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Utilization of Crude Glycerin in Nonruminants

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1. Introduction

During digestion in non-ruminants, intestinal absorption of glycerol has been shown to range from 70 to 90% in rats (Lin, 1977) to more than 97% in pigs and laying hens (Bartlet and Schneider, 2002). Glycerol is water soluble and can be absorbed by the stomach, but at a rate that is slower than that of the intestine (Lin, 1977). Absorption rates are high, likely due to glycerin's small molecular weight and passive absorption rather than forming a micelle that is required for absorption of medium and long chain fatty acids (Guyton, 1991). Once absorbed, glycerol can be converted to glucose via gluconeogenesis or oxidized for energy production via glycolysis and citric acid cycle with the shuttling of protons and electrons between the cytosol and mitochondria depicted in Figure 1 (Robergs and Griffin, 1998). Glycerol metabolism largely occurs in the liver and kidney where the amount of glucose carbon arising from glycerol depends upon metabolic state and level of glycerol consumption (Lin, 1977; Hetenyi et al., 1983; Baba et al., 1995). With gluconeogenesis from glycerol being limited by the availability of glycerol (Cryer and Bartley, 1973; Tao et al., 1983), crude glycerin has the potential of being a valuable dietary energy source for monogastrics.

2. Crude glycerin: Caloric value for swine and poultry

Pure glycerin is a colorless, odorless, and a sweet-tasting viscous liquid, containing approximately 4.3 Mcal of gross energy (GE)/kg as-is basis (Kerr et al., 2009). However, crude glycerin can range from 3 to 6 Mcal GE/kg, depending upon its composition (Brambilla and Hill, 1966; Lammers et al., 2008b; Kerr et al., 2009). The difference in GE of crude glycerin compared with pure glycerin is not surprising, given that crude glycerin typically contains about 85% glycerin, 10% water, 3% ash (typically Na or K chloride), and a trace amount of free fatty acids. As expected, high amounts of water negatively influence GE levels while high levels of free fatty acids elevate the GE concentration. Various

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NOTE: In the current text, use of the word "glycerin" refers to the chemical compound or feedstuff while 'glycerol' refers to glycerin on a biochemical basis relative to its function in living organisms. In addition, because glycerin is marketed on a liquid basis, all data are presented on an 'as-is' basis.

