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Digestibility and retention of zinc, copper, manganese, iron, calcium, and phosphorus in pigs fed diets containing inorganic or organic minerals[1]

Y. Liu,* Y. L. Ma,† J. M. Zhao,† M. Vazquez-Añón,† and H. H. Stein*[2]

*Department of Animal Sciences, University of Illinois, Urbana 61801; and †Novus International Inc., St. Charles, MO 63304

ABSTRACT: The objective of this experiment was to measure the apparent total tract digestibility (ATTD) and the retention rate of Zn, Cu, Mn, and Fe in pigs fed either inorganic or organic sources of Zn, Cu, Mn, and Fe. The experimental design was a randomized complete block design with a 2 × 3 factorial arrangement of treatments. There were 2 types of diets (corn grits-based or corn–soybean meal [SBM]-based diets) and 3 micromineral treatments (basal micromineral premix [BMM], inorganic micromineral premix [IMM], and organic micromineral premix [OMM]). The BMM contained no added Zn, Cu, Mn, or Fe; the IMM microminerals were provided as sulfates of Zn, Cu, Mn, and Fe at 40, 50, 20, and 100 mg/kg, respectively. The OMM contained the same levels of the 4 microminerals as IMM, but Zn, Cu, Mn, and Fe in this premix were provided by Zn(2-hydroxy-4-methylthio butanoic acid [HMTBa])$_2$, Cu(HMTBa)$_2$, Mn(HMTBa)$_2$, and FeGly, respectively. Forty-eight barrows (initial BW: 31.1 ± 4.2 kg) were housed individually and allowed ad libitum access to the corn grits diet with BMM for 2 wk. All pigs were then moved to metabolism cages and randomly assigned to 1 of the 6 treatment diets with 8 replicates per diet. Fecal and urine samples were collected for 5 d following a 5-d adaptation period. Compared with corn grits diets, pigs fed corn–SBM diets had greater ($P < 0.05$) absorption and retention of Zn, Cu, and Mn but less ($P < 0.05$) ATTD of Zn and Cu. Compared with BMM, supplementation of IMM or OMM increased ($P < 0.05$) absorption, retention, ATTD, and retention rate of Zn, Cu, Mn, and Fe. Compared with IMM, adding OMM to the corn–SBM diet improved ($P < 0.05$) the absorption and retention of Cu and Mn and the ATTD of Cu, but these differences were not observed in the corn grits diets (interaction, $P < 0.05$). In addition, adding OMM to the corn–SBM diet increased ($P < 0.05$) absorption and retention of Zn and Fe and ATTD of Zn, Mn, and Fe compared with adding IMM to the corn–SBM diet. Supplementation of OMM also increased ($P < 0.05$) the ATTD and retention rate of P in corn–SBM diets. Results indicate that Zn(HMTBa)$_2$ has greater digestibility and Cu(HMTBa)$_2$ and Mn(HMTBa)$_2$ have greater digestibility and retention rates compared with their inorganic sulfates, if included in a corn–SBM diet. Supplementation of organic microminerals also improves the digestibility of P in a corn–SBM diet.

Key words: apparent total tract digestibility, inorganic microminerals, organic microminerals, pigs, retention

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INTRODUCTION

Supplementation of microminerals to swine diets in concentrations at the requirements is crucial for animal growth, reproduction, and immune system development and as a defense against oxidative stress and cell damage (Underwood and Suttle, 1999; NRC, 2012). However, supplemented levels often exceed requirements, which results in elevated excretions of minerals (Carlson et al., 1999; Hill et al., 2000). Therefore, diets formulated with concentrations of microminerals that meet, but not exceed, requirements may result in reduced mineral excretion from pigs and more economical feeding strategies.

Use of organic instead of inorganic microminerals may also reduce excretion of minerals from pigs (Veum et al., 2004; Burkett et al., 2009; Jolliff and Mahan, 2012). Usually, Zn, Cu, Mn, and Fe are included in pig diets using inorganic salts such as oxides or sulfates. However, one theory is that the low gastric pH may induce dissociation of micromineral salts, resulting in formation of antagonisms among microminerals or between microminerals

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[2]Corresponding author: hstein@illinois.edu
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and phytic acid, which may impair mineral absorption and bioavailability (Henderson et al., 1995; Sandström, 2001; Richards et al., 2010). Organic microminerals may, therefore, be more bioavailable than inorganic minerals when fed to pigs or poultry (Yu et al., 2000; Leeson, 2003; Creech et al., 2004). However, the apparent total tract digestibility (**ATTD**) and retention rates of inorganic versus organic microminerals have not been evaluated when they were fed to growing pigs at the same concentrations.

Therefore, the objective of this experiment was to test the hypothesis that organic microminerals (2-hydroxy-4-methylthio butanoic acid [**HMTBa**] or Gly forms) have greater ATTD and retention rates than inorganic microminerals (sulfate form) when added to diets fed to growing pigs. The second objective was to test the hypothesis that microminerals have less ATTD if added to traditional corn–soybean meal (**SBM**) diets than to low-phytate corn grits diets.

MATERIALS AND METHODS

General

The Institutional Animal Care and Use Committee at the University of Illinois at Urbana-Champaign reviewed and approved the protocol for this experiment. Pigs used in this experiment were the offspring of G-Performer boars that were mated to Fertilis 25 females (Genetiporc Inc., Alexandria, MN).

