ABSTRACT: Two studies were conducted with refined glycerin (97.7 and 97.5% glycerin for studies I and II, respectively) to determine ME content and effects on growth performance and carcass and pork quality measures of finishing pigs. An energy balance study using 24 barrows (21.5 ± 0.6 kg initial BW) determined the apparent ME content of glycerin using a generalized randomized block design with 2 dietary treatments: 1) control (99.85% corn + vitamins and minerals) and 2) glycerin (30% of corn in the control diet replaced with glycerin). A 7-d adaptation was followed by a 5-d collection period for feces and urine. The energy content of diets, feces, and urine was determined by bomb calorimetry. The DE of the glycerin diet was greater \((P < 0.01)\) than that of the control diet (4,298 vs. 3,902 kcal/kg of DM); however, the ME content of the 2 diets was similar (3,820 vs. 3,723 kcal/kg of DM). The ME of refined glycerin (estimated by difference) was 3,584 kcal/kg of DM. A growth study was conducted with 128 gilts housed in groups of 4 and reared from 92.5 ± 0.24 kg of BW for a 28-d period, using a split-plot design with a \(4 \times 2\) factorial arrangement of treatments: 1) dietary glycerin level (0, 5, 10, and 15%) and 2) preslaughter handling (gentle vs. intense). The handling treatment was included to simulate the range in handling intensities that are likely to be experienced in practice. At the end of the 28-d period, one-half of the pens on study were slaughtered and used for carcass and pork quality evaluation with 2 pigs from each pen being subjected to each of the preslaughter handling treatments. There were no interactions \((P > 0.05)\) between dietary glycerin and preslaughter handling treatment. Dietary glycerin had no effect \((P > 0.05)\) on growth performance, carcass measures, or meat quality. There were no differences \((P > 0.05)\) between the gentle and intense handling treatments for carcass or pork quality measures. In conclusion, feeding glycerin to finishing pigs at up to 15% of the diet had no negative effect on growth performance or carcass and pork quality characteristics.

Key words: glycerin, growth performance, metabolizable energy, pig, pork quality, preslaughter handling

INTRODUCTION

Glycerin, a major coproduct of the production of biodiesel from vegetable oils, is a potential feedstuff for pigs (Mourot et al., 1994; Thompson and He, 2006). There is wide variation in the ME values of glycerin reported in the literature. Lammers et al. (2008a) reported a ME value of 3,207 kcal/kg for crude glycerin (86.5% glycerin), and Bartelt and Schneider (2002) reported values of 2,524 to 4,177 kcal/kg for pure glycerin (99.9% glycerin), depending on inclusion level. Studies evaluating the effects of feeding glycerin to growing-finishing pigs have also shown variable results.

Lammers et al. (2008b) and Mourot et al. (1994) reported no effect on growth performance (ADG, ADFI, and G:F) when feeding diets with up to 10% glycerin. However, Kijora and Kupsch (1996) and Groesbeck et al. (2008) found improvements in ADG, ADFI, and G:F from including glycerin in the diet. Crude glycerin is variable in composition and can contain several contaminants that could affect animal performance (Lammers et al., 2008a,b). It is important to determine the value of glycerin as a feedstuff for pigs independent of any effect of contaminants.

There is evidence that including glycerin in the diet of finishing pigs can improve the water-holding capacity of pork (Mourot et al., 1994). However, Kijora and Kupsch (1996), and Lammers et al. (2008b) showed no effect of dietary glycerin on pork quality. Differences between studies in the pork quality response to feeding...
glycerin could be related to the stress experienced by the pig before slaughter. Intense preslaughter handling can increase muscle temperature, decrease muscle pH, and consequently, increase drip loss (Brown et al., 1998; Hambrecht et al., 2005). The objectives of this research were to determine the ME content of refined glycerin and the effects of feeding glycerin on growth performance and its interactions with preslaughter handling on carcass and pork quality.

**MATERIALS AND METHODS**

Two studies, an energy balance (study I) and a growth performance evaluation (study II), were conducted at the Swine Research Center at the University of Illinois. The experimental protocols for these studies were approved by the University of Illinois Institutional Animal Care and Use Committee.

**Experimental Design and Treatments**

Study I was conducted as a generalized randomized block design (starting date was used as the blocking factor) with 2 dietary treatments: 1) control (99.85% corn + vitamins and minerals) and 2) glycerin (30% of the corn in the control diet replaced with glycerin). There were 3 blocks and 4 replicates within each block for a total of 12 replicates per treatment.

Study II was conducted in 2 parts. The first part used 32 pens of 4 pigs per pen and consisted of a 28-d feeding period and was conducted as a generalized randomized block design with 4 dietary glycerin inclusion rates (0, 5, 10, and 15%) with 8 replicates in 5 blocks. Starting date was used as the blocking factor. For the second part of the study, a subset of 16 pens was used for carcass and meat quality evaluation using a split-plot design with a factorial arrangement of the following factors: 1) glycerin dietary inclusion levels [0, 5, 10, and 15% (main plot)] and 2) preslaughter handling (gentle vs. intense (subplot)). Immediately before slaughter, one-half of the pigs from each pen were subjected to 1 of the 2 preslaughter handling treatments. The gentle handling treatment involved moving the pigs from the lairage pen at their own pace using a movement board and a livestock paddle up and down a passageway 3 times and to the point of slaughter. The intense handling treatment involved moving the pigs rapidly using a movement board and an electric goad from the lairage pen up and down the passageway 3 times and to the point of slaughter, with animals receiving a shock with the electric goad at the start and end of each time through the passageway for a total of 6 shocks (Bertol et al., 2005).