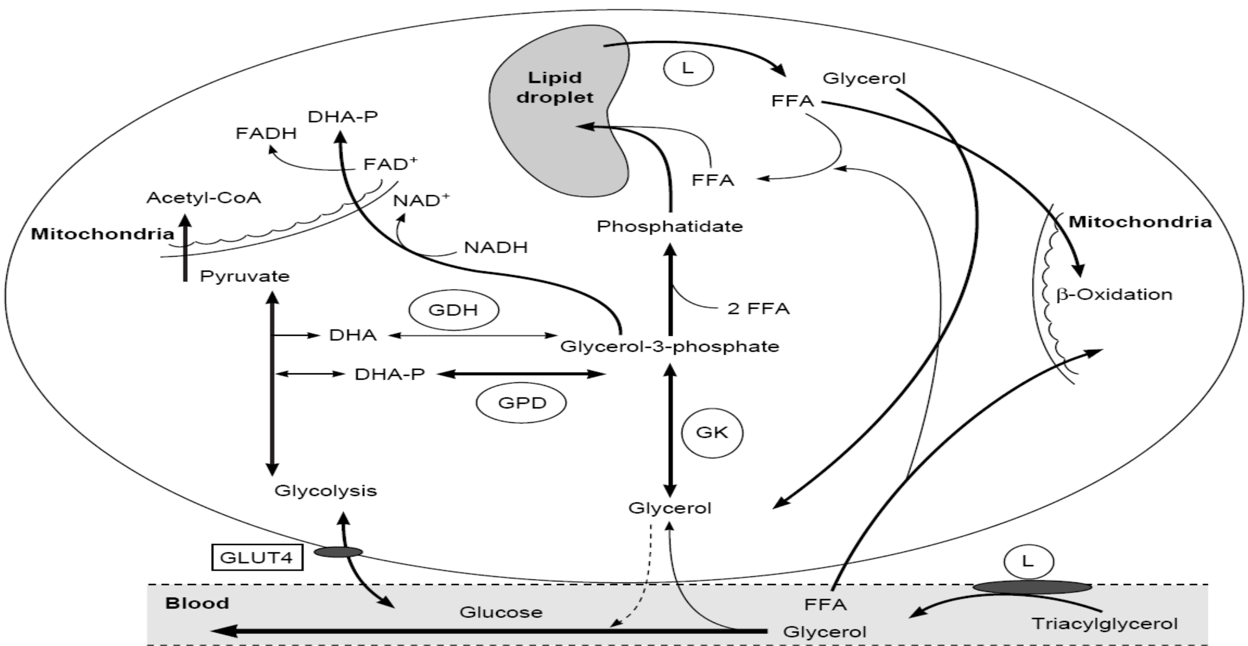

Fig. 1. Biochemical reactions involved in glycerol synthesis and metabolic conversation to glycerol-3-phosporate, phosphatidate and triacylglycerol.
DHA= dihydroxyacetone; DHA-P = dihydroxyacetone phosphate; FAD^+ = oxidised from flavin adenine dinucleotide; FADH = reduced from of flavin adenine dinucleotide; FFA = free fatty acid; GHD = glycerol dehydrogenase; GK = glycerol kinase; GLUT4 = glucose transport protein; GPD = glycerol phosphate dehydrogenase; L = lipase; NAD^+ = oxidised from of nicotinamide adenine dincleotide; NADH = reduced from of nicotinamide adenine dinucleotide.

experiments evaluating glycerin have assumed the metabolizable energy (swine nutrition terminology) or apparent metabolizable energy (poultry nutrition terminology), hereafter just called metabolizable energy (ME), of glycerin to be approximately 95% of its GE in dietary formulation (Brambilla and Hill, 1966; Lin et al., 1976; Rosebrough et al., 1980; Cerrate et al., 2006). Empirical determinations of ME content in crude glycerin have been lacking in non-ruminants until recently.

Bartlet and Schneider (2002) reported ME values of refined glycerin in broiler, laying hen, and swine diets, and showed that the ME value of glycerin decreased as the level of dietary glycerin increased (Table 1). On average, these values were 3,993, 3,929, and 3,292 kcal/kg for broilers, laying hens, and swine, respectively. Since pre-cecal digestiblity of glycerin is approximately 97% (Bartlet and Schneider, 2002), a possible explanation for the observed decrease in ME value may be a result of increased blood glycerol levels (Kijora et al., 1995; Kijora and Kupsch, 2006; Simon et al., 1996) after glycerin absorption, such that complete renal reabsorption is prevented and glycerol excretion in the urine is increased (Kijora et al., 1995; Robergs and Griffin, 1998).

Dietary glycerin, %	Broiler, kcal/kg	Laying hen, kcal/kg	Swine, kcal/kg
5	4,237	4,204	4,180
10	4,056	4,108	3,439
15	3,686	3,475	2,256

[1] Bartlet and Schneider, 2002

Table 1. Metabolizable energy of refined glycerin, as-is basis[1]

Lammers et al. (2008b) obtained a crude glycerin co-product (87% glycerin) and determined in nursery and finishing pigs that its ME was 3,207 kcal/kg, and did not differ between pigs weighing 10 or 100 kg (Table 2). Strictly based on glycerin content, this would equate to 3,688 kcal ME/kg on a 100% glycerin basis (3,207 kcal ME/kg/87% glycerin), which would be slightly lower than the 3,810 kcal ME/kg (average of the 5 and 10% inclusion levels) reported by Bartlet and Schneider (2002), but similar to the 3,656 kcal ME/kg as reported by Mendoza et al. (2010) using a 30% inclusion level of glycerin.

Trial	Pigs	Initial BW, kg	DE, kcal/kg	SEM	ME, kcal/kg	SEM
1[2]	18	11.0	4,401	282	3,463	480
2[3]	23	109.6	3,772	108	3,088	118
3[4]	19	8.4	3,634	218	3,177	251
4[4]	20	11.3	4,040	222	3,544	237
5[4]	22	99.9	3,553	172	3,352	192

[1] All experiments represent data from 5 d energy balance experiments following a 10 d adaptation period (Lammers et al., 2008b).
[2] Included pigs fed diets containing 0, 5, and 10% crude glycerin.
[3] Included pigs fed diets containing 0, 5, 10, and 20% crude glycerin.
[4] Included pigs fed diets containing 0 and 10% glycerin.

Table 2. Digestible and metabolizable energy of crude glycerin fed to pigs, as-is basis[1]

Similar to data reported by Bartlet and Schneider (2002) in 35 kg pigs, increasing crude glycerin from 5 to 10 or 20% in 10 kg pigs (Lammers et al., 2008b) quadratically reduced ME (3,601, 3,239, and 2,579 kcal ME/kg, respectively), which suggests that high dietary concentrations of crude glycerin may not be fully utilized by 10 kg pigs. In contrast, dietary concentrations of crude glycerin had no effect on ME determination in 100 kg pigs (Lammers et al., 2008b). The ratio of DE:GE is an indicator of how well a product is digested, and for the crude glycerin evaluated by Lammers et al. (2008b), it equaled 92% suggesting that crude glycerin is well digested. Similarly, Bartlet and Schneider (2002) reported that greater than 97% of the glycerin is digested before the cecum. In addition, the ratio of ME:DE indicates how well energy is utilized once digested, and for the crude glycerin evaluated by Lammers et al. (2008b) the ratio was 96%, which is identical to the ME:DE ratio for soybean oil, and is comparable to the ratio of ME:DE (97%) for corn grain (NRC, 1998), all of which support the assertion that crude glycerol is well utilized by the pig as a source of energy.