The basal micromineral premix (**BMM**), the inorganic micromineral premix (**IMM**), and the organic micromineral premix (**OMM**) were provided by Novus International, Inc. (St. Charles, MO). The BMM included at 0.15% in the diets provided 0.3 mg of Na_2SeO_3 and 0.27 mg of $Ca(IO_3)_2$ per kilogram of complete diet (Table 1). The IMM included at 0.15% in the diets provided 40 mg of Zn as $ZnSO_4 \cdot 7H_2O$, 50 mg of Cu as $CuSO_4 \cdot 5H_2O$, 20 mg of Mn as $MnSO_4 \cdot H_2O$, 100 mg of Fe as $FeSO_4 \cdot H_2O$, 0.3 mg of Na_2SeO_3, and 0.27 mg of $Ca(IO_3)_2$ per kilogram of complete diet. The OMM included at 0.15% in the diets provided 40 mg of Zn as $Zn(HMTBa)_2$, 50 mg of Cu as $Cu(HMTBa)_2$, 20 mg of Mn as $Mn(HMTBa)_2$, 100 mg of Fe as FeGly, 0.3 mg of Na_2SeO_3, and 0.27 mg of $Ca(IO_3)_2$ per kilogram of complete diet. The $Zn(HMTBa)_2$, $Cu(HMTBa)_2$, and $Mn(HMTBa)_2$ are chelates of 1 molecule of mineral and 2 molecules of 2-hydroxy-4(methylthio) butanoic acid (MINTREX), and FeGly is a chelate of 1 molecule of Fe and 1 molecule of Gly (MAAC). All the organic microminerals were manufactured by Novus International, Inc. (St. Charles, MO). Copper sulfate ($CuSO_4 \cdot 5H_2O$) was produced by Pestell Mineral and Ingredients (New Hamburg, ON, Canada) with 149 to 420 μm particle size and over 98% purity, and manganese sulfate ($MnSO_4 \cdot H_2O$) was produced by Erachem (Veracruz, Mexico). Zinc sulfate ($ZnSO_4 \cdot 7H_2O$) was produced by Tetra Micronutrients, Inc. (Fairbury, NE) with 2 to 4 mm particle size and 99% purity whereas ferrous sulfate ($FeSO_4 \cdot H_2O$) was produced by QC Corporation (Baltimore, MD) with 149 μm to 1.19 mm particle size and minimal 30% iron. All the sulfate microminerals were feed grade.

Table 1. Concentration (g/kg) of minerals in basal micromineral premix (BMM), inorganic micromineral premix (IMM), and organic micromineral premix (OMM)[1]

Item[2]	BMM	IMM	OMM
$ZnSO_4 \cdot 7H_2O$	0	75	0
$Zn(HMTBa)_2$	0	0	148
$CuSO_4 \cdot 5H_2O$	0	132	0
$Cu(HMTBa)_2$	0	0	185
$MnSO_4 \cdot H_2O$	0	42	0
$Mn(HMTBa)_2$	0	0	89
$FeSO_4 \cdot H_2O$	0	222	0
FeGly	0	0	417
Na_2SeO_3	20	20	20
$Ca(IO_3)_2$	0.28	0.28	0.28

[1]All values were calculated. All mineral premixes were provided by Novus International, Inc., St. Charles, MO. All organic microminerals were manufactured by Novus International, Inc. Copper sulfate ($CuSO_4 \cdot 5H_2O$) was produced by Pestell Mineral & Ingredients (New Hamburg, ON, Canada). Manganese sulfate ($MnSO_4 \cdot H_2O$) was produced by Erachem (Veracruz, Mexico). Zinc sulfate ($ZnSO_4 \cdot 7H_2O$) was produced by Tetra Micronutrients, Inc. (Fairbury, NE). Ferrous sulfate ($FeSO_4 \cdot H_2O$) was produced by QC Corporation (Baltimore, MD). All sulfate microminerals were feed grade.

[2]HMTBa = 2-hydroxy-4-methylthio butanoic acid. The $Zn(HMTBa)_2$, $Cu(HMTBa)_2$, and $Mn(HMTBa)_2$ are chelates of 1 molecule of mineral and 2 molecules of HMTBa (MINTREX; Novus International) and FeGly is a chelate of 1 molecule of Fe and 1 molecule of glycine (MAAC; Novus International). The molecular weight of $Zn(HMTBa)_2$, $Cu(HMTBa)_2$, $Mn(HMTBa)_2$, and FeGly are 366, 364, 355, and 131 g/mol, respectively.

Experimental Design and Diets

The experimental design was a randomized complete block design with a 2 × 3 factorial arrangement of treatments. There were 2 types of diets (corn grits-based diets and corn–SBM diets) and 3 micromineral treatments (no added Zn, Cu, Mn, or Fe [BMM]; inorganic Zn, Cu, Mn, and Fe [IMM]; and organic Zn, Cu, Mn, and Fe [OMM]). A total of 48 barrows were used in this experiment and divided into 2 groups with 24 pigs in each group. Four pigs were fed each treatment diet in each group, and therefore, a total of 8 replicate pigs were fed each diet. Six diets were formulated (Table 2). The 3 corn grits diets were based on corn grits, soy protein, sorghum, and corn oil, and the remaining 3 diets were based on corn and SBM. Within each type of diet, 1 diet contained the BMM that did not contain added Zn, Cu, Mn, or Fe; 1 diet contained the IMM that contained Zn, Cu, Mn, and Fe from inorganic sources; and the last diet contained the OMM that

Table 2. Composition of the corn grits diet and the corn–soybean meal diet, as-fed basis[1]

Item	Corn grits diet	Corn–soybean meal diet
Ingredient, %		
Corn	–	74.93
Soybean meal	–	22.63
Corn grits	64.37	–
Soy protein concentrate	10.00	–
Sorghum	20.00	–
Corn oil	2.60	–
Dicalcium phosphate	0.78	0.82
Limestone	0.95	0.89
Salt	0.40	0.40
L-Lys HCl	0.50	0.08
MHA[2]	0.09	–
L-Thr	0.05	–
L-Trp	0.01	–
Micromineral premix[3]	0.15	0.15
Vitamin premix[4]	0.10	0.10
Calculated nutrient composition		
ME, kcal/kg	3,331	3,331
SID[5] Lys, %	0.83	0.83
SID Met + Cys, %	0.49	0.52
SID Thr, %	0.53	0.54
SID Trp, %	0.15	0.17

[1]Six diets were formulated by adding the basal micromineral premix (BMM), the inorganic micromineral premix (IMM), or the organic micromineral premix (OMM) to the corn grits diet and the corn–soybean meal diet.