**Animals and Housing**

Both studies used pigs that were the progeny of PIC 337 sires mated to PIC C22 dams (PIC, Hendersonville, TN). Before the start of the studies, pigs were reared under standard conditions in nursery and grower facilities, housed in groups of 5 pigs, and had access to standard diets that were formulated to meet or exceed the recommendations for nutrient requirements recommended by NRC (1998).

In study I, 24 barrows (initial average BW of 21.5 ± 0.6 kg) in 3 blocks of 8 pigs each were used. Within block, groups consisting of 2 pigs of similar BW were formed, and pigs were randomly allotted from within group to metabolism crate and to dietary treatment.

The study was conducted in an environmentally controlled metabolism room with the air temperature maintained between 22 and 26°C throughout the study period using thermostatically controlled space heaters and fan ventilation; the lighting in the room remained on continuously. The metabolism crates were constructed of stainless steel and were equipped with screens and trays that allowed for the total, but separate, collection of feces and urine. Crate dimensions were 0.66 × 0.81 m, providing a floor space of 0.54 m²/pig and each crate had a single-space feeder and a nipple-type water drinker.

Study II used a total of 128 crossbred gilts (initial average BW of 92.5 ± 0.2 kg) in 5 blocks. Within block, pigs were formed into groups of 4 pigs of similar BW and were randomly allotted from within group to 1 of 4 pens. This process was repeated until there were 4 pigs/pen; pens were randomly allotted to dietary treatment.

Pigs were housed in a mechanically ventilated building that had part-solid, part-slotted concrete floors. Pen divisions and gates consisted of vertical steel rods, and pen dimensions were 2.59 × 1.83 m, which provided a floor space of 1.19 m²/pig. Each pen had a single-space dry feeder mounted to the front gate and a nipple-type water drinker. Air temperature in the building was maintained between 22 and 24°C throughout the study period using thermostatically controlled heaters and fan ventilation.

**Diet Preparation and Feeding**

The experimental diets for study I and II were manufactured using 2 different batches of refined glycerin (Evonik Industries, Mapleton, IL; Table 1). In study I, the corn-based control diet contained 99.85% corn fortified with trace minerals and vitamins to meet or exceed NRC requirements (NRC, 1998) for growing pigs. The glycerin diet was prepared by substituting 30% of the corn with refined glycerin (Table 2). This amount was chosen to reduce the error in estimation of DE and ME values of glycerin relative to using a smaller inclusion level. The daily amount of feed provided per pig was 2.5 times the energy requirement for maintenance (106 kcal ME per kg of BW⁰.⁷⁵) recommended by NRC (1998). The daily feed allowance was divided into 2 equal meals, which were given at 0800 and 1600 h; water was available to the pigs at all times.
Table 1. Chemical composition of the refined glycerin for study I and II (as-fed basis)\textsuperscript{1,2}

<table>
<thead>
<tr>
<th>Item</th>
<th>Study I</th>
<th>Study II</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM, %</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Total glycerin, %</td>
<td>97.70</td>
<td>97.50</td>
</tr>
<tr>
<td>Acid hydrolysis fat, %</td>
<td>0.98</td>
<td>0.78</td>
</tr>
<tr>
<td>Ash, %</td>
<td>0.66</td>
<td>0.64</td>
</tr>
<tr>
<td>S, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>P, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>K, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Mg, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Ca, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Na, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Fe, mg/kg</td>
<td>&lt;5.00</td>
<td>&lt;5.00</td>
</tr>
<tr>
<td>Mn, mg/kg</td>
<td>1.00</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td>Cu, mg/kg</td>
<td>&lt;1.00</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td>Zn, mg/kg</td>
<td>2.00</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td>NaCl, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Methanol, %</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cl, %</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Free fatty acid, % of crude fat</td>
<td>0.47</td>
<td>0.32</td>
</tr>
<tr>
<td>Insolubles, %</td>
<td>3.37</td>
<td>5.29</td>
</tr>
<tr>
<td>Unsaponifiable matter, %</td>
<td>1.80</td>
<td>1.57</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Refined glycerin, Evonik Industries, Mapleton, IL.  
\textsuperscript{2}Analysis carried out by Midwest Laboratories Inc., Omaha, NE.

The formulation and composition of the experimental diets used in study II are presented in Table 3. Glycerin diets were formulated using the published ME value of 3,207 kcal/kg for glycerin (Lammers et al., 2008a) because the estimate of ME from the current study was not available at the time of initiating the growth study. Diets were based on corn and soybean meal with refined glycerin added to create the dietary treatments. All diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements of finishing pigs and were iso-caloric and had the same standard ileal digestible Lys:ME ratio. Feed was available ad libitum via a single-space dry feeder, and water was freely available from a nipple-type water drinker in each pen.