The energy value of crude glycerin in poultry has also been recently evaluated. Bartlet and Schneider (2002) reported that the ME content for refined glycerin is 3,929 and 3,993 kcal/kg for laying hens and broilers, respectively (Table 1). Studies by Lammers et al. (2008a) using laying hens, and Dozier et al. (2008) using broilers, reported a ME value of 3,805 and 3,434 kcal/kg, respectively, for the same lot of crude glycerin (87% glycerin). These estimates equate to 4,376 and 3,949 kcal/kg for laying hens and broilers, respectively, on a 100% purity basis, and compare favorably to the Bartlet and Schneider (2002) values for broilers, but higher than their value for laying hens. Contrary to the observations of Bartlet and Schneider (2002), Dozier et al. (2008) and Lammers et al. (2008a) reported no reduction in ME of crude glycerin as dietary inclusion level increased. However, Dozier et al. (2008) used ≤ 9% crude glycerin (equivalent to ≤ 7.8% pure glycerin) and Lammers et al. (2008a) used ≤ 15% crude glycerin (equivalent to ≤ 13.0% pure glycerin), which were slightly less than the inclusion levels (up to 15% refined glycerin) studied by Bartlet and Schneider (2002). Swiatkiewicz and Koreleski (2009) recently determined the ME of crude glycerin to be 3,970 kcal/kg in diets containing up to 6% crude glycerin fed to laying hens, but did not report the purity of the crude glycerin source.

Similar to other co-products used to feed livestock, the chemical composition of crude glycerin can vary widely (Thompson and He, 2006; Kijora and Kupsch, 2006; Hansen et al., 2009; Kerr et al., 2009). The consequences of this variation in energy value to animals have not been well described for crude glycerin. Recently, 10 sources of crude glycerin from various biodiesel production facilities in the U.S. were evaluated for energy utilization in non-ruminants (Table 3). The crude glycerin sources originating from soybean oil averaged 84% glycerin, with minimal variability noted among 6 of the sources obtained. Conversely, sources from commercial plants using tallow, yellow grease, and poultry oil as initial lipid feedstock ranged from 52 to 94% glycerin. The crude glycerin co-products derived from either non-acidulated yellow grease or poultry fat had the lowest glycerin content, but had the highest free fatty acid composition. The high fatty acid content of the non-acidulated yellow grease product was expected because the acidulation process results in greater separation of methyl esters which subsequently results in a purer form of crude glycerin containing lower amounts of free fatty acids (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006). In contrast, the relatively high free fatty acid content in the crude glycerin obtained from the plant utilizing poultry fat as a feedstock source is difficult to explain because details of the production process were not available. Moreover, both of these two crude glycerin co-products (derived from non-acidulated yellow grease and poultry fat) had higher methanol concentrations than the other glycerin sources. Recovery of

Sample ID[3]	Glycerin	Moisture	Methanol	pH	NaCl	Ash	Fatty acids
USP	99.62	0.35	ND[2]	5.99	0.01	0.01	0.02
Soybean oil	83.88	10.16	0.0059	6.30	6.00	5.83	0.12
Soybean oil[4]	83.49	13.40	0.1137	5.53	2.84	2.93	0.07
Soybean oil	85.76	8.35	0.0260	6.34	6.07	5.87	ND
Soybean oil	83.96	9.36	0.0072	5.82	6.35	6.45	0.22
Soybean oil	84.59	9.20	0.0309	5.73	6.00	5.90	0.28
Soybean oil	81.34	11.41	0.1209	6.59	6.58	7.12	0.01
Tallow	73.65	24.37	0.0290	3.99	0.07	1.91	0.04
Yellow grease	93.81	4.07	0.0406	6.10	0.16	1.93	0.15
Yellow grease[5]	52.79	4.16	3.4938	8.56	1.98	4.72	34.84
Poultry fat	51.54	4.99	14.9875	9.28	0.01	4.20	24.28

[1] Samples analyzed as described in Lammers et al. (2008b) courtesy of Ag Processing Inc., Omaha, NE, 68154. Glycerin content determined by difference as: 100 - % methanol - % total fatty acid - % moisture - % ash.
[2]ND = not detected.
[3] USP=USP grade glycerin or initial feedstock lipid source.
[4] Soybean oil from extruded soybeans. All other soybean oil was obtained by hexane extraction of soybeans.
[5] Crude glycerin that was not acidulated.