[2]MHA is a methionine source from Novus International, Inc., St. Charles, MO.

[3]All minerals were provided by Novus International, Inc., St. Charles, MO. The BMM did not contain Zn, Cu, Mn, or Fe; the IMM provided the following quantities of microminerals per kilogram of complete diet: 40 mg of Zn as $ZnSO_4 \cdot 7H_2O$, 50 mg of Cu as $CuSO_4 \cdot 5H_2O$, 20 mg of Mn as $MnSO_4 \cdot H_2O$, and 100 mg of Fe as $FeSO_4 \cdot H_2O$; and the OMM provided the following quantities of microminerals per kilogram of complete diet: 40 mg of Zn as Zn(2-hydroxy-4-methylthio butanoic acid [HMTBa])$_2$, 50 mg of Cu as Cu(HMTBa)$_2$, 20 mg of Mn as Mn(HMTBa)$_2$, and 100 mg of Fe as FeGly.

[4]Provided the following quantities of vitamins per kilogram of complete diet: 2,273 μg of vitamin A as retinyl acetate, 17 μg of vitamin D_3 as cholecalciferol, 88 mg of vitamin E as DL-α-tocopheryl acetate, 4 mg of menadione from menadione sodium bisulfite complex, 33 mg of niacin, 24 mg of D-pantothenic acid as D-calcium pantothenate, 9 mg of riboflavin, 35 μg of vitamin B_{12}, and 324 mg of choline chloride.

[5]SID = standardized ileal digestible.

was fortified with organic sources of Zn, Cu, Mn, and Fe. Vitamins and all minerals other than Zn, Cu, Mn, and Fe were included in the diets according to current requirements (NRC, 2012), and the same levels of vitamins and minerals other than Zn, Cu, Mn, and Fe were used in all diets. Diet samples were collected for chemical analysis when they were prepared.

Housing, Feeding, and Sampling Collection

During a 2-wk depletion period, all pigs (initial BW: 31.1 ± 4.2 kg) were housed individually in 0.9 by 1.8 m pens that had fully slatted concrete floors, a stainless steel feeder, and a stainless steel bowl-type drinker. All pigs were fed the corn grits diet containing BMM during this period. Pigs were then transferred to metabolism cages and randomly allotted to the 6 experimental diets. The average weight of the pigs at the time of transfer was 40.2 ± 6.2 kg. The stainless steel metabolism cages were equipped with a fully perforated floor, a screen floor for fecal collection, and a stainless steel tray for urine collection. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy (i.e., 106 kcal ME per $kg^{0.75}$; NRC, 1998) and divided into 2 equal meals. Water was provided by a bowl-type drinker and available at all times. Experimental diets were provided for 12 d. The initial 5 d was considered an adaptation period to the diet. Fecal markers were fed on d 6 and on d 11 and fecal collections were initiated when the first marker appeared in the feces and ceased when the second marker appeared (Adeola, 2001). Urine was collected from d 6 to 11 in urine buckets over a preservative of 50 mL of 6 *N* HCl. Buckets were covered by gauze to prevent solids from contaminating the urine. Fecal samples and 20% of the collected urine were stored at –20°C immediately after collection.

Sample Analysis and Data Processing

Pigs remained healthy throughout the experiment, and the average BW was 47.5 ± 6.2 kg at the conclusion of the experiment. Urine samples were thawed and mixed within animal, and a 200-mL subsample was collected for chemical analysis. All collected fecal samples were dried at 65°C in a forced-air drying oven and finely ground through a 1-mm screen in a Wiley Mill (Model 4; Thomas Scientific, Swedesboro, NJ) before analysis, and urine samples were filtered before analysis. Diet and fecal samples were analyzed in duplicate for DM by oven drying at 135°C for 2 h (method 930.05; AOAC, 2007). Diets were analyzed in duplicate for ash (method 942.05; AOAC, 2007), CP (method 990.03; AOAC, 2007), and crude fiber (method 978.10; AOAC, 2007). Acid hydrolyzed ether extract in diets was determined by acid hydrolysis using 3 *N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06; AOAC, 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diets were also analyzed in duplicate for phytic acid (Ellis and Morris, 1983), and the concentration of phytate P in each diet was calculated as 28.2% of phytate (Sauvant et al., 2004), and nonphytate P was calculated as the difference between the concentration of total P and phytate P. Diet, fecal, and urine samples were analyzed in duplicate for Fe (method 937.03; AOAC, 2007) and for Zn, Cu, Mn, Ca, and P by inductively coupled plasma optical emissions spectrometry using an internally validated method

(method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation (method 975.03 B(b); AOAC, 2007). Water was collected and also analyzed in duplicate for Zn, Cu, Mn, and Fe. Standard reference material Tomato Leaves (Standard Reference Material [**SRM**] number 1573a; National Institute of Standards and Technology, Gaithersburg, MD) and Industrial Sludge (SRM number 2782; National Institute of Standards and Technology) were used as reference standards to validate micromineral analyses. The inductively coupled plasma calibration standard (ICM-103; Ultra Scientific Analytical Solutions, Kingstown, RI) was diluted with 5% nitric acid and used as calibration curves and PlasmaCAL (QC 19; Qmx Laboratories, Thaxted, UK) was included for every 20 samples to serve as quality control standards.