**Sample Collections and Analysis**

Study I used a 12-d test period consisting of a 7-d adaptation period, used to acclimate the pigs to the metabolism crates and the dietary treatments, followed by a 5-d collection period during which total, but separate, collection of feces and urine was carried out. Chromic oxide (0.3%) was added to the feed given in the morning meal of d 8 (start of collection period) and ferric oxide (0.3%) was added to the feed given in the morning meal of d 13. Fecal collection was initiated as soon as the chromic oxide appeared in the feces after d 8 and ended on the first appearance of the ferric oxide in the feces after d 13 as described by Adeola (2001). During the collection period, fecal material was collected twice daily approximately 1 h after feeding, weighed, placed in a plastic storage bag, and stored in a freezer at −18°C. Urine collection started 2 h after the pigs were fed in the morning of d 8 and ended 2 h after the pigs were fed in the morning of d 13. Urine was collected into buckets containing 20 mL of 6 N sulfuric acid that were placed under the metabolism cages and emptied morning and afternoon (Stein et al., 2004). The volume of urine was measured, and the urine was placed into plastic containers and stored in a freezer at −18°C. At the end of the collection period, all urine samples from each pig were thawed, strained through cheesecloth to remove particulate matter, and mixed thoroughly before a subsample of 100 mL was taken for analysis. Fecal samples from each pig were dried in a forced-air oven at 60°C for 72 h, ground through a 2-mm screen, and thoroughly mixed before a subsample of 100 g was taken for analysis.

All analyses were conducted in duplicate and were repeated if duplicate values differed by more than ±5%. Samples of diets and feces were analyzed for DM (procedure 930.15; AOAC, 2000). The GE of feed, feces, and urine plus cellulose was determined via bomb calorimetry (model 1281, Parr Instrument Co., Moline, IL). Urine (approximately 2 mL) was dried at 55°C for 24 h onto 1 g of dried cellulose (Solkafloc, International Fiber Corporation, North Tonawanda, NY) before energy determination as described by Fent (2001).

**Growth Performance and Carcass and Meat Quality Measurements**

For study II, pigs were individually weighed at the start and at d 14 and 28 of the feeding period. Daily

Table 2. Formulation and analyzed nutrient content of the experimental diets for study I (as-fed basis)\textsuperscript{1}

<table>
<thead>
<tr>
<th>Item</th>
<th>Control</th>
<th>Glycerin\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredient, %</td>
<td>50.08</td>
<td>50.08</td>
</tr>
<tr>
<td>Basal diet\textsuperscript{3}</td>
<td>49.92</td>
<td>19.92</td>
</tr>
<tr>
<td>Corn</td>
<td>50.08</td>
<td>30.00</td>
</tr>
<tr>
<td>Glycerin</td>
<td>49.92</td>
<td></td>
</tr>
<tr>
<td>Analyzed composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM, %</td>
<td>84.36</td>
<td>81.53</td>
</tr>
<tr>
<td>CP, %</td>
<td>7.59</td>
<td>5.44</td>
</tr>
<tr>
<td>Ash, %</td>
<td>1.58</td>
<td>1.14</td>
</tr>
<tr>
<td>Ether extract, %</td>
<td>2.11</td>
<td>0.48</td>
</tr>
<tr>
<td>Crude fiber, %</td>
<td>1.40</td>
<td>0.60</td>
</tr>
<tr>
<td>ADF, %</td>
<td>2.38</td>
<td>0.67</td>
</tr>
<tr>
<td>NDF, %</td>
<td>8.01</td>
<td>5.78</td>
</tr>
<tr>
<td>P, %</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>Ca, %</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>GE, kcal/kg</td>
<td>3,744</td>
<td>3,897</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Analysis carried out by Midwest Laboratories Inc., Omaha, NE.
\textsuperscript{2}Refined glycerin, Evonik Industries, Mapleton, IL.
\textsuperscript{3}Basal diet consisted of corn (99.7%) plus added vitamins (0.1%) and microminerals (0.2%) to provide the following quantities of vitamins and trace minerals per kilogram of complete diet: vitamin A, 8,820 IU as vitamin A acetate; vitamin D3, 1,654 IU as vitamin D-activated animal sterol; vitamin E, 44 IU as α-tocopherol acetate; menadione, 1.1 mg as menadione bisulfate complex; vitamin B12, 0.04 mg; riboflavin, 8 mg; pantothenic acid, 27.6 mg as calcium pantothenate; niacin, 8 mg; thiamin, 0.30 mg as sodium selenite.

Analysis carried out by Midwest Laboratories Inc., Omaha, NE.

Analysis carried out by Midwest Laboratories Inc., Omaha, NE.

Refined glycerin, Evonik Industries, Mapleton, IL.
feed additions to the feeders were recorded and feeders were weighed each time pig BW were taken and used to calculate pen feed intake and G:F. At the completion of the study, all pigs were individually weighed and tattooed with an individual identification number and were transported approximately 5 km to the Meat Science Laboratory of the University of Illinois. Pigs were held in lairage overnight for approximately 16 h without feed but with access to water. The handling intensity treatment was applied immediately before slaughter, which was conducted using standard procedures.