Table 3. Chemical analysis of crude glycerin, % as-is basis[1]

methanol is also indicative of production efficiency because it is typically reused during the production process (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006). The high amount of methanol content in crude glycerin from non-acidulated yellow grease was expected because this product has not been fully processed at the production facility. Why the crude glycerin obtained from the plant utilizing poultry fat had relatively high methanol content is unclear as no processing information was obtained from the plant, but it may be due to the lower overall efficiency of the production process at this plant (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006).

The average ME of the 11 sources of glycerin described in Table 3 was 3,486 kcal/kg (Table 4; Kerr et al., 2009), with little differences among the sources with two exceptions. The two co-products with high levels of free fatty acids (co-products obtained from non-acidulated yellow grease and poultry fat) had higher ME values than the other crude glycerin co-products, which was not surprising given that these two co-products also had a higher GE concentration than the other crude glycerin co-products. The ME:GE ratio among all glycerin co-products was similar averaging 85%, which is similar to that reported by others (88%, Lammers et al., 2008b; 88%, Bartlet and Schneider, 2002; 85%, Mendoza et al., 2010). Because the GE of the crude glycerin can differ widely among co-products, comparison of ME as a percentage of GE provides valuable information on the caloric value of crude glycerin for non-ruminants, with a high ME:GE ratio indicating that a given crude glycerin source is well digested and utilized.

When the same glycerin co-products evaluated in swine by Kerr et al. (2009) were fed to broilers (Dozier et al., 2011) the ME averaged 3,646 kcal/kg (Table 4). When evaluating ME as a percent of GE in broilers, crude glycerin co-products originating from soybean oil resulted in similar values compared with co-products produced from tallow and acidulated yellow grease. In contrast, crude glycerin sources with high free fatty acid content had a

		Broiler, AME[1]		Swine, ME[2]	
Sample ID[3]	GE, kcal/kg	kcal/kg	% of GE	kcal/kg	% of GE
USP	4,325	3,662	84.7	3,682	85.2
Soybean oil	3,627	3,364	92.8	3,389	93.4
Soybean oil[4]	3,601	3,849	106.9	2,535	70.5
Soybean oil	3,676	3,479	94.6	3,299	89.9
Soybean oil	3,670	3,889	106.0	3,024	82.5
Soybean oil	3,751	3,644	97.2	3,274	87.3
Soybean oil	3,489	3,254	93.3	3,259	93.5
Tallow	3,173	3,256	102.6	2,794	88.0
Yellow grease	4,153	4,100	98.7	3,440	92.9
Yellow grease[5]	6,021	4,135	68.7	5,206	86.6
Poultry fat	5,581	3,476	62.3	4,446	79.7

[1] Dozier et al., 2011.
[2] Kerr et al., 2009.
[3] USP=USP grade glycerin or initial feedstock lipid source.
[4] Soybean oil from extruded soybeans. All other soybean oil was obtained by hexane extraction of soybeans.
[5] Crude glycerin that was not acidulated.

Table 4. Energy values of crude glycerin co-products in broilers and swine, as-is basis

lower ME as a percentage of GE compared to the other glycerin co-products. If one excludes these two high free fatty acid products from the data set, ME as a percentage of GE averaged 97% (Dozier et al., 2011) which compares favorably to the 96% (5 and 10% inclusion levels only) reported by Bartlet and Schneider (2002), the 105% reported in laying hens by Lammers et al. (2008a), and the 95% reported in broilers by Dozier et al. (2008). Similar to data in swine, this indicates that crude glycerin is well digested and utilized by poultry.

The reduced ability of broilers to efficiently utilize glycerin co-products having relatively high free fatty acid content as indicated by their lower ME:GE ratio warrants additional discussion. Wiseman and Salvador (1991) reported a linear reduction of ME content in broiler diets containing increasing concentrations of free fatty acids, which was supported by others (Artman, 1964; Sklan, 1979) who reported that free fatty acids reduce the rate of absorption compared with lipid sources containing triglycerides and free fatty acids. This reduced absorption in products containing free fatty acids may be partially due to the absence of a monoglyceride backbone to aid absorption because the relatively low concentration of monoglycerides in the duodenum, which may depress the amount of fatty acids entering micellular solution. Furthermore, 2-monoglycerides promote water solubility which results in a mixed bile salt-monoglyceride fatty acid micelle (Hofmann and Borgstrom, 1962; Johnston, 1963; Senior, 1964) which can aid in lipid absorption.

