Voltage	247.7	248.4	250.1	249.9	245.8	249.4	249.3	1.53	0.28	0.82	0.40	0.11	0.45	0.62
Amperage[5,6]	28.3	23.7	22.8	23.0	19.6	20.9	16.0	0.52	<0.01	<0.01	<0.01	0.10	<0.01	0.03
Motor load,[5,6] %	53.6	42.9	41.6	45.9	34.6	36.3	26.9	2.22	<0.01	0.05	<0.01	0.41	<0.01	0.09
Pellet durability														
Standard,[5,6,7] %	92.6	94.7	95.5	81.6	58.3	85.4	80.3	1.84	0.26	0.79	<0.01	<0.01	<0.01	0.52
Modified,[5,6,7] %	89.9	91.9	92.2	74.7	40.0	78.3	65.8	1.80	0.39	0.69	<0.01	<0.01	<0.01	0.82
Production rate,[7] t/h	1.25	1.23	1.25	1.28	1.27	1.27	1.24	0.02	0.95	0.16	0.29	0.19	0.44	0.16
Production efficiency, [5,6,7] kWh/t	8.36	7.17	6.81	6.71	5.69	6.01	4.89	0.16	<0.01	<0.01	<0.01	0.04	<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 3 times; each run consisted of 340-kg batches.
[3]Addition of 50% soy oil and 50% crude glycerol.
[4]Linear (L) and quadratic (Q) contrasts.
[5]Contrast: soy oil vs. blend, $P < 0.01$.
[6]Contrast: crude glycerol vs. blend, $P < 0.01$.
[7]Contrast: crude glycerol vs. soy oil, $P < 0.01$.

Exp. 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% crude glycerol, 3% soy oil, and the 6% blend treatments to have a greater conditioning temperature (66.2°C) compared with all other treatments (65.9°C; Table 4). Although statistically significant, this small difference is of little practical importance. Hot pellet temperature and delta temperature decreased (linear, $P < 0.01$) with the addition of crude glycerol, soy oil, and the soy oil/glycerol blend. Delta temperature, however, decreased only slightly with the greatest addition of crude glycerol or the soy oil/crude glycerol blend (quadratic, $P = 0.03$ and $P < 0.01$, respectively). The addition of the soy oil/glycerol blend resulted in a similar response in hot pellet temperature (quadratic, $P < 0.01$). A lower delta temperature is an indication of reduced die friction. As die friction increases, delta temperature would be expected to increase. The greatest improvement occurred with the initial liquid addition of crude glycerol or the soy oil/crude glycerol blend, and decreasing only slightly with the addition of either the 6% crude glycerol or the 12% blend addition. Hot pellet temperature and delta temperature had a greater decrease ($P < 0.01$) for the soy oil/crude glycerol blend when compared with soy oil and crude glycerol additions, indicating that crude glycerol and soy oil combined can reduce die friction more than when either ingredient is added to the diet individually. There was no difference in hot pellet temperature and delta temperature between the crude glycerol and soy oil treatments, indicating that crude glycerol had a lubrication effect on the pellet die similar to that of soy oil.

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

Pellet quality was not affected with the addition of crude glycerol; however, 6% added crude glycerol diet had the greatest PDI compared with all other treatments. Soy oil is typically added to nursery diets to aid in pelleting and reduce 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 (linear and quadratic, $P < 0.01$) PDI. The soy oil/crude glycerol blend decreased (linear; $P < 0.01$) PDI; however, PDI of the blend was greater ($P < 0.01$) than soy oil alone. The addition of the 6 and 12% soy oil/crude glycerol blends resulted in a 5 to 37% improvement in PDI compared with the addition of 3 or 6% soy oil alone. Similar to Exp. 1, the addition of crude glycerol improved PDI. The addition of crude glycerol improved ($P < 0.01$) PDI by an average of 15% when compared with the soy oil/crude glycerol blends and 26% compared with the soy oil treatments. These data indicate that crude glycerol added to a diet before pelleting, with or without added soy oil, will result in an improved PDI.

Diets containing soy oil had increased ($P < 0.01$) pellet production rate compared with diets containing the addition of crude glycerol. Production rate was not different between crude glycerol and the soy oil/crude glycerol blend or the control, and the soy oil/crude glycerol blend was not different from any of the other treatments. Production efficiency improved (linear, $P < 0.01$; quadratic, $P \leq 0.04$) with the addition of soy oil, crude glycerol, or the soy oil/crude glycerol blend compared with the control diet. However, the greatest benefit occurred with the initial addition of any of the liquid sources. The control diet had the poorest production, and the soy oil/crude glycerol blend had the largest improvement compared with the control diet, requiring the least total production energy. Pelleting of soy oil/crude glycerol blend diets had improved ($P < 0.01$) production efficiency compared with soy oil or crude glycerol. Improvement in production efficiency results in energy savings by the feedmill, and the results of the present study demonstrated the importance of liquid addition to meal diets before pelleting.

Several studies have evaluated the use of crude 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 biodiesel production from rapeseed oil. The crude glycerol used in those studies should be similar to the crude glycerol used in our studies; however, the impurities will likely vary among sources. In our study, pigs were fed a crude glycerol source containing 90.7% glycerol and 136 mg/kg of methanol from a Midwestern US biodiesel plant, which used soy oil as the initial feedstock (Minnesota Soybean Processors, Brewster, MN).

For the overall period (d 0 to 26), pigs fed diets with increasing crude glycerol had increased (linear, $P = 0.03$) ADG (Table 5). 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% soy oil and no additional improvement observed with 6% soy oil. The improvement in ADG with diets containing added fat are consistent with findings of Ratliff et al. (2004), where 3% added fat optimized growth in 10- to 23-kg pigs. In addition, pigs fed increasing soy oil/crude glycerol blend had a tendency for increased (linear, $P = 0.06$) ADG. The increase in ADG of pigs in our study is in contrast to the data of Lammers et al. (2007) who observed no difference in growth of pigs fed 0, 5, or 10% glycerol. One possible explanation for the slightly different response might be that in our study, the crude glycerol was 90.7% pure vs. 84.5% pure for the crude glycerol used by Lammers et al. (2007).

Pigs fed diets with crude glycerol had a tendency for increased ADFI or increased ADFI compared with pigs fed diets containing soy oil ($P = 0.08$) or the soy oil/glycerol blend ($P = 0.03$). The increased ADG of pigs fed glycerol seems to be the result of increased feed intake.

Increasing crude glycerol had no effect on G:F, but pigs fed diets with increasing soy oil or the soy oil/crude glycerol blend had increased (linear, $P < 0.01$) G:F. Although both responses to increasing soy oil or the soy oil/glycerol blend were linear, the greatest improvement occurred with the first 3% added soy oil or 6% of the soy oil/glycerol blend (quadratic, $P = 0.06$ and 0.09 for soy oil and the blend, respectively). Pigs fed soy oil or the soy oil/crude glycerol blend had greater ($P = 0.03$) G:F compared with pigs fed diets containing crude glycerol. In our study, we assigned glycerol an energy value equal to that of corn. However, Lammers et al. (2008) have observed crude glycerol to contain 95 and 94% the DE and ME, respectively, of corn. Therefore, the differences in G:F may be related to the energy content of the diets.

Other than the data of Lammers et al. (2008), who evaluated the DE and ME content of glycerol, few studies have examined the effects of crude glycerol on nutrient digestibility in pigs. Fecal excretion of DM tended to increase in pigs fed crude glycerol compared with pigs fed soy oil ($P = 0.07$) or the soy oil/crude glycerol blend ($P = 0.10$; Table 6). Percentage of N digested tended ($P = 0.07$) to decrease in pigs fed diets containing crude glycerol compared with pigs fed diets containing soy oil. However, previous research by Simon et al. (1997) showed that N retention in broilers increased as crude glycerol inclusion increased up to 20%. Gross energy intake tended ($P = 0.10$) to decrease in pigs fed the soy oil/crude glycerol blend compared with pigs fed crude glycerol. This was expected, as pigs fed the soy oil/crude glycerol blend had decreased ADFI compared with pigs fed crude glycerol. Fecal excretion of GE tended ($P = 0.10$) to decrease in pigs fed the soy oil/crude glycerol blend compared with pigs fed crude glycerol. Gross energy retention tended ($P = 0.08$) to increase in pigs fed soy oil compared with pigs fed the soy oil/crude glycerol blends. Pigs fed the added soy oil treatments tended ($P = 0.07$) to have increased GE digestibility compared with pigs fed crude glycerol.

Previous research conducted by Lammers et al. (2007) showed that the addition of crude glycerol to swine diets did not affect growth performance. Our data differ slightly from these previous data because crude glycerol tended to increase ADFI compared with pigs fed the control diets. Lammers et al. (2007) reported no difference in ADG, ADFI, G:F, or carcass composition in pigs fed 5 or 10% crude glycerol. Lammers et al. (2008)

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

		Crude glycerol, %		Soy oil, %		Blend,[2] %			*P*-value[3]					
									Crude glycerol		Soy oil		Blend	
Item	Control	3	6	3	6	6	12	SE	L	Q	L	Q	L	Q
d 0 to 26														
ADG, g	528	568	570	571	554	555	564	18.2	0.03	0.23	0.18	0.07	0.06	0.58
ADFI,[4,5] g	782	809	814	782	761	757	762	33.9	0.32	0.69	0.52	0.72	0.55	0.60
G:F,[5,6] g/g	0.68	0.70	0.70	0.73	0.73	0.73	0.74	0.01	0.12	0.31	<0.01	0.06	<0.01	0.09
Final wt, kg	24.7	25.8	25.8	25.8	25.4	25.4	25.7	0.97	0.03	0.23	0.17	0.07	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 BW and randomly allotted to 1 of 7 dietary treatments with 5 or 6 pigs/pen and 5 pens/treatment.

[2]Contained a 50:50 blend of soy oil and crude glycerol.

[3]Linear (L) and quadratic (Q) contrasts.

[4]Contrast: crude glycerol vs. soy oil, $P = 0.08$.

[5]Contrast: crude glycerol vs. blend, $P = 0.03$.

[6]Contrast: crude glycerol vs. soy oil, $P = 0.03$.

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

		Crude glycerol, %		Soy oil, %		Blend,[2] %			*P*-value[3]					
									Crude glycerol		Soy oil		Blend	
Item	Control	3	6	3	6	6	12	SE	L	Q	L	Q	L	Q
DM intake, g/d	689	711	709	700	677	670	671	30.0	0.62	0.74	0.78	0.63	0.69	0.79
Fecal excretion of DM,[4,5] g/d	102	110	110	100	98	93	101	6.09	0.30	0.63	0.68	1.00	0.91	0.31
DM retention, g/d	586	601	600	600	580	576	572	25.4	0.71	0.78	0.86	0.59	0.69	0.93
DM digestibility, %	85.1	84.4	84.4	85.7	85.5	86.0	85.0	0.46	0.35	0.58	0.50	0.41	0.99	0.12
N intake, g/d	26.8	27.3	27.4	28.3	26.6	25.2	27.3	1.43	0.76	0.89	0.92	0.36	0.79	0.31
Fecal excretion of N, g/d	4.8	4.8	5.0	4.6	4.2	3.8	4.6	0.47	0.79	0.88	0.35	0.82	0.79	0.13
N retention, g/d	22.0	22.5	22.4	23.9	22.4	21.4	22.6	1.04	0.81	0.83	0.81	0.21	0.71	0.48
N digestibility,[5] %	82.2	82.8	82.2	84.0	84.5	84.5	83.0	0.93	0.97	0.64	0.10	0.60	0.56	0.11
GE intake,[6] Mcal/d	2.85	2.98	2.98	2.97	2.96	2.76	2.77	0.12	0.51	0.69	0.58	0.66	0.64	0.72
Fecal excretion of GE,[6] Mcal/d	0.42	0.45	0.45	0.42	0.40	0.39	0.42	0.03	0.39	0.62	0.66	0.80	1.00	0.35
GE retention,[7] Mcal/d	2.44	2.52	2.53	2.56	2.56	2.37	2.36	0.11	0.55	0.74	0.44	0.67	0.58	0.86
GE digestibility,[5] %	85.3	85.0	85.0	86.0	86.5	86.0	85.0	0.56	0.71	0.81	0.16	0.83	0.64	0.21

[1]Fecal samples were collected on d 19 with a minimum of 2 pigs/pen for apparent digestibility assays. Values represent the mean of 5 observations.
[2]Contained a 50:50 blend of soy oil and crude glycerol.
[3]Linear (L) and quadratic (Q) contrasts.
[4]Contrast: crude glycerol vs. blend, $P < 0.05$.
[5]Contrast: crude glycerol vs. soy oil, $P = 0.07$.
[6]Contrast: crude glycerol vs. blend, $P = 0.10$.
[7]Contrast: soy oil vs. blend, $P = 0.08$.

estimated that the apparent DE of crude glycerol in a nursery pig diet is 3,344 ± 8 kcal/kg. This energy value of crude glycerol for nursery pigs is approximately 95% of the DE value for corn (3,525 kcal/kg; NRC, 1998). Additional research has also shown that crude glycerol can be used 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 previous studies focused on using crude glycerol as an energy source for replacing cereal grains in the diet. It seems that crude glycerol can replace part of cereal grains in swine diets without negatively affecting ADG. Our studies indicated that adding crude glycerol may have positive effects on ADFI. Additional research is needed to further evaluate crude glycerol in swine diets, as well as crude glycerol storage and oxidation. Further evaluation of crude glycerol product variability, and storage of feed manufactured with crude glycerol also needs to be conducted.

Adding crude glycerol to a corn-soybean meal diet before pelleting seems to be a management strategy that can enhance the overall pelleting process by improving total production efficiency (kWh/t) and pellet quality without compromising growth performance. Our data indicated that up to 6% crude glycerol can be included in diets for pigs weighing 11 to 27 kg to improve the pelleting process without reducing pig performance.

LITERATURE CITED

AOAC. 1995. Official Methods of Analysis. 16th ed. Assoc. Off. Anal. Chem., Arlington, VA.

ASAE. 1983. Method for determining and expressing fineness of feed material by sieving. Page 325 in ASAE Standard: ASAE 319.1. American Society of Agriculture Engineers, St. Joseph, MI.

ASAE. 2003. Wafers, crumbles, and crumblers – Definitions and methods for determining density, durability, and moisture content. Pages 70–72 in ASAE Standard: ASAE 269.3. American Society of Agriculture Engineers, St. Joseph, MI.

Bernal, G., J. D. Garza, M. Viana, E. Avila, A. S. Shimada, and M. Montano. 1978. Effect of inclusion of glycerol or vegetable oil in diets with molasses for growing pigs and poultry. Vet. Mex. 9:91–94.

Briggs, J. L., D. E. Maier, B. A. Watkins, and K. C. Behnke. 1999. Effect of ingredients and processing parameters on pellet quality. Poult. Sci. 78:1464–1471.

Cerrate, S., F. Yan, Z. Wang, C. Coto, P. Sacaki, and P. W. Waldroup. 2006. Evaluation of glycerine from biodiesel production as a feed ingredient for broilers. Int. J. Poult. Sci. 5:1001–1007.

DeRouchey, J. M., M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. L. Nelssen. 2007. Swine Nutrition Guide. MF-2300. Kansas State Univ. Agric. Exp. Stn. Coop. Ext. Serv., Manhattan.

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

Kimura, F., and V. L. Miller. 1957. Improved determination of chromic oxide in cow feed and feces. J. Agric. Food Chem. 5:216.

Lammers, P. J., M. S. Honeyman, B. J. Kerr, T. E. Weber, and K. Bregendahl. 2007. Growth performance and carcass characteristics of growing pigs fed crude glycerol. J. Anim. Sci. 85(Suppl. 1):508. (Abstr.)

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

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

Ratliff, B. W., A. M. Gains, P. Srichana, G. L. Allee, and J. L. Usry. 2004. Evaluation of an optimum fat level for late nursery pigs. J. Anim. Sci. 82(Suppl. 2):78. (Abstr.)

Simon, A., M. Schwabe, and H. Bergner. 1996. Glycerol—Feed ingredient for broiler chickens. Arch. Anim. Nutr. 49:103–112.

Simon, A., M. Schwabe, and H. Bergner. 1997. Glycerol supplementation to broiler rations with low crude protein content. Arch. Anim. Nutr. 50:271–282.

United States Environmental Protection Agency (USEPA). 2007. EPA finalizes regulations for a renewable fuel standard (RFS) program for 2007 and beyond. EPA420-F-07–019, Office of Transportation and Air Quality, Ann Arbor, MI.

Williams, C. H., D. J. David, and O. Iismaa. 1962. The determination of chromic oxide in feces samples by atomic absorption spectrophotometry. J. Agric. Sci. 59:381.