After slaughter, HCW was taken immediately after carcass dressing, LM temperature and pH were taken 45 min postmortem, and pH was taken at 24 h postmortem at the 10th rib (Star Probe; SKF Technologies, Cedar Rapids, IA). At 24 h postmortem, carcasses were ribbed at the 10th rib and backfat depth was measured over the LM, and LM area was measured using a plastic grid placed directly on the cross-sectional surface of the muscle (NPPC, 2000). Subjective scores for color, firmness, and marbling were taken on the cut surface of the LM using 5-point scales (1 = pale, soft, and devoid of marbling; 5 = dark, firm, and moderately abundant or greater marbling) as described by NPPC (1991). Carcass fat-free lean content was calculated using the equation from NPPC (2000) for ribbed carcasses. Objective color scores (Minolta L*, a*, and b*) were taken on the cut surface of the LM at the 10th rib (settings: illuminant D65 and 0° viewing angle; Minolta Chromameter CR-300; Minolta Camera Co., Osaka, Japan). A section of boneless loin was removed posterior to the 10th rib, and three 2.5-cm-thick chops were obtained from the LM. One chop was weighed, trimmed of epimysium and external fat, placed in a bag (Whirl-Pak, Nasco, Fort Atkinson, WI), suspended in a cooler (4°C) for 24 h, reweighed, and drip loss was calculated (Honikel, 1987). A second chop was vacuum packaged and aged in a cooler (4°C) for 10 d and frozen (−20°C) for subsequent Warner-Bratzler shear force determination. The third chop was placed in a bag (Whirl-Pak) and frozen (−20°C) for subsequent chemical analysis.

For Warner-Bratzler shear force determination, chops were thawed overnight at 4°C, trimmed to a uniform size, and cooked on an oven (Farberware Open Table 3. Diet formulation and analyzed composition\(^1\) of experimental diets for study II (as-fed basis)

<table>
<thead>
<tr>
<th>Ingredient, %</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>84.91</td>
<td>79.68</td>
<td>74.41</td>
<td>69.15</td>
</tr>
<tr>
<td>Soybean meal</td>
<td>12.83</td>
<td>12.83</td>
<td>12.83</td>
<td>12.83</td>
</tr>
<tr>
<td>Glycerin(^2)</td>
<td>—</td>
<td>5.00</td>
<td>10.00</td>
<td>15.00</td>
</tr>
<tr>
<td>L-Lys</td>
<td>0.17</td>
<td>0.19</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>L-Thr</td>
<td>—</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.87</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Salt</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Monocalcium phosphate (21% P)</td>
<td>0.72</td>
<td>0.73</td>
<td>0.74</td>
<td>0.75</td>
</tr>
<tr>
<td>Fat, choice white grease</td>
<td>—</td>
<td>0.22</td>
<td>0.45</td>
<td>0.68</td>
</tr>
<tr>
<td>Vitamins(^3)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Trace minerals(^4)</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analyzed composition</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DM, %</td>
<td>87.3</td>
<td>87.4</td>
<td>86.2</td>
<td>83.9</td>
</tr>
<tr>
<td>CP, %</td>
<td>13.0</td>
<td>12.2</td>
<td>12.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Ash, %</td>
<td>3.6</td>
<td>3.9</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Ether extract, %</td>
<td>2.9</td>
<td>3.0</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Crude fiber, %</td>
<td>2.3</td>
<td>2.3</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>ADF, %</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>NDF, %</td>
<td>7.6</td>
<td>7.1</td>
<td>7.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Ca, %</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>P, total, %</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Na, %</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Cl, %</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>ME,(^5) kcal/kg</td>
<td>3,338</td>
<td>3,337</td>
<td>3,335</td>
<td>3,334</td>
</tr>
</tbody>
</table>

\(^1\)Analysis carried out by Midwest Laboratories Inc., Omaha, NE.
\(^2\)Refined glycerin, Evonik Industries, Mapleton, IL.
\(^3\)Provided the following quantities of vitamins per kilogram of complete diet: vitamin A, 8,820 IU as vitamin A acetate; vitamin D\(_3\), 1,654 IU as vitamin D-activated animal sterol; vitamin E, 44 IU as α-tocopherol acetate; menadione, 1.1 mg as menadione bisulphate complex; vitamin B\(_12\), 0.04 mg; riboflavin, 8 mg; pantothenic acid, 27.6 mg as calcium pantothenate; niacin, 42 mg.
\(^4\)Provided the following quantities of trace minerals per kilogram of complete diet: Fe, 165 mg as iron sulfate; Zn, 165 mg as zinc sulfate; Mn, 39 mg as manganese sulfate; Cu, 16.5 mg as copper sulfate; I, 0.30 mg as calcium iodate; and Se, 0.30 mg as sodium selenite.
\(^5\)Calculated diet ME content using published value for glycerin by Lammers et al. (2008a).
Glycerin for growing pigs

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Hearth grill, model 455N, Walter Kidde, Bronx, NY). The internal temperature was monitored with Cu-constantan thermocouples (type T, Omega Engineering, Stamford, CT) connected to a digital scanning thermometer (model 92000-00, Barnant Co., Barington, IL). Chops were cooked on 1 side to an internal temperature of 35°C, turned over, and cooked on the other side to a final internal temperature of 70°C. The chops were weighed before and after cooking to determine cooking loss. Chops were allowed to cool to 25°C, and four 1.3-cm-diameter cores were removed parallel to the orientation of the muscle fibers. An analyzer (Texture Analyzer T. A. HD Plus, Texture Technologies Corp., Scarsdale, NY, and Stable Microsystems, Godalming, UK) fitted with a Warner-Bratzler shear attachment was used to shear the cores. The full scale load was set at 100 kg, and the chart drive and crosshead speed was 200 mm/min. Shear force was determined for each core, and these values were averaged for each sample.

Calculations and Statistical Analysis

For study I, all concentrations used in the calculations were adjusted to 100% DM. Gross energy intake was calculated by multiplying the GE of the diet by the feed intake over the collection period. Apparent DE values of the experimental diets were calculated by subtracting the total fecal energy from total GE intake and dividing by total feed intake. Apparent ME values were calculated by subtracting total fecal and urinary energy from total GE intake and dividing by total feed intake. By subtracting the DE and ME contributed by the corn to the glycerin diet, the apparent DE and ME values of glycerin were calculated by difference as described by Adeola (2001). Observations from 1 pig exceeded the treatment mean by more than 3 SD and were considered outliers and were, therefore, removed from the data set before analysis.

For both studies, the PROC UNIVARIATE procedure (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the variables, and all data were analyzed using the PROC MIXED (Littell et al., 1996) procedure of SAS. The LSMEANS procedure was used to calculate mean values, and the PDIFF option was used to separate treatment means. An α-value of 0.05 was used to assess differences among treatment means.

For study I, the pig was considered the experimental unit, and the model used for analysis included the fixed effect of dietary treatment and the random effects of block (date of start) and replicate nested within block. For study II, the pen was considered the experimental unit for growth performance data, and the model used for analysis included the fixed effect of glycerin inclusion level and the random effects of block (starting date) and replicate nested within block. For carcass and meat quality measurements, one-half of the pen (consisting of the 2 pigs that were subjected to the gentle or the intense handling treatment) was considered the experimental unit. The model used included the fixed effects of glycerin inclusion level (main plot) and preslaughter handling intensity (subplot), the 2-way interaction, and the random effects of slaughter date, replicate nested within slaughter date, the 2-way interactions of slaughter date × glycerin inclusion level, replicate × glycerin inclusion level within slaughter date, and slaughter date × handling intensity, and the 3-way interaction.

RESULTS AND DISCUSSION

Energy Digestibility Study

Least squares means for the effect of dietary treatment on daily energy balance for pigs fed the experimental diets are presented in Table 4. All values presented and discussed are expressed on a DM basis. There was no effect of dietary treatment on GE intake; however, fecal GE excretion was 23% less (P < 0.05) for the pigs fed the glycerin compared with the control diet. In contrast, urinary GE excretion was 540% greater (P < 0.01) for the pigs fed the glycerin diet compared with those fed the control diet. This treatment difference resulted from a combination of a greater concentration (P < 0.05) of energy in the urine (2,758 vs. 3,672 kcal/kg for the control and glycerin diets, respectively; data not shown) and a greater (P < 0.01) urine output (81.9 vs. 17.2 g/d for the glycerin and the control diets, respectively; data not shown). Lammers et al. (2008a) fed growing (11.0 ± 0.5 kg) and finishing (109.6 ± 5.5 kg) pigs diets containing 0 or 20% crude glycerin (86.95% glycerin) and showed that the glycerin-fed pigs had more than double the urinary energy excretion than control pigs (47 vs. 108 kcal of GE/d and 298 vs. 600 kcal of GE/d for growing and finishing pigs, respectively). Equivalent values in the current study were 47.6 and 304.8 kcal of GE/d for pigs fed the control and glycerin diets, respectively.

The greater urine output for pigs fed the glycerin compared with the control diet indicates that glycerin can have a diuretic effect, and there is evidence from other studies that feeding glycerin leads to increased water consumption and urine output. For example, Johnson et al. (1933) showed that rats fed increased glycerin (either 60 or 100% of the carbohydrate in the diet substituted by glycerin) increased water consumption by 30 or 230%, respectively, compared with those fed a control diet without glycerin. These authors also showed that dogs fed diets with more than 60% of the carbohydrates substituted by glycerin had increased water intake and 5 times the urine volume than dogs fed a control diet without glycerin. Interestingly, Cryer and Bartley (1973) showed that when 100% of the carbohydrate in diets for rats was replaced by glycerin, water intake increased from an average of 30 mL/d to in excess of 100 mL/d after 3 d of feeding and urine production increased from 10 to 90 mL/d. In an earlier study, Johnson et al. (1933) administered 2.5 g of
glycerin/kg of BW by stomach tube to dogs fitted with bladder fistulas and showed that the rate of urine production increased by 3-fold in the first 15 min after glycerin ingestion, and by 9-fold after 30 min.

The apparent DE value for the glycerin diet was 10% greater ($P < 0.01$) compared with the control diet (4,298 vs. 3,902 kcal/kg of DM; Table 4), indicating a greater ($P < 0.05$) digestibility of energy for the glycerin compared with the control diet (91.6 vs. 89.5% of GE intake). This is in agreement with the results of Lammers et al. (2008a) who reported energy digestibility values of 90.7 and 89.6% for glycerin and control diets, respectively. In the current study, the metabolizability of energy was 10% less ($P < 0.05$) for the glycerin compared with the control diet (79.3 vs. 87.6%). Consequently, the ME content of the control and glycerin diets was similar at 3,820 and 3,723 kcal/kg of DM, respectively (Table 4). The ME content of the diet expressed as a percentage of the DE content of the diet was greater ($P < 0.05$) for the control (97.9%) than for the glycerin diet (86.6%).

Thus, the results of this study show that, although the digestibility of energy was greater for the glycerin compared with the control diet, losses of energy in the urine were substantially greater for the glycerin diet. It has been shown that absorbed glycerin is converted into glucose in the liver; however, glycerin in excess of the capacity of the liver is excreted in urine rather than being metabolized by the animal (Lin, 1977; Kijora et al., 1995). In the current study, the dietary glycerin inclusion was 30%, which may have been above the upper limit for glycerin metabolism and could explain the increased energy excretion in the urine and decreased metabolizability for glycerin compared with the control diet.

The ME value of the corn was calculated by adjusting the ME value of the control diet for the proportion of corn in the experimental diet (ME of control diet ÷ 99.85 (percentage of corn in the control diet)) × 100. ME of glycerin calculated by subtracting the ME contributed by the corn from the ME of the glycerin diet divided by the glycerin inclusion level.

The ME value of the corn was calculated by adjusting the ME value of the control diet for the proportion of corn in the experimental diet (ME of control diet ÷ 99.85 (percentage of corn in the control diet)) × 100. ME of glycerin calculated by subtracting the ME contributed by the corn from the ME of the glycerin diet divided by the glycerin inclusion level.

### Growth Performance Study

The effect of glycerin inclusion on growth performance is summarized in Table 5. During the overall 4-wk study period, there was no effect of dietary glycerin on the growth performance of finishing pigs. Several studies have also shown no effect of dietary inclusion of glycerin on growth performance. For example, Lammas et al. (2008b) used crude glycerin inclusion levels of 0, 5, and 10%, and Mourot et al. (1994) used levels of 0 and 5% crude glycerin and found no effect of glycerin inclusion level on pig growth performance. Also, Hansen et al. (2009) reported no effect of glycerin supplementation at up to 16% of the diet on growth rates of grow-finish pigs. Interestingly, Kijora and Kupsch (1996) and

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**Table 4. Least squares means for the effect of dietary treatment on energy balance of growing pigs (DM basis)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Control</th>
<th>Glycerin</th>
<th>SEM</th>
<th>$P$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pigs</td>
<td>12</td>
<td>12</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>BW, kg</td>
<td>21.6</td>
<td>21.5</td>
<td>0.2</td>
<td>0.79</td>
</tr>
<tr>
<td>ADFI, kg</td>
<td>0.59</td>
<td>0.53</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>GE intake, kcal/d</td>
<td>2,557</td>
<td>2,485</td>
<td>226</td>
<td>0.41</td>
</tr>
<tr>
<td>Fecal energy, kcal/d</td>
<td>268</td>
<td>206</td>
<td>18</td>
<td>0.01</td>
</tr>
<tr>
<td>Urine energy, kcal/d</td>
<td>47.6</td>
<td>304.8</td>
<td>32.3</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy digestibility, %</td>
<td>89.5</td>
<td>91.6</td>
<td>0.6</td>
<td>0.02</td>
</tr>
<tr>
<td>DE of experimental diet, kcal/kg</td>
<td>3,902</td>
<td>4,298</td>
<td>25</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy metabolizability, %</td>
<td>87.6</td>
<td>79.3</td>
<td>1.4</td>
<td>0.01</td>
</tr>
<tr>
<td>ME of experimental diet, kcal/kg</td>
<td>3,820</td>
<td>3,723</td>
<td>64</td>
<td>0.30</td>
</tr>
<tr>
<td>ME:DE ratio of experimental diet, %</td>
<td>97.9</td>
<td>86.6</td>
<td>1.3</td>
<td>0.01</td>
</tr>
<tr>
<td>DE of ingredient, kcal/kg</td>
<td>3,908</td>
<td>5,244</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ME of ingredient, kcal/kg</td>
<td>3,826</td>
<td>3,584</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

1DE of corn = (DE control diet ÷ 99.85 (percentage of corn in the control diet)) × 100. DE of glycerin calculated by subtracting the DE contributed by the corn from the DE of the glycerin diet divided by the glycerin inclusion level.

2ME of corn = (ME control diet ÷ 99.85 (percentage of corn in the control diet)) × 100. ME of glycerin calculated by subtracting the ME contributed by the corn from the ME of the glycerin diet divided by the glycerin inclusion level.
Groesbeck et al. (2008) showed improved growth rates for pigs fed diets containing glycerin compared with those fed a control diet without glycerin. In addition, Zijlstra et al. (2009) fed diets with up to 8% glycerin to weaned pigs over a 28-d period and showed an increase in final BW compared with the control diet without glycerin. However, some studies have shown a negative effect of feeding glycerin on growth performance. For example, Kijora et al. (1995) fed diets with 0, 5, 10, 20, or 30% glycerin and showed a small reduction in growth rate at the largest level compared with the other glycerin inclusion levels. In addition, Della Casa et al. (2009) found that feeding diets containing 10%, but not 5%, pure glycerin to pigs between 43 and 160 kg of BW had a negative effect on growth rate and feed efficiency. Also, Kerr et al. (2009) found a negative effect of a range of different sources of crude glycerin included at between approximately 7 and 9% of the diet on the growth rate and feed efficiency of nursery pigs.

Carcass and Meat Quality Characteristics

Least squares means for the effects of dietary glycerin inclusion level on growth performance of finishing pigs are presented in Table 5. There were no interactions between glycerin inclusion level and preslaughter handling intensity treatments for any of the traits measured; therefore, only the main effects are presented and discussed.

There was no effect of glycerin inclusion level on any of the carcass characteristics measured in the study. This result is not surprising given that there was no effect of glycerin inclusion level on growth performance and is also consistent with the results of other studies. For example, Mourot et al. (1994) fed crude glycerin at 0 or 5% inclusion rates, and Kijora et al. (1995), Kijora and Kupsch (1996), and Lammers et al. (2008b) fed crude glycerin at 0, 5, and 10% of the diet and found no effect of glycerin inclusion on carcass measures. Similarly, Della Casa et al. (2009) found no change in carcass yield or lean content from feeding diets with 0, 5, or 10% glycerin in the growing and finishing phases.

Adding glycerin to the diet had no impact on any of the meat quality traits measured in this study. In general, the means for pork quality traits observed in this study were similar to those found in other research carried out at the University of Illinois and elsewhere and were within the range associated with pork of normal quality (Cisneros et al., 1996; Brown et al., 1998; Hamilton et al., 2002). The results of Kijora et al. (1995), Kijora and Kupsch (1996), and Hansen et al. (2009) are generally in agreement with those of the current study in showing no effect of dietary glycerin inclusion on meat quality measurements. In contrast, however, Mourot et al. (1994) showed that drip loss and cooking loss of the LM and semimembranosus muscle were reduced in pigs fed diets with 5 compared with 0% crude glycerin, indicating that glycerin increases water-holding capacity of the muscles.

The intense preslaughter handling treatment had no effect on the pork quality traits measured compared with the gentle handling treatment. Brown et al. (1998) also reported no effect of subjecting pigs to a simulated commercial handling compared with minimal stress handling immediately before slaughter on pork quality traits. In addition, Hambrecht et al. (2005) and Channon et al. (2000) showed that Warner-Bratzler shear force and cooking loss were not influenced by increased compared with decreased preslaughter stress treatment, which agrees with the present study. However, Channon et al. (2000) and Hambrecht et al. (2005) reported that pigs subjected to increased stress before slaughter had a greater LM temperature and reduced pH at 40 min postmortem, resulting in a greater 24-h drip loss when compared with minimally stressed animals. In the present study, several measures, such as pH 45 min, Minolta L*, and drip loss, were numerically less for the pigs subjected to the intense compared with the gentle handling treatment; however, the treatment differences were not statistically significant ($P \geq 0.22$). In conclusion, the results of the present study indicate that including glycerin in diets for finishing pigs at relatively small amounts ($\leq 15\%$) has no detrimental effects on growth performance or carcass and meat quality characteristics.

### Table 5. Least squares means for the effect of dietary glycerin inclusion level on growth performance of finishing pigs

<table>
<thead>
<tr>
<th>Item</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>SEM</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pens</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BW, kg</td>
<td>92.44</td>
<td>92.60</td>
<td>92.52</td>
<td>92.61</td>
<td>0.09</td>
<td>0.52</td>
</tr>
<tr>
<td>Wk 0</td>
<td>120.25</td>
<td>122.01</td>
<td>120.33</td>
<td>118.98</td>
<td>1.52</td>
<td>0.45</td>
</tr>
<tr>
<td>CV, %</td>
<td>2.87</td>
<td>2.98</td>
<td>2.76</td>
<td>2.68</td>
<td>0.17</td>
<td>0.27</td>
</tr>
<tr>
<td>Wk 4</td>
<td>3.98</td>
<td>5.27</td>
<td>3.60</td>
<td>3.65</td>
<td>0.77</td>
<td>0.31</td>
</tr>
<tr>
<td>ADG, kg</td>
<td>0.99</td>
<td>1.05</td>
<td>0.99</td>
<td>0.94</td>
<td>0.06</td>
<td>0.46</td>
</tr>
<tr>
<td>ADFI, kg</td>
<td>3.08</td>
<td>3.24</td>
<td>3.12</td>
<td>3.07</td>
<td>0.19</td>
<td>0.63</td>
</tr>
<tr>
<td>G:F</td>
<td>0.325</td>
<td>0.329</td>
<td>0.320</td>
<td>0.308</td>
<td>0.015</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Glycerin for growing pigs
Table 6. Least squares means for the effect of dietary glycerin inclusion level and preslaughter handling on carcass and meat quality measurements

<table>
<thead>
<tr>
<th>Item</th>
<th>Glycerin inclusion level, %</th>
<th>Handling intensity</th>
<th>SEM</th>
<th>Gentle</th>
<th>Intense</th>
<th>SEM</th>
<th>Glycerin Handling</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of observations</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BW at slaughter, kg</td>
<td>117.27</td>
<td>117.46</td>
<td>117.81</td>
<td>114.29</td>
<td></td>
<td></td>
<td>1.64</td>
<td>117.14</td>
</tr>
<tr>
<td>Carcass measures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCW, kg</td>
<td>90.30</td>
<td>90.31</td>
<td>91.06</td>
<td>87.83</td>
<td>1.52</td>
<td></td>
<td>90.02</td>
<td>89.73</td>
</tr>
<tr>
<td>Carcass yield, %</td>
<td>76.98</td>
<td>76.86</td>
<td>77.29</td>
<td>76.85</td>
<td>0.34</td>
<td></td>
<td>76.84</td>
<td>77.15</td>
</tr>
<tr>
<td>LM area, mm</td>
<td>49.60</td>
<td>49.33</td>
<td>49.36</td>
<td>49.26</td>
<td>1.19</td>
<td></td>
<td>48.55</td>
<td>50.22</td>
</tr>
<tr>
<td>10th-rib backfat depth, mm</td>
<td>23.10</td>
<td>21.05</td>
<td>22.15</td>
<td>21.93</td>
<td>0.95</td>
<td></td>
<td>22.31</td>
<td>21.80</td>
</tr>
<tr>
<td>Predicted fat-free lean, %</td>
<td>52.50</td>
<td>53.26</td>
<td>52.78</td>
<td>52.94</td>
<td>0.54</td>
<td></td>
<td>52.55</td>
<td>53.19</td>
</tr>
<tr>
<td>pH, 45 min</td>
<td>6.00</td>
<td>5.83</td>
<td>5.88</td>
<td>5.80</td>
<td>0.08</td>
<td></td>
<td>5.93</td>
<td>5.83</td>
</tr>
<tr>
<td>pH, 24 h</td>
<td>5.46</td>
<td>5.49</td>
<td>5.49</td>
<td>5.49</td>
<td>0.05</td>
<td></td>
<td>5.48</td>
<td>5.49</td>
</tr>
<tr>
<td>Temperature, 45 min, °C</td>
<td>40.83</td>
<td>40.93</td>
<td>41.03</td>
<td>40.78</td>
<td>0.28</td>
<td></td>
<td>40.86</td>
<td>40.91</td>
</tr>
<tr>
<td>Minolta color</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L*</td>
<td>49.66</td>
<td>51.16</td>
<td>50.66</td>
<td>51.33</td>
<td>1.12</td>
<td></td>
<td>50.06</td>
<td>51.34</td>
</tr>
<tr>
<td>a*</td>
<td>8.86</td>
<td>8.74</td>
<td>9.11</td>
<td>7.88</td>
<td>0.56</td>
<td></td>
<td>8.25</td>
<td>9.04</td>
</tr>
<tr>
<td>b*</td>
<td>5.05</td>
<td>6.00</td>
<td>5.75</td>
<td>5.14</td>
<td>0.50</td>
<td></td>
<td>5.03</td>
<td>5.94</td>
</tr>
<tr>
<td>Subjective score for LM³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>2.81</td>
<td>2.56</td>
<td>2.69</td>
<td>2.69</td>
<td>0.20</td>
<td></td>
<td>2.75</td>
<td>2.63</td>
</tr>
<tr>
<td>Marbling</td>
<td>1.56</td>
<td>1.56</td>
<td>1.69</td>
<td>1.38</td>
<td>0.20</td>
<td></td>
<td>1.63</td>
<td>1.47</td>
</tr>
<tr>
<td>Firmness</td>
<td>2.25</td>
<td>2.25</td>
<td>2.31</td>
<td>2.44</td>
<td>0.23</td>
<td></td>
<td>2.50</td>
<td>2.13</td>
</tr>
<tr>
<td>Drip loss, %</td>
<td>6.25</td>
<td>5.94</td>
<td>5.90</td>
<td>5.05</td>
<td>0.92</td>
<td></td>
<td>5.16</td>
<td>6.26</td>
</tr>
<tr>
<td>Cooking loss, %</td>
<td>23.37</td>
<td>24.72</td>
<td>23.62</td>
<td>22.67</td>
<td>1.36</td>
<td></td>
<td>24.24</td>
<td>22.95</td>
</tr>
<tr>
<td>Shear force, kg</td>
<td>3.71</td>
<td>3.59</td>
<td>3.70</td>
<td>3.66</td>
<td>0.20</td>
<td></td>
<td>3.54</td>
<td>3.79</td>
</tr>
</tbody>
</table>

¹G × H = glycerin inclusion level × handling intensity interaction.
²The experimental units for the glycerin inclusion level and handling intensity were the pen and half pen, respectively.
³Subjective scores for color, firmness, and marbling were taken on the cut surface of the LM at the 10th rib using 5-point scales (1 = pale, soft, and devoid of marbling; 5 = dark, firm, and moderately abundant or greater marbling) as described by NPPC (1991).
LITERATURE CITED