Because more than one chemical component can influence energy content of feed ingredients, stepwise regression was used to predict GE and ME values, and ME as a percentage of GE among glycerin sources for both swine (Kerr et al., 2009) and broiler (Dozier et al., 2011) experiments utilizing the same crude glycerin co-products. If the GE of a crude glycerin is not known, the data indicate it can be predicted by: GE, kcal/kg = - 236 + (46.08 × % of glycerin) + (61.78 × % of methanol) + (103.62 × % of fatty acids), (R^2 = 0.99). In swine, ME content could subsequently be predicted by multiplying GE by 84.5% with no adjustment for composition (Kerr et al., 2009). For poultry, ME content could subsequently be predicted as: GE, kcal/kg × (91.63% – (0.61 × % free fatty acids) – (1.17 × % methanol) + (0.60 × % water)). Because free fatty acids, methanol and water may not be known, ME in poultry could also be predicted by multiplying GE by 97.4% if total fatty acid concentration is less than 0.5%, or by multiplying GE by 65.6% if total fatty acid concentrations range from 25 to 35% (Dozier et al., 2011). Additional research is needed to refine and validate these equations relative to glycerin, methanol, ash, and total fatty acid concentrations for both broilers and pigs.

3. Crude glycerin as a feed ingredient for swine

In swine, German researchers (Kijora and Kupsch, 2006; Kijora et al., 1995, 1997) have suggested that up to 10% crude glycerin can be fed to pigs with little effect on pig performance. Likewise, Mourot et al. (1994) indicated that growth performance of pigs from 35 to 102 kg was not affected by the addition of 5% glycerin (unknown purity) to the diet. The impact of dietary glycerin on carcass quality in pigs has been variable. Kijora et al. (1995) and Kijora and Kupsch (2006) showed no consistent effect of 5 or 10% crude glycerin addition to the diet on carcass composition or meat quality parameters, while in an additional study, pigs fed 10% crude glycerin exhibited a slight increase in backfat, 45 min pH, flesh color, marbling, and leaf fat (Kijora et al., 1997). Although they did not note any significant change in the saturated fatty acid profile of the backfat, there was a slight increase in oleic acid, accompanied by a slight decrease in linoleic and linolenic acid concentrations, resulting in a decline in the polyunsaturated to monounsaturated fatty acid ratio in backfat. Likewise, Mourot et al. (1994) reported no consistent change in carcass characteristics due to 5% crude glycerin supplementation of the diet, but did note an increase in oleic acid and a reduction in linoleic acid in backfat and *semimembranosus* muscle tissue. Kijora and Kupsch (2006) found no effect of glycerin supplementation on water loss of retail pork cuts. However, Mourot et al. (1994) reported a reduction in 24-h drip loss (1.75 versus 2.27%) and cooking loss was also reduced (25.6 vs 29.4%) from the the *Longissimus dorsi* and *semimembranosus* muscles due to dietary supplementation with 5% glycerin. Likewise, Airhart et al. (2002) reported that oral administration of glycerin (1 g/kg BW) 24 h and 3 h before slaughter tended to decrease drip and cooking loss of *Longissimus dorsi* muscle.

Recently, there has been increased interest in utilization of crude glycerin in swine diets due to the high cost of feedstuffs typically used in swine production. For newly weaned pigs, it appears that crude glycerin can be utilized as an energy source up to 6% of the diet, but crude glycerin does not appear to be a lactose replacement (Hinson et al., 2008). In 9 to 22 kg pigs, Zijlstra et al. (2009) reported that adding up to 8% crude glycerol to diets as a wheat replacement, improved growth rate and feed intake, but had no effect on gain:feed. In 28 to 119 kg pigs, supplementing up to 15% crude glycerol to the diet quadratically increased average daily gain and linearly increased average daily feed intake, but the net effect on feed efficiency was a linear reduction (Stevens et al., 2008). These authors also reported that crude glycerin supplementation appeared to increase backfat depth and Minolta L* of loin muscle, but decreased loin marbling and the percentage of fat free lean with increasing dietary glycerin levels. In 78 to 102 kg pigs, increasing crude glycerin from 0 or 2.5% to 5% reduced average daily feed intake when fat was not added to the diet, but had no effect when 6% fat was supplemented (Duttlinger et al., 2008a). This decrease in feed intake resulted in depressed average daily gain, but had no effect on feed efficiency. In contrast, Duttlinger et al. (2008b) reported supplementing up to 5% crude glycerin to diets had no effect on growth performance or carcass traits of pigs weighing 31 to 124 kg.

Supplementing 3 or 6% crude glycerin in pigs from 11 to 25 kg body weight increased average daily gain even though no effect was noted on feed intake, feed efficiency, dry matter, nitrogen, or energy digestibility (Groesbeck et al., 2008). Supplementing 5% pure glycerin did not affect pig performance from 43 to 160 kg, but pigs fed 10% glycerin had reduced growth rate and feed efficiency compared to pigs fed the control or 5% glycerin supplemented diets (Casa et al., 2008). In addition, diet did not affect meat or fat quality, or meat sensory attributes. In 51 to 105 kg pigs, including up to 16% crude glycerin did not affect pig growth performance or meat quality parameters (Hansen et al., 2009). Lammers et al. (2008c) fed pigs (8 to 133 kg body weight) diets containing 0, 5, or 10% crude glycerin and reported no effect of dietary treatment on growth performance, backfat depth, loin eye area, percentage fat free lean, meat quality, or sensory characteristics of the *Longissimus dorsi* muscle. In addition, dietary treatment did not affect blood metabolites or frequency of histological lesions in the eye, liver, or kidney, and only a few minor differences were noted in the fatty acid profile of loin adipose tissue. Likewise, Mendoza et al. (2010) fed heavy pigs (93 to 120 kg) up to 15% refined glycerin and reported no effect on growth performance, carcass characteristics, or meat quality. Schieck et al. (2010b) fed pigs either a control diet (16 weeks, 31 to 128 kg), 8% crude glycerin during the last 8 weeks (45 to 128 kg) or 8% crude glycerin for the entire 16 week period (31 to 128 kg) and reported that feeding crude glycerin during the last 8 weeks before slaughter supported similar growth performance, with little effect on carcass composition or pork quality, except for improvement in belly firmness,

Glycerin equivalency[2]	Daily gain	Daily feed intake	Gain:feed ratio
Ziljstra et al., 2009 / Wheat-soybean meal-fish meal-lactose / 9-22 kg			
4.0[3]	105	109	98
8.0[3]	108	105	104
Hinson et al., 2008 / Corn- soybean meal / 10-22 kg			
5.0	98	100	99
Goresbeck et al., 2008 / Corn- soybean meal / 11-25 kg			
2.7	107	103	103
5.4	108	104	103
Kijora et al., 1995 / Barley- soybean meal / 31-82 kg			
4.8	105	108	97
9.7	112	112	100
19.4	96	103	94
29.4	82	105	78
Kijora and Kupsch, 2006 / Barley- soybean meal / 24 to 95 kg			
2.9	103	108	97
4.9	102	106	97
7.6	102	101	101
8.3	102	107	97
10.0	103	104	100
Kijora et al., 1997 / Barley- soybean meal / 27-100 kg			
10.0	106	110	96
Kijora et al., 1995 / Barley- soybean meal / 32-96			
4.6	114	110	103
9.7	119	113	106
Mourot et al., 1994 / Wheat- soybean meal / 35-102 kg			
5.0	97	101	96
Lammers et al., 2008c / Corn- soybean meal (whey in Phase 1) / 8-133 kg			
4.2	101	102	97
8.5	100	103	97
Stevens et al., 2008 / Corn- soybean meal / 28-119 kg			
4.2	103	103	100
8.4	103	104	99
12.6	100	108	92
Duttlinger et al., 2008b / Corn- soybean meal / 31-124 kg			
2.5	99	99	99
5.0	99	101	98
Hansen et al., 2009 / Wheat-barley-lupin, soybean meal -blood meal-meat meal / 51-105 kg			
3.0	98	104	93
6.1	87	93	95
9.1	96	102	94
12.2	91	98	93

Schieck et al., 2010b / Corn-soybean meal / 31-127 kg			
6.6	104	105	98
Duttlinger et al., 2008a / Corn – soybean meal / 78-102 kg			
2.5	97	99	98
5.0	95	97	98
Casa et al., 2008 / Corn-barley-wheat bran- soybean meal / 43-159 kg			
5.0	101	100	101
10.0	96	100	95
Mendoza et al., 2010 / Corn- soybean meal / 93-120 kg			
5.0	106	105	101
10.0	100	101	98
15.0	95	100	95

[1] Percentage relative to pigs fed the diet containing no supplemental glycerin. Percentage difference does not necessarily mean there was a significant difference from pigs fed the diet containing no supplemental glycerin. Main dietary ingredients and weight range of pigs tested are also provided with each citation.
[2] Represents a 100% glycerin basis. In studies utilizing crude glycerin, values adjusted for purity of glycerin utilized.
[3] Unknown purity, but product contained 6.8% ash and 15.6% ether extract.

Table 5. Relative performance of pigs fed supplemental glycerin[1]

compared to pig fed the corn-soybean meal control diet. Longer term feeding (16 weeks) resulted in a slight improvement in growth rate, but a small depression in feed efficiency. Some minor differences in carcass composition were noted, but there was no impact on pork quality. When considering the results from all of these studies (Table 5), there appears to be no consistent (positive or negative) effect of feeding up to 15% crude glycerin on growth performance, carcass composition, or pork quality in growing-finishing pigs compared with typical cereal grain-soybean meal based diets.

Only one study has been reported relative to feeding crude glycerin to lactating sows. In that study, lactating sows fed diets containing up to 9% crude glycerin performed similar to sows fed a standard corn-soybean meal diet (Schieck et al., 2010a).

4. Crude glycerin as a feed ingredient for poultry

Several researchers have reported that glycerin is an acceptable feed ingredient for poultry (Campbell and Hill, 1962; Brambilla and Hill, 1966; Lin et al., 1976; Lessard et al., 1993; Simon et al., 1996, 1997; Cerrate et al., 2006; Swiatkiewicz and Koreleski, 2009; Min et al., 2010). Adding glycerin up to 5% of the diet had no adverse effects on growth performance or carcass yield in broilers (Lessard et al., 1993; Simon et al., 1996; Cerrate et al., 2006). Increasing dietary glycerin above 10%, however, can adversely affect growth performance and meat yield of broiler chickens (Simon et al., 1996; Cerrate et al., 2006), although this may be due to reduced flowability of feed observed when 10% glycerin was supplemented (Cerrate et al., 2006).

Although designed as an energy balance trial, Lammers et al. (2008a) reported no impact on egg production of layer chickens during the 8-day experiment. In an extensive study with laying hens, Swiatkiewica and Koreleski (2009) reported no effects of feeding up to 6% dietary crude glycerin on laying performance or egg quality parameters. In turkeys, Rosebrough et al. (1980) found no adverse effects on egg production, egg weight, or feed utilization in hens fed a pure source of glycerin as an energy source over a 16-wk period. In conclusion, there appears to be no consistent (positive or negative) impact of feeding up to 10% crude glycerin on growth performance in growing broilers (Table 6), or in laying hens.

Glycerin equivalency[2]	Gain	Feed intake	Gain:feed ratio
Campbell and Hill, 1962 / Semipurified ingredients / 1-28 days of age			
20.0	99	103	97
Brambila and Hill, 1966 / Semipurified ingredients / 1-28 days of age			
3.0	111	-	-
Lin et al., 1976 / Semipurified ingredients/ 1-21 days of age			
20.3	98	105	93
42.1	56	60	79
Simon et al., 1996 / Corn-slybean meal-fish meal / 1-31 days of age			
5.0	103	103	99
10.0	104	104	100
15.0	97	103	95
20.0	89	100	89
25.0	75	75	79
Simon et al., 1997 / Corn-soybean meal / 1-23 days of age			
10.0[3]	109	108	101
Cerrate et al., 2006 / Corn-soybean meal-poultry meal / 1-42 days of age			
2.0[4]	104	103	99
4.0[4]	103	103	99
Cerrate et al., 2006 / Corn-soybean meal-poultry meal / 1-42 days of age			
4.0[4]	100	99	101
8.0[4]	94	97	97

[1] Percentage relative to broilers fed the diet containing no supplemental glycerin. Percentage difference does not necessarily mean there was a significant difference from broilers fed the diet containing no supplemental glycerin. Main dietary ingredients and age of broilers tested are also provided with each citation.
[2] Represents a 100% glycerin basis. In studies utilizing crude glycerin, values adjusted for purity of glycerin utilized.
[3] Average of chicks fed the 15% and 18% crude protein diets with amino acid supplementation only.
[4] An assumed purity of 80%.

Table 6. Relative performance of broilers fed supplemental glycerin[1]

5. Special considerations

Biodiesel can be produced from a variety of feedstocks, such as oils from soy, canola, and corn, waste cooking oils, and animal fats (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006). Consequently, the composition of crude glycerin can vary, but typically ranges from: 78 to 85% glycerin, 8 to 15% water, 2 to 10% salt (NaCl or KCl), 0.5% free fatty acids (although non-acidulated co-products may be up to 35% FFA), and ≤ 0.5% methanol (Table 3). In addition to the variation in energy content, the amount of salt and methanol in crude glycerin may require modifications in diet formulation. Depending on the salt level in the crude glycerin, supplemental levels of dietary salt may need to be limited depending upon the species being fed. However, data suggests that in swine and poultry, up to 3% dietary NaCl will have no adverse effects on animal performance as long as adequate water is freely available (adapted from NRC, 1980), although the impact of increased water intake on increased manure volume and composition (Sutton et al., 1976) or wet litter (Hogge et al., 1999) needs to be considered.

Utilization of crude glycerin may also affect the ability of feed to flow in bulk bins and automatic feeding systems as suggested by Cerrate et al. (2006) and Hansen et al. (2009). We also noted that 10 and 20% glycerin levels seemed to affect feed flow (Lammers et al. 2008b; Kerr et al., 2009), especially in feeds containing dried whey. No scientific measures were taken in any of the above experiments; so, the potential interactions among the level of glycerin supplementation, diet type, and feed handling system flowability of feed are yet to be characterized. Such information will allow establishment of practical limits for crude glycerin supplementation.

Methanol levels in crude glycerin warrant special consideration. Methanol is a potentially toxic compound and has been reviewed in detail by others (Roe, 1982; Medinsky and Dorman, 1995; Skrzydlewska, 2003). Methanol can be introduced orally, by respiration, or through the skin, and is distributed by the blood to all organs and tissues in proportion to their water content (Liesivuori and Savolainen, 1991). Metabolic elimination of methanol is much slower than that of ethanol, and its metabolism is illustrated in Figure 2 (adapted from Skrzydlewska, 2003).

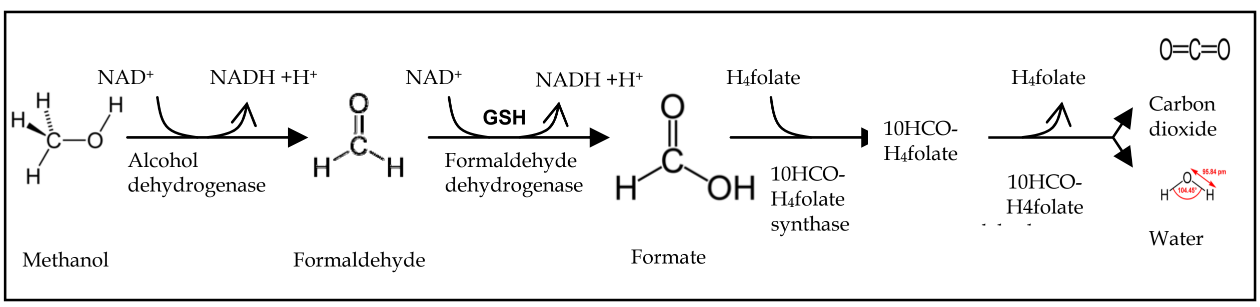

Fig. 2. Methanol Metabolism

Small amounts of methanol are excreted in the kidney and lung, but the majority is metabolized by the liver and released as CO_2. Acute methanol intoxication is manifested initially by signs of narcosis followed by a latent period in which formic acid accumulates causing metabolic acidosis (reduced blood pH, depletion of blood bicarbonate, visual degeneration, and abdominal, leg, and back pain). Chronic exposure to methanol causes headache, insomnia, gastrointestinal problems, and blindness. Animals differ widely in their ability to metabolize methanol depending upon enzyme activity and hepatic folate levels (Roe, 1982; Black et al., 1985; Medinsky and Dorman, 1995; Skrzydlewska, 2003). Little research on methanol metabolism or toxicity has been conducted in pigs. Makar et al. (1990) reported that the pig, compared to all other species studies, has extremely low levels of folates and very low levels of a key enzyme in the folate pathway, 10-formyl H_4folate dehydrogenase, suggesting the ability of the pig to dispose of formate is limited, and slower than that observed in rats or monkeys. However, Dorman et al. (1993) indicated that methanol- and formate-dosed minipigs did not develop optic nerve lesions, toxicologically significant formate accumulation, or metabolic acidosis, indicating that female minipigs do not appear to be overtly sensitive to methanol toxicity.

When considering the potential for methanol and formate toxicity, it is interesting to note that in some countries, formaldehyde, a methanol metabolite, can be used as a silage preservative, and formic acid can be used in finished feeds to reduce bacterial loads. Formic acid or formate salts have also been used safely in diets for swine (Overland et al., 2000; Canibe et al., 2005) and formaldehyde in diets for laying hens (Khan et al., 2006). It is also interesting to note that calcium formate has been used as a dietary calcium supplement for humans (Hanzlik et al., 2005).

As a general purpose feed ingredient, glycerin is regulated in the U.S. under 21CFR583.1320 requiring that levels of methanol in methyl esters of higher fatty acids should not exceed 0.015%. Recently, however, crude glycerin has been defined by the Association of American Feed Control Officials (AAFCO, 2010) and can be fed to non-ruminants up to 10% of the complete feed as long as it contains not less than 80% glycerin, not more than 15% water, not more than 0.15% methanol, up to 8% salt, up to 0.1% sulfur, and not more than 5 ppm heavy metals. German regulations (Normenkommission fur Einzelfuttermittel im Zentralausschuss der Deutschen Landwirtschaf, 2006) allow 0.5% (5,000 ppm) methanol in crude glycerin.

6. Conclusions

With a ME value of crude glycerin (adjusted to 85% glycerin) approximating 3,200 kcal/kg in swine and 3,600 kcal/kg in poultry (depending upon source), crude glycerin is an excellent source of calories in diets for non-ruminants. In general, feeding levels of up to 10% crude glycerin appear to have no consistent, positive or negative, effects on growth performance, carcass composition, lactation performance, or egg or meat quality. Levels of sodium- or potassium chloride, however, must be monitored to make formulation adjustments to supplemental salt additions, if necessary, to avoid increased manure volume for swine and wet litter for poultry. Concentrations of methanol in crude glycerin need to be monitored closely to ensure pig and poultry producers are in compliance with governmental regulations for feeding crude glycerin. Lastly, effects on feed handling and manufacturing characteristics need to be considered when determining inclusion rates of crude glycerin in practical diets for swine and poultry because of reduced feed flowability at high dietary inclusion rates.

7. References

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