

Kansas Agricultural Experiment Station Research Reports

Volume 0
Issue 10 *Swine Day (1968-2014)*

Article 1153

2007

Effect of glycerol on pellet mill production efficiency

C N. Groesbeck

Leland J. McKinney

Michael D. Tokach

See next page for additional authors

Follow this and additional works at: <https://newprairiepress.org/kaesrr>



Part of the [Other Animal Sciences Commons](#)

Recommended Citation

Groesbeck, C N.; McKinney, Leland J.; Tokach, Michael D.; Nelssen, Jim L.; Behnke, Keith C.; DeRouchey, Joel M.; Goodband, Robert D.; and Dritz, Steven S. (2007) "Effect of glycerol on pellet mill production efficiency," *Kansas Agricultural Experiment Station Research Reports*: Vol. 0: Iss. 10. <https://doi.org/10.4148/2378-5977.6993>

This report is brought to you for free and open access by New Prairie Press. It has been accepted for inclusion in Kansas Agricultural Experiment Station Research Reports by an authorized administrator of New Prairie Press. Copyright 2007 the Author(s). Contents of this publication may be freely reproduced for educational purposes. All other rights reserved. Brand names appearing in this publication are for product identification purposes only. No endorsement is intended, nor is criticism implied of similar products not mentioned. K-State Research and Extension is an equal opportunity provider and employer.



Effect of glycerol on pellet mill production efficiency

Authors

C N. Groesbeck, Leland J. McKinney, Michael D. Tokach, Jim L. Nelssen, Keith C. Behnke, Joel M. DeRouchey, Robert D. Goodband, and Steven S. Dritz

EFFECT OF GLYCEROL ON PELLET MILL PRODUCTION EFFICIENCY

C. N. Groesbeck, L. J. McKinney¹, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. M. Nelssen, S. S. Dritz², and K. C. Behnke¹

Summary

Crude glycerol is a by-product of the bio-fuels industry, which 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 processing efficiency. Three experiments were conducted to evaluate the effects of glycerol on production efficiency of a pellet mill. In all three experiments, diets were manufactured, pelleted, and data collected at the KSU Grain Science Feed Mill. All diets were steam conditioned to 85°F and pelleted at 150°F using a CPM pellet mill equipped with a 4 mm × 32 mm pellet die. In Exp. 1, the six treatments were a corn-soybean meal-based swine grower diet formulated to contain 0, 3, 6, 9, 12, and 15% crude glycerol. Experiment 2 included seven treatments: the 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 to glycerol blend. Experiment 3 included five treatments: a control with no added lactose or glycerol, the control diet with 3.6 or 7.2% lactose, or the control with 3.6 or 7.2% glycerol. Each experimental diet was replicated by manufacturing a new batch of feed three times. Glycerol lowered delta temperature, amperage, and motor load in Exp. 1, 2, and 3. The addition of glycerol consistently im-

proved pellet quality. Production rate was not affected by the addition of glycerol; however, glycerol decreased total energy usage (KWh/t). Furthermore, glycerol can be added to a diet in combination with soy oil in a blend to improve production efficiency and pellet quality compared to a diet containing only soy oil. The addition of glycerol will improve the production efficiency of pelleting, pellet quality, and decrease energy cost when included in diets prior to pelleting.

(Key words: feed manufacturing, glycerol, pelleting.)

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 bio-fuels consumption level was set at four billion gallons with expectations of doubling by 2012. Consequently, there has and will continue to be an unprecedented level of growth in the biofuels industries. 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

¹Department of Grain Science and Industry.

²Food Animal Health and Management Center, College of Veterinary Medicine.

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 billion gallons. This level of production will yield nearly 1.3 million tons of glycerol, the primary co-product of the biodiesel production process. Glycerol constitutes 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 continue as more and more biodiesel production facilities come online. Consequently, there has been much interest in utilizing crude glycerol as a feed ingredient in animal diets to reduce diet costs. However, little is known about glycerol's nutritional value or how it impacts feed quality and feed processing efficiency. Therefore, the objective of these trials was to evaluate the effects of glycerol on pelleting production efficiency.

Materials and Methods

In all three experiments, diets were manufactured, pelleted, and data collected at the KSU Grain Science Feed Mill. All diets were steam conditioned to 85°F and pelleted at 150°F using a CPM pellet mill (Master Model HD, Series 2000) equipped with a 4 mm × 32 mm pellet die. In all three experiments, each diet 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.

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).

Experiment 2 included seven treatments: the 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 to glycerol blend (Table 2). All diets were formulated to the same lysine to metabolizable energy ratio. The metabolizable energy value used for glycerol was 1,555 kcal/lb.

Experiment 3 included five treatments: a control with no added lactose or glycerol, the control diet with 3.6 or 7.2% lactose, or the control with 3.6 or 7.2% glycerol (Table 3).

Results and Discussion

Experiment 1. There was no difference ($P>0.11$) in conditioning temperature, indicating that all diets were indeed pelleted at 150°F (Table 4). Hot pellet temperature initially decreased (quadratic; $P<0.05$) through 6% added glycerol, increased at 9% added glycerol, and again decreased through 15% added glycerol. Delta temperature also decreased (quadratic; $P<0.01$) though 6% added glycerol, increased at 9% added glycerol, and again decreased through 15% added glycerol. Delta temperature should follow a similar pattern to hot pellet temperature as delta temperature is calculated using both hot pellet temperature and conditioning temperature. There was no difference ($P>0.46$) in voltage (volts) with increasing added glycerol. Amperage (Amps) decreased (quadratic; $P<0.01$) 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 was also decreased (quadratic; $P<0.01$) with the addition of glycerol. Similar to amps, motor load decreased the greatest with the initial addition of 3% glycerol and again from 9 to 12% glycerol addition. Voltage, amps, and motor load are measures of energy. 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. The decrease in motor load when glycerol is added to the diet indicates a decrease in pellet die friction. Pellet quality was also improved ($P<0.01$) with the addition of glycerol. Pellet durability index (PDI) increased (linear; $P<0.01$) through 15% added glycerol for both the standard and modified PDI. The addition of glycerol had no effect ($P>0.14$) on production rate (t/h). The kWh/t production rate decreased (quadratic; $P<0.01$) with the addition of glycerol; it increased at 9%, and decreased again through 15% glycerol addition. The response exhibited at the 9% added glycerol treatment doesn't follow the trend for all other glycerol levels. This spike at the 9% added glycerol treatment is not completely understood. The 9% diet caused problems when attempting to pellet the diet at higher conditioning temperatures. It continually overloaded the pellet mill at approximately 168°F. This phenomenon warrants further investigation of a potential interaction with added glycerol and conditioning temperature.

Experiment 2. Similar to Exp. 1, a conditioning temperature of 150°F was targeted. 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 151°F compared to all other treatments at 150°F (Table 5). 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, glycerol, and their blend. Hot pellet temperature and delta temperature decreased ($P<0.01$) when soy oil, glycerol, or the blend was added to the diet when compared to the control. Hot pellet temperature and delta temperature was also decreased ($P<0.01$) for the soy oil/glycerol blend when compared to soy oil and glycerol additions. There was no difference ($P>0.10$) between hot pellet temperature and delta temperature between soy oil and glycerol addi-

tions. 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, glycerol, and their blend. The addition of 3 and 6% glycerol decreased (quadratic, $P<0.05$) amps and motor load; the greatest decrease occurred with the initial addition of glycerol to the diet.

The addition of the soy oil/glycerol blend had the greatest decrease in motor load, and amps (quadratic; $P<0.03$), with the 12% blend addition decreasing amps and motor load the greatest. The addition of soy oil, glycerol, and soy oil/glycerol blend all decreased ($P<0.01$) amps and motor load compared to the control. The addition of soy oil and glycerol resulted in increased ($P<0.01$) amps and motor load compared to the blend. The soy oil/glycerol blend had the lowest amps and motor load compared to all other treatments, indicating the largest reduction in pellet die friction.

Pellet quality was not affected ($P>0.26$) with the addition of glycerol; however, the 6% added glycerol had the greatest standard and modified PDI compared to all other treatments. The addition of soy oil decreased (quadratic; $P<0.01$) PDI. The blend of soy oil and glycerol decreased (linear; $P<0.01$) PDI but the overall PDI of the blend was greater ($P<0.01$) than the PDI of soybean oil alone. The overall PDI was greater ($P<0.01$) for glycerol when compared to the soy oil/glycerol blend and soy oil treatments. Soy oil had a slightly increased ($P>0.01$) production rate compared to glycerol. Production rate (t/h) was not different ($P>0.10$) between glycerol and the soy oil/glycerol blend or the control. The soy oil/glycerol blend was not different ($P>0.10$) from any of the other treatments. The kWh/t production rate decreased (quadratic; $P<0.01$) with the addition of soy oil, glycerol, and the soy oil/glycerol blend. The greatest benefit occurred with the initial addition of any of the liquid sources.

All treatment means were different ($P<0.01$), with the control having the highest kWh/h and the soy oil/glycerol blend having the lowest. Glycerol had a slightly higher mean than the soy oil, but it was intermediate to the control and soy oil/glycerol blend.

Experiment 3. There was no difference ($P>0.12$) in conditioning temperature among treatments: all treatments were pelleted at 150 °F (Table 6). Hot pellet temperature and delta temperature decreased (linear; $P<0.01$) through 7.2% added glycerol. Hot pellet temperature and delta temperature increased (linear; $P<0.01$) through 7.2% added lactose. Hot pellet temperature and delta temperature were different ($P<0.01$) among all treatments. The diet containing lactose had the highest hot pellet temperature and delta temperature, and the diet containing glycerol had the lowest. The control diet hot pellet and delta temperatures were intermediate to the lactose and control treatment temperatures. The addition of lactose also resulted in an increase (linear; $P<0.01$) in amps and motor load. The increase in amps and motor load indicates an increase in pellet die friction with added lactose. The addition of glycerol decreased (linear; $P<0.01$) amps and motor load, similar to Exp. 1 and 2, indicating a decrease in pellet die friction. The added lactose resulted in an increased ($P<0.01$) hot pellet temperature and delta temperature compared with the control and glycerol. The added glycerol resulted in decreased ($P<0.01$) hot pellet temperature and delta temperature compared with the control and lactose diets. Pellet quality was improved (linear; $P<0.01$) with either added lactose or glycerol. Standard and modified PDI were not different ($P>0.10$) between lactose and gly-

cerol. Lactose and glycerol resulted in an increased ($P<0.01$) standard and modified PDI compared with the control. Standard and modified PDI were greatest for the 7.2% added lactose and 7.2% added glycerol. Production rate (t/h) increased (quadratic; $P<0.04$) with the addition of lactose. The increase in production rate was greatest at the 3.6% added lactose, with no additional production rate benefit at the 7.2% added lactose. Adding glycerol had no effect ($P>0.10$) on production rate. Adding lactose increased ($P<0.01$) production rate when compared with the control and glycerol. The kWh/t decreased (linear; $P<0.01$) through 7.2% added glycerol, indicating a decrease in energy consumption without decreasing pellet mill output compared with the control. The diet containing lactose had an increased ($P<0.01$) kWh/t compared with the diet containing glycerol and the control diet.

In conclusion, glycerol consistently lowered delta temperature (less die friction), amperage, and motor load. The addition of glycerol also improved pellet quality in Exp. 1, 3, and tended to improve pellet quality in Exp. 2. Production rate was not affected by the addition of glycerol in Exp 1 and 3; however, glycerol decreased kWh/t in Exp 1, 2 and 3. This indicates that a pellet mill could decrease energy cost without decreasing tons of feed produced. These data also indicate that glycerol can be added to a diet in combination with soy oil to improve production efficiency and pellet quality compared to a diet containing only soy oil. The addition of glycerol improved production efficiency of pelleting, pellet quality, and decreased energy cost for the pellet mill.

Table 1. Composition of Diets, Exp. 1 (as-fed basis)

Item	Added Glycerol, %					
	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 ^a	---	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	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix	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	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Total lysine, %	1.38	1.38	1.38	1.38	1.38	1.38
ME, kcal/lb	1,496	1,496	1,496	1,496	1,496	1,496
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

^aContained 90.7% glycerin and 136 ppm methanol.

Table 2. Composition Diets, Exp. 2 (as-fed basis)

Item	Control	Soy Oil, %		Glycerol, %		Blend ^a , %	
		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 ^b	---	---	---	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	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix	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 ^c	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis							
Total lysine, %	1.38	1.45	1.50	1.38	1.38	1.45	1.51
ME, kcal/lb	1,489	1,555	1,621	1,489	1,489	1,555	1,621
Protein, %	20.9	21.7	22.3	20.8	20.6	21.6	22.1
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

^aContained a 50:50 blend of soy oil to crude glycerol.^bContained 90.7 % glycerin and 136 ppm methanol.^cProvided 140 g of Neomycin sulfate and 140 g Oxytetracycline HCl per ton of complete feed.

Table 3. Composition Diets, Exp. 3 (as-fed basis)

Item	Control	Lactose, %		Glycerol, %	
		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
Crude glycerol ^a	---	---	---	3.60	7.20
Fish meal	4.50	4.50	4.50	4.50	4.50
Lactose	---	3.60	7.20	---	---
Soybean oil	1.00	1.00	1.00	1.00	1.00
Monocalcium phosphate (21% P)	1.40	1.40	1.40	1.40	1.40
Limestone	0.70	0.70	0.70	0.70	0.70
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix	0.25	0.25	0.25	0.25	0.25
Trace mineral premix	0.15	0.15	0.15	0.15	0.15
L-lysine HCl	0.30	0.30	0.30	0.30	0.30
DL-methionine	0.14	0.14	0.14	0.14	0.14
L-threonine	0.14	0.14	0.14	0.14	0.14
Antibiotic ^b	0.70	0.70	0.70	0.70	0.70
Total	100.00	100.00	100.00	100.00	100.00
Calculated analysis					
Total lysine, %	1.43	1.43	1.43	1.43	1.43
ME, kcal/lb	1,512	1,512	1,512	1,511	1,511
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

^aProvided 90.7% glycerin and 136 ppm methanol.

^bProvided 140 g of Neomycin sulfate and 140 g Oxytetracycline HCl per ton of complete feed.

Table 4. Effects of Added Glycerol on Production Efficiency, Exp 1^{ab}

Item	Added Glycerol, %						SE	Contrast, <i>P</i> <	
	0	3	6	9	12	15		Linear	Quadratic
Conditioning temp, °F	149.7	150.0	150.2	150.2	149.8	149.8	0.37	0.11	0.98
Hot pellet temp, °F	169.1	167.8	166.1	169.9	161.9	163.0	2.16	0.26	0.05
Delta temp, °F	18.9	17.3	15.5	19.2	11.7	12.6	2.04	0.33	0.01
Voltage, volts	250.4	250.0	248.9	252.3	250.1	250.3	1.94	0.74	0.46
Amperage, amps	29.3	25.2	23.6	22.9	19.5	18.1	0.85	0.11	0.01
Motor load, %	54.7	45.7	41.7	41.0	33.3	30.3	2.00	0.12	0.01
Pellet durability									
Standard, %	90.1	92.1	93.5	95.7	94.9	94.7	0.73	0.01	0.33
Modified, %	87.5	89.4	91.2	93.9	92.3	91.6	1.14	0.01	0.97
Production rate, t/hr	1.32	1.27	1.24	1.11	1.09	1.10	0.04	0.14	0.35
Total energy, kWh/t	7.62	6.81	6.51	7.09	6.10	5.60	0.26	0.91	0.01

^aAll diets were corn-soybean meal-based swine grower diets.

^bEach experimental diet was replicated by manufacturing a new batch of feed three times.

Table 5. Effects of Added Glycerol on Production Efficiency, Exp 2^{ab}

									Contrasts, $P <^d$											
									Soy Oil,%		Glycerol, %		Blend ^c , %		Soy		Glycerol		Blend	
									Control	3	6	3	6	6	12	SE	L	Q	L	Q
Item																				
Conditioning temp, °F	150.4	151.3	150.6	151.3	150.5	151.1	150.4	0.36	0.70	0.07	0.82	0.06	0.94	0.07						
Hot pellet temp, °F ^{fg}	171.1	165.5	161.0	165.4	164.1	159.9	156.7	1.30	0.01	0.71	0.01	0.11	0.01	0.01						
Delta temp, °F ^{fg}	20.2	13.9	10.0	13.7	13.2	8.4	5.9	1.28	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 ^{fg}	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, % ^{fg}	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, % ^{efg}	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, % ^{efg}	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 ^e	1.38	1.42	1.40	1.35	1.38	1.40	1.36	0.02	0.29	0.19	0.95	0.16	0.44	0.16						
Total energy, kWh/t ^{efg}	7.58	6.09	5.16	6.50	6.18	5.45	4.44	0.14	0.01	0.01	0.01	0.01	0.01	0.01						

^aAll diets were formulated to the same lysine to metabolizable energy ratio.

^bEach experimental diet was replicated by manufacturing a new batch of feed three times; each run consisted of 750 lb batches.

^cAddition of 50% soy oil and 50% glycerol.

^dLinear (L) and quadratic contrasts (Q).

^eContrast soy oil vs. glycerol, $P < 0.01$.

^fContrast soy oil vs. blend, $P < 0.01$.

^gContrast glycerol vs. blend, $P < 0.01$.

Table 6. Effects of Added Glycerol on Production Efficiency, Exp 3^a

							Contrasts, $P <^b$			
							Lactose		Glycerol	
							Linear	Quadratic	Linear	Quadratic
Item	Control	Lactose, %		Glycerol, %		SE				
		3.6	7.2	3.6	7.2					
Conditioning temp, °F	150.3	150.2	150.3	149.7	150.3	0.28	1.00	0.64	0.93	0.12
Hot pellet temp, °F ^{bcd}	166.9	168.3	171.3	164.5	158.3	1.01	0.01	0.56	0.01	0.17
Delta temp, °F ^{bcd}	16.5	18.2	20.9	14.7	8.0	0.95	0.01	0.63	0.01	0.06
Voltage, volts	252.2	251.9	248.0	251.7	252.3	2.10	0.19	0.51	0.97	0.82
Amperage, amps ^{bcd}	21.6	22.2	23.0	19.3	17.2	0.34	0.01	0.79	0.01	0.64
Motor Load, % ^{bcd}	33.8	37.1	38.4	30.1	27.1	1.32	0.01	0.40	0.01	0.78
Pellet durability										
Standard, % ^{bc}	86.1	88.5	90.1	89.9	91.8	1.15	0.01	0.75	0.01	0.39
Modified, % ^{bc}	87.0	89.2	90.8	89.8	92.0	1.17	0.01	0.81	0.01	0.80
Production rate, t/hr ^{bd}	0.98	1.03	1.02	0.99	0.97	0.01	0.01	0.04	0.19	0.10
Total energy, kWh/t ^{cd}	8.10	8.00	8.20	7.20	6.60	0.65	0.65	0.42	0.01	0.28

^aEach experimental diet was replicated by manufacturing a new batch of feed three times; each run consisted of 750 lb batches.

^bContrast control vs. lactose, $P < 0.01$.

^cContrast control vs. glycerol, $P < 0.01$.

^dContrast lactose vs. glycerol, $P < 0.01$.