The ATTD (%) of DM, Zn, Cu, Mn, Fe, Ca, and P in each diet were calculated according to the following equation (Almeida and Stein, 2010):

$$\text{ATTD} = [(\text{intake} - \text{output})/\text{intake}] \times 100.$$

The retention (%) of Zn, Cu, Mn, Fe, Ca, and P were calculated using the following equation (Almeida and Stein, 2010):

$$\text{Retention} = [\text{intake} - (\text{fecal excretion} + \text{urine excretion})/\text{intake}] \times 100.$$

Normality of data was verified and outliers were identified using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC); outliers were identified as values that deviated from the treatment mean by more than 3 times the interquartile range. Data were analyzed by ANOVA using Proc Mixed of SAS (SAS Stat. Inc., Cary, NC) as a randomized complete block design with the pig as the experimental unit. The statistical model included type of diet, source of microminerals, and their interaction as fixed effects and group as random effect. Treatment means were calculated using the LSMEANS statement and means were separated using the PDIFF option of PROC MIXED. Significance and tendency were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

RESULTS

The concentrations of Zn, Cu, Mn, and Fe in the BMM corn grits diet were 10.23, 3.88, 10.55, and 97 mg/kg, whereas the concentrations of Zn, Cu, Mn, and Fe in the BMM corn–SBM diet were 19.84, 4.21, 12.73, and 103 mg/kg, respectively (Table 3). The IMM and OMM diets contained 44.34 to 60.24 mg/kg of Zn, 59.89 to 64.31 mg/kg of Cu, 27.77 to 32.77 mg/kg of Mn, and 187 to 207 mg/kg of Fe, respectively. The Ca concentrations in the 3 corn grits diets were 0.55 to 0.56%, compared with 0.61% in the 3 corn–SBM diets. The 3 corn grits diets contained 0.41 to 0.48% phytic acid and 0.52 to 0.56% crude fiber, and the 3 corn–SBM diets contained 0.79 to 0.87% phytic acid and 1.92 to 2.07% crude fiber. The concentration of Cu was undetectable in drinking water, whereas the concentration of Zn, Mn, and Fe was 0.4 mg/kg in the water (data not shown).

Table 3. Chemical composition of experimental diets[1]

	Corn grits diets			Corn–soybean meal diets		
Item	BMM[2]	IMM[3]	OMM[4]	BMM	IMM	OMM
DM, %	91.69	91.25	91.52	89.84	90.01	90.04
Ash, %	2.21	2.16	2.52	3.93	3.97	3.97
CP, %	12.64	13.26	14.17	16.47	16.16	16.20
AEE,[5] %	2.95	2.86	3.31	2.76	2.60	2.57
Crude fiber, %	0.53	0.56	0.52	2.07	1.92	1.98
Zn, mg/kg	10.23	44.34	51.15	19.84	56.60	60.24
Cu, mg/kg	3.88	59.89	60.06	4.21	62.87	64.31
Mn, mg/kg	10.55	27.77	28.47	12.73	32.23	32.77
Fe, mg/kg	97	187	197	103	201	207
Ca, %	0.55	0.56	0.55	0.61	0.61	0.61
Total P, %	0.35	0.35	0.35	0.49	0.49	0.49
Phytic acid, %	0.48	0.41	0.43	0.87	0.81	0.79
Phytate P, %	0.14	0.12	0.12	0.25	0.23	0.22
Nonphytate P, %	0.21	0.23	0.23	0.24	0.26	0.27

[1]All values were analyzed except phytate P, which was calculated as 28.2% of phytic acid (Tran and Sauvant, 2004), and nonphytate P, which was calculated as the difference between phytate P and total P.

[2]BMM = basal micromineral premix (without supplementation of Zn, Cu, Mn, or Fe).

[3]IMM = inorganic micromineral premix (with supplemented Zn, Cu, Mn, and Fe as sulfate salts).

[4]OMM = organic micromineral premix (with supplemented Zn(2-hydroxy-4-methylthio butanoic acid [HMTBa])$_2$, Cu(HMTBa)$_2$, Mn(HMTBa)$_2$, and FeGly).

[5]AEE = acid hydrolyzed ether extract.

Compared with pigs fed corn grits diets, pigs fed corn–SBM diets had greater (diet, $P < 0.05$) fecal excretion, but less (diet, $P < 0.05$) ATTD of DM (Table 4). However, there was no effect of source of microminerals on fecal excretion or ATTD of DM and no interactions between source of minerals and type of diets were observed.

Compared with corn grits diets, pigs fed corn–SBM diets had greater (diet, $P < 0.05$) fecal excretion of Zn, Cu, Mn, and Fe and greater (diet, $P < 0.05$) absorption and retention of Zn, Cu, and Mn, but less (diet, $P < 0.05$) ATTD of Zn and Cu. Compared with corn grits diets, pigs fed corn–SBM diets had greater (diet, $P < 0.05$) retention:absorption ratio of Mn. Compared with BMM, supplementation with OMM or IMM increased (mineral, $P < 0.05$) absorption, retention, ATTD, and retention rate of Zn, Cu, Mn, and Fe and increased (mineral, $P < 0.05$) retention:absorption ratio of Zn and Cu. Compared with IMM diets, pigs fed OMM diets had greater (mineral, $P < 0.05$) absorption, retention, and ATTD of Zn, Cu, Mn and absorption and retention of Fe. Interactions be-

Table 4. Retention and digestibility of Zn, Cu, Mn, and Fe in pigs fed diets containing the basal micromineral premix (BMM), the inorganic micromineral premix (IMM), or the organic micromineral premix (OMM), DM basis

	Corn grits diets			Corn–soybean meal diets				*P*-value		
Item	BMM	IMM	OMM	BMM	IMM	OMM	SEM	Diet	Mineral	Diet × mineral
DM intake, g/d	1,210	1,220	1,185	1,319	1,287	1,298				
Fecal output, g/d DM	48.95^{c}	51.59^{c}	53.71^{c}	132.46^{a}	123.56^{ab}	115.93^{b}	11.09	<0.01	0.500	0.113
Urinary output, kg/d	4.94	4.86	4.77	5.10	4.29	4.92	0.85	0.862	0.745	0.775
ATTD[1] of DM, %	96.00^{a}	95.76^{a}	95.51^{a}	89.98^{c}	90.39^{bc}	91.13^{b}	0.35	<0.01	0.598	0.062
Zn										
Intake, mg/d	13.55	59.27	66.63	29.28	81.63	87.53				
Fecal excretion, mg/d	7.67^{d}	26.44^{b}	28.23^{b}	19.15^{c}	45.37^{a}	41.03^{a}	2.19	<0.01	<0.01	<0.01
Urinary excretion, mg/d	5.51	4.37	6.20	4.78	2.71	3.61	1.39	0.179	0.403	0.765
Absorption, mg/d	5.86^{d}	33.16^{c}	38.10^{b}	10.40^{d}	35.91^{bc}	46.58^{a}	1.62	<0.01	<0.01	0.217
Retention, mg/d	0.32^{c}	28.83^{b}	31.88^{b}	5.48^{c}	31.52^{b}	42.95^{a}	2.51	<0.01	<0.01	0.207
ATTD, %	43.60^{cd}	54.59^{ab}	58.95^{a}	33.93^{d}	45.11^{bc}	53.78^{a}	3.54	<0.05	<0.01	0.705
Retention:intake, %	3.57^{b}	46.91^{a}	50.25^{a}	18.30^{b}	39.16^{a}	49.20^{a}	7.37	0.763	<0.01	0.249
Retention:absorption, %	–5.78^{c}	86.11^{a}	82.76^{ab}	31.15^{bc}	92.34^{a}	92.05^{a}	18.99	0.250	<0.01	0.646
Cu										
Intake, mg/d	5.12	80.67	78.37	6.21	90.54	93.19				
Fecal excretion, mg/d	2.62^{c}	45.96^{b}	43.85^{b}	4.24^{c}	58.26^{a}	46.43^{b}	3.39	<0.05	<0.05	0.073
Urinary excretion, mg/d	1.31^{c}	2.71^{ab}	2.91^{a}	1.50^{bc}	2.17^{abc}	2.42^{abc}	0.46	0.463	<0.05	0.685
Absorption, mg/d	2.50^{c}	34.71^{b}	34.52^{b}	1.97^{c}	32.28^{b}	46.76^{a}	2.38	<0.05	<0.01	<0.01
Retention, mg/d	–0.09^{c}	32.00^{b}	31.61^{b}	0.47^{c}	30.10^{b}	44.34^{a}	2.55	<0.05	<0.01	<0.01
ATTD, %	55.43^{a}	42.93^{bc}	44.61^{bc}	31.79^{d}	37.08^{cd}	50.46^{ab}	3.05	<0.01	<0.05	<0.01
Retention:intake, %	–1.56^{c}	38.58^{ab}	40.83^{a}	7.42^{bc}	33.14^{ab}	47.88^{a}	11.88	0.735	<0.01	0.767
Retention:absorption, %	–12.77^{b}	91.74^{a}	91.42^{a}	27.49^{b}	93.14^{a}	94.77^{a}	20.73	0.381	<0.01	0.577
Mn										
Intake, mg/d	13.96	37.32	37.10	18.77	46.48	47.51				
Fecal excretion, mg/d	10.22^{d}	23.14^{bc}	22.22^{c}	14.04^{d}	32.80^{a}	26.62^{b}	2.20	<0.01	<0.01	0.073
Urinary excretion, mg/d	0.57^{c}	1.44^{ab}	1.60^{a}	0.46^{c}	1.05^{ab}	1.28^{ab}	0.32	0.090	<0.01	0.751
Absorption, mg/d	3.75^{c}	14.18^{b}	14.88^{b}	4.73^{c}	13.68^{b}	20.89^{a}	1.06	<0.01	<0.01	<0.01
Retention, mg/d	3.17^{c}	12.74^{b}	13.28^{b}	4.27^{c}	12.63^{b}	19.61^{a}	0.90	<0.01	<0.01	<0.01
ATTD, %	27.28^{b}	37.80^{a}	40.79^{a}	25.29^{b}	29.50^{b}	44.31^{a}	3.22	0.389	<0.01	0.192
Retention:intake, %	23.37^{c}	34.12^{ab}	36.54^{ab}	22.84^{c}	27.22^{bc}	41.67^{a}	3.30	0.777	<0.01	0.203
Retention:absorption, %	82.18^{b}	89.64^{a}	89.38^{a}	91.70^{a}	92.41^{a}	93.90^{a}	3.11	<0.01	0.133	0.376
Fe										
Intake, mg/d	128.69	251.57	254.51	152.02	289.40	299.84				
Fecal excretion, mg/d	100.03^{c}	154.05^{b}	149.48^{b}	107.42^{c}	203.50^{a}	158.87^{b}	18.22	<0.05	<0.01	0.210
Urinary excretion, mg/d	6.29	5.19	4.08	3.58	6.41	5.69	1.15	0.963	0.672	0.135
Absorption, mg/d	27.39^{c}	97.52^{b}	105.03^{b}	44.38^{c}	85.90^{b}	140.96^{a}	11.48	0.133	<0.01	0.097
Retention, mg/d	21.28^{c}	92.33^{b}	100.96^{b}	39.89^{c}	79.49^{b}	135.27^{a}	11.77	0.155	<0.01	0.107
ATTD, %	20.64^{b}	38.57^{ab}	42.03^{a}	29.08^{ab}	30.16^{ab}	47.37^{a}	6.74	0.736	<0.05	0.386
Retention:intake, %	16.06^{c}	36.48^{ab}	40.41^{ab}	26.11^{bc}	28.00^{abc}	45.48^{a}	6.94	0.686	<0.01	0.362
Retention:absorption, %	88.29	93.54	95.83	90.45	95.80	95.80	3.95	0.883	0.156	0.707

$^{a–e}$Within a row, means followed by the same or no superscript letter are not different ($P > 0.05$).

[1]ATTD = apparent total tract digestibility.

tween type of diet and source of minerals were observed for the absorption and retention of Cu and Mn and the ATTD of Cu, because supplementation with OMM increased the absorption and retention of Cu and Mn and the ATTD of Cu compared with IMM in the corn–SBM diet, but not in the corn grits diet (interaction, $P < 0.05$).

Supplementation with OMM to the corn–SBM diet reduced ($P < 0.05$) fecal excretion of Cu, Mn, and Fe, but increased ($P < 0.05$) absorption, retention, and ATTD of Zn, Cu, Mn, and Fe. However, no differences were observed between IMM and OMM when they were added to the corn grits diet, except that OMM increased ($P < 0.05$) absorption of Zn compared with IMM.

Pigs fed corn–SBM diets had greater (diet, $P < 0.05$) fecal excretion, absorption, and retention of Ca and P, but less (diet, $P < 0.05$) ATTD of Ca and P compared with pigs fed corn grits diets (Table 5). Compared with BMM, feeding IMM or OMM reduced ($P < 0.05$) fecal

Table 5. Retention and digestibility of Ca and P in pigs fed diets containing the basal micromineral premix (BMM), the inorganic micromineral premix (IMM), or the organic micromineral premix (OMM), DM basis

	Corn grits diets			Corn–soybean meal diets			SEM	*P*-value		
Item	BMM	IMM	OMM	BMM	IMM	OMM		Diet	Mineral	Diet × mineral
Ca										
Intake, mg/d	7,293	7,470	7,202	9,083	8,842	8,904				
Fecal excretion, mg/d	2,655^{bc}	2,056^{cd}	1,865^{d}	3,929^{a}	3,250^{b}	2,916^{b}	413	<0.01	<0.01	0.879
Urinary excretion, mg/d	643^{a}	533^{abc}	582^{ab}	272^{c}	368^{bc}	337^{bc}	160	<0.01	0.995	0.539
Absorption, mg/d	4,638^{c}	5,415^{ab}	5,337^{ab}	5,154^{b}	5,592^{ab}	5,988^{a}	330	<0.05	<0.01	0.608
Retention, mg/d	3,995^{c}	4,882^{b}	4,754^{b}	4,883^{b}	5,223^{ab}	5,651^{a}	250	<0.01	<0.01	0.447
ATTD[1], %	64.50^{b}	72.53^{a}	74.34^{a}	56.80^{c}	63.22^{bc}	67.27^{ab}	3.03	<0.01	<0.01	0.909
Retention:intake, %	55.96^{b}	65.55^{a}	66.46^{a}	53.90^{b}	59.05^{ab}	63.47^{a}	4.06	0.097	<0.01	0.703
Retention:absorption, %	85.82^{b}	90.32^{ab}	89.63^{bc}	94.85^{a}	93.38^{ac}	94.27^{ac}	2.78	<0.01	0.571	0.204
P										
Intake, mg/d	4,625	4,666	4,564	7,234	7,046	7,076				
Fecal excretion, mg/d	1,860^{c}	1,559^{cd}	1,429^{d}	3,721^{a}	3,565^{a}	3,093^{b}	284	<0.01	<0.01	0.487
Urinary excretion, mg/d	91.7	91.4	108.7	117.0	89.0	125.1	37.7	0.368	0.326	0.725
Absorption, mg/d	2,765^{d}	3,108^{cd}	3,135^{c}	3,512^{b}	3,505^{b}	3,983^{a}	221	<0.01	<0.01	0.198
Retention, mg/d	2,674^{c}	3,016^{c}	3,027^{c}	3,395^{b}	3,417^{b}	3,858^{a}	193	<0.01	<0.05	0.229
ATTD, %	60.44^{b}	66.48^{a}	68.87^{a}	48.60^{c}	49.61^{c}	56.62^{b}	2.06	<0.01	<0.01	0.404
Retention:intake, %	58.55^{b}	64.56^{a}	66.53^{a}	47.01^{c}	48.34^{c}	54.89^{b}	2.34	<0.01	<0.01	0.448
Retention:absorption, %	96.66	97.10	96.57	96.68	97.46	96.92	0.99	0.570	0.454	0.934

$^{a–d}$Within a row, means followed by the same or no superscript letter are not different ($P > 0.05$).

[1]ATTD = apparent total tract digestibility.

Ca and P excretion, but increased (mineral, $P < 0.05$) absorption, retention, ATTD, and retention rate of Ca and P. Compared with IMM, feeding OMM increased (mineral, $P < 0.05$) ATTD and retention of P. Adding OMM to the corn–SBM diet reduced ($P < 0.05$) fecal P excretion, but increased ($P < 0.05$) absorption, retention, ATTD, and retention rate of P compared with addition of IMM to the corn–SBM diet, but that was not the case when OMM was added to the corn grits diets.

DISCUSSION

The BMM diets without micromineral supplementation contained much less Zn compared with the requirement of pigs (NRC, 2012). However, the analyzed concentrations of Cu, Fe, and Mn in all diets were equal to or greater than the requirement for growing pigs (4 mg/kg of Cu, 60 mg/kg of Fe, and 2 mg/kg of Mn; NRC, 2012). The concentrations of Cu and Mn in the IMM and OMM diets were greater than requirements (NRC, 2012), which enabled us to determine ATTD of these minerals. As a result, the ratios between Zn, Cu, Fe, and Mn were also different from requirement estimates, but reflect current industry usage of these minerals.

The improved absorption of Zn that was observed for $Zn(HMTBa)_2$ compared with $ZnSO_4$ resulted in increased ATTD of Zn in the pigs fed corn–SBM diets. These results are consistent with data by Burkett et al. (2009), who also reported a greater ATTD for Zn chelated with small peptides compared with ZnO and $ZnSO_4$. A possible reason for this observation is that $Zn(HMTBa)_2$ is more stable in the upper gastrointestinal tract, which may minimize the formation of the complex between Zn and phytic acid and allow $Zn(HMTBa)_2$ to be delivered to the absorptive cells in the jejunum and ileum and, therefore, increase Zn absorption (Leeson and Summers, 2001; Yi et al., 2007; Richards et al., 2010). The observation that no differences were observed in the absorption and ATTD of Zn between $Zn(HMTBa)_2$ and $ZnSO_4$ if pigs were fed the low-phytate corn grits diets further indicates that it may be the phytate in the corn–SBM diet that results in the reduced absorption of Zn from $ZnSO_4$.

The observation that supplementation with $Cu(HMTBa)_2$ to corn–SBM diets decreased fecal Cu excretion and increased Cu absorption, retention, and ATTD compared with supplementation with $CuSO_4$ is in agreement with results of previous studies (Creech et al., 2004; Veum et al., 2004; Huang et al., 2010). The increased ATTD of $Cu(HMTBa)_2$ compared with $CuSO_4$ is the main reason for the reduced fecal Cu concentration in pigs fed diets supplemented with $Cu(HMTBa)_2$. The fact that there was no difference in ATTD of Cu between organic and inorganic forms of Cu added to the corn grits diets indicates that if there is limited levels of phytic acid in the diet, Cu from $CuSO_4$ is as well digested as Cu from $Cu(HMTBa)_2$. The low pH in the stomach may result in low ATTD of Cu from $CuSO_4$ (Underwood and Suttle, 1999; Leeson and Summers, 2001; Suttle, 2010), and the current data indicate that this may also be the case for the Cu from $Cu(HMTBa)_2$. The likely reason for the reduced

ATTD of $CuSO_4$ in corn–SBM diets compared with $Cu(HMTBa)_2$ is that the phytic acid in the corn–SBM diet may have formed complexes with $CuSO_4$, which rendered this Cu unavailable for absorption (Leeson and Summers, 2001). The ATTD of Cu is increased by phytase supplementation, which further indicates the negative effect of phytic acid on the digestibility of Cu (Kies et al., 2005, 2006). However, using $Cu(HMTBa)_2$ instead of $CuSO_4$ may reduce the formation of phytate mineral complexes and, therefore, decrease fecal Cu excretion and increase Cu absorption and digestibility (Jolliff and Mahan, 2012). The present results support this hypothesis.

There is no perfect method to measure absorption and digestion of microminerals due to the complexity of endogenous micromineral excretion in animals. In the present experiment, the BMM diets contained Zn and Cu, which were close to or less than the requirement for growing pigs (NRC, 2012). Therefore, the negative retention:absorption of Zn and Cu observed in the corn grits diet without supplementation of Zn indicates that the BMM diet was Zn and Cu deficient and endogenous Zn and Cu may have been secreted into the intestinal tract via pancreatic juice, bile, or the transepithelial flux from mucosal cells (Hambridge et al., 1986).

The reduced fecal Mn excretion and greater absorption, retention, and ATTD of Mn for pigs fed the corn–SBM diet supplemented with $Mn(HMTBa)_2$ compared with pigs fed the corn–SBM diet supplemented with $MnSO_4$ are consistent with previous data (Creech et al., 2004). However, these differences were not observed in the corn grits diets, which indicates that the reason for the difference in ATTD of Mn in the corn–SBM diet may be that $MnSO_4$ binds more easily than $Mn(HMTBa)_2$ to phytic acid, which results in a reduced digestibility. Supplementation of $Mn(HMTBa)_2$ reduces the formation of complex between Mn and phytic acid and, therefore, reduces the negative effects of phytic acid on the ATTD of Mn (Kies et al., 2005, 2006).

Iron balance is generally maintained by regulation of absorption in the upper small intestine and most of the Fe in the feces represents unabsorbed dietary Fe (IOM, 2001). The reason pigs fed the diets containing FeGly had greater retention of Fe than pigs fed $FeSO_4$ is that FeGly is better digested and absorbed by the pigs compared with $FeSO_4$. These results are in close agreement with data from Burkett et al. (2009), who reported that fecal Fe excretion is reduced if pigs are fed peptide-chelated Fe compared with pigs fed $FeSO_4$. Iron glycinate also has a greater ATTD of Fe than Fe from $FeSO_4$ when fed to weanling pigs (Ettle et al., 2008). Iron from a Fe-AA complex has also improved absorption from the duodenum compared with $FeSO_4$ (Yu et al., 2000). As was the case with Cu and Mn, the difference between organic and inorganic microminerals was reduced when they were added to the corn grits diet compared with the corn–SBM diet, presumably because of the reduced levels of phytic acid in the corn grits diets. This observation indicates that supplementation of FeGly can reduce the formation of complexes between Fe and phytic acid and, therefore, alleviate the negative effects of phytic acid in the corn–SBM diets on ATTD and absorption of Fe. Copper is required for the efficient absorption of Fe (Reeves et al., 2005) and the observation that pigs fed the BMM corn grits diet had less ATTD and retention rate of Fe compared with pigs fed the IMM and OMM corn grits diets indicates that low level of Cu may reduce Fe absorption and digestibility.

The fact that the retention:absorption ratio was not different between organic and inorganic sources of Zn, Cu, Mn, and Fe indicates that the organic forms of the minerals that were used in this experiment are utilized after absorption with the same efficiency as inorganic forms of these minerals. The implication of this observation is that the increased retention that was observed for the organic minerals compared with the inorganic minerals is a result of increased digestibility of the organic minerals, whereas postabsorptive utilization is not different between the 2 sources. This also indicates that the forms the minerals are absorbed in most likely are the same regardless of the sources, which further indicates that HMTBa and Gly are separated from the minerals before absorption. The fact that the ATTD of the microminerals is not greater when intake is reduced clearly indicated that the concentration of the mineral in the intestinal tract does not significantly influence percent absorption and, therefore, also not influence percent excretion. This is true for all microminerals as well as for Ca and P.

The absorption, retention, and digestibility of Ca were not affected by organic or inorganic sources of microminerals, which indicate that the different forms of microminerals have no influence on Ca digestibility. However, the concentrations of microminerals in the diets may affect the retention and digestibility of Ca. In the present study, the ATTD of Ca in the corn–SBM diets supplemented with OMM or IMM were between 62 and 70%, which are in good agreement with values reported by Stein et al. (2008) and Almeida and Stein (2010), but the ATTD of Ca in the corn–SBM diet without micromineral supplementation was only 56.8%. The low levels of Cu and Zn in these diets may have impaired the efficiency of Ca absorption in the corn–SBM diet (Dove, 1995). Compared with corn–SBM diets, the increased Ca retention and ATTD in pigs fed corn grits diets also indicates that feeding low-phytic acid diets may increase the efficiency of Ca absorption, which agree with data from Spencer et al. (2000), Veum et al. (2001), and Bohlke et al. (2005).

The ATTD of P in the corn–SBM diets observed in this experiment is in agreement with published values

(Stein et al., 2008). The decreased fecal P excretion and increased P absorption and digestibility that was observed as OMM was added to the corn–SBM diet indicate that supplementation with OMM may improve the efficiency of P absorption. The likely reason for this observation is that OMM may reduce the formation of complexes between P and other minerals, such as Zn and Ca, and, therefore, increase P absorption in the small intestine. Another possible reason is that the HMTBa released from the organic minerals may increase phytate P utilization as reported by Liem et al. (2008), although the mechanism is not clear. Compared with corn–SBM diets, the increased ATTD of P in the corn grits diets is mainly due to the reduced level of phytic acid in these diets.

In conclusion, organic forms of microminerals ($Zn(HMTBa)_2$, $Cu(HMTBa)_2$, $Mn(HMTBa)_2$, and FeGly) have improved digestibility and retention rates compared with Zn, Cu, Mn, and Fe in the form of sulfate salts when fed to growing pigs. This is particularly true if these organic microminerals are added to corn–SBM diets. Supplementation of diets with these organic microminerals also increased the digestibility of P in the corn–SBM diet but not the digestibility of Ca. Adding $Zn(HMTBa)_2$, $Cu(HMTBa)_2$, $Mn(HMTBa)_2$, and FeGly to pig diets may reduce fecal excretion of these microminerals and P compared with pig fed diets containing inorganic minerals. Inclusion of these organic microminerals in high-phytate diets may be more beneficial than in low-phytate diets.

LITERATURE CITED

Adeola, O. 2001. Digestion and balance techniques in pigs. In: A. J. Lewis and L. L. Southern, editors, Swine nutrition. 2nd ed. CRC Press, Washington, DC. p. 903–916.

Almeida, F. N., and H. H. Stein. 2010. Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus. J. Anim. Sci. 88:2968–2977.

AOAC. 2007. Official methods of analysis. 18th ed. W. Hortwitz and G. W. Latimer Jr., ed. AOAC Int., Gaithersburg, MD.

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396–2403.

Burkett, J. L., K. J. Stalder, W. J. Powers, K. Bregendahl, J. L. Pierce, T. J. Baas, T. Bailey, and B. L. Shafer. 2009. Effect of inorganic and organic trace mineral supplementation on the performance, carcass characteristics, and fecal mineral excretion of phase-fed, grow-finish swine. Asian-Australas. J. Anim. Sci. 22:1279–1287.

Carlson, M. S., G. M. Hill, and J. E. Link. 1999. Early- and traditionally weaned nursery pigs benefit from phase-feeding pharmacological concentrations of zinc oxide: Effect on metallothionein and mineral concentrations. J. Anim. Sci. 77:1199–1207.

Creech, B. L., J. W. Spears, W. L. Flowers, G. M. Hill, K. E. Lloyd, T. A. Armstrong, and T. E. Engle. 2004. Effect of dietary trace mineral supplementation and source (inorganic vs. chelated) on performance, mineral status, and fecal mineral excretion in pigs from weaning through finishing. J. Anim. Sci. 82:2140–2147.

Dove, C. R. 1995. The effect of copper level on nutrient utilization of weanling pigs. J. Anim. Sci. 73:166–171.

Ellis, R., and E. R. Morris. 1983. Improved ion-exchange phytate method. Cereal Chem. 60:121–124.

Ettle, T., P. Schlegel, and F. X. Roth. 2008. Investigations on iron bioavailability of different sources and supply levels in piglets. J. Anim. Physiol. Anim. Nutr. (Berl.) 92:35–43.

Hambridge, K. M., C. E. Casey, and N. F. Krebs. 1986. Zinc. In: W. Mertz, editor, Trace elements in human and animal nutrition. Academic Press, New York. p. 1–138.

Henderson, L. M., G. J. Brewer, J. B. Dressman, S. Z. Swidan, D. J. DuRoss, C. H. Adair, J. L. Barnett, and R. R. Berardi. 1995. Effect of intragastric pH on the absorption of oral zinc acetate and zinc oxide in young healthy volunteers. JPEN J. Parenter. Enteral. Nutr. 19:393–397.

Hill, G. M., G. L. Cromwell, T. D. Crenshaw, C. R. Dove, R. C. Ewan, D. A. Knabe, A. J. Lewis, G. W. Libal, D. C. Mahan, G. C. Shurson, L. L. Southern, and T. L. Veum. 2000. Growth promotion effects and plasma changes from feeding high dietary concentrations of zinc and copper to weanling pigs (regional study). J. Anim. Sci. 78:1010–1016.

Huang, Y., J. S. Yoo, H. J. Kim, Y. Wang, Y. J. Chen, J. H. Cho, and I. H. Kim. 2010. The effects of different copper (inorganic and organic) and energy (tallow and glycerol) sources on growth performance, nutrient digestibility, and fecal excretion profiles in growing pigs. Asian-Australas. J. Anim. Sci. 23:573–579.

Institute of Medicine (IOM). 2001. Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc. National Academy Press, Washington, DC.

Jolliff, J. S., and D. C. Mahan. 2012. Effect of dietary inulin and phytase on mineral digestibility and tissue retention in weanling and growing swine. J. Anim. Sci. 90:3012–3022.

Kies, A. K., W. J. J. Gerrits, J. W. Schrama, M. J. W. Heetkamp, K. L. van der Linden, T. Zandstra, and M. W. A. Verstegen. 2005. Mineral absorption and excretion as affected by microbial phytase, and their effect on energy metabolism in young piglets. J. Nutr. 135:1131–1138.

Kies, A. K., P. A. Kemme, L. B. J. Sebek, J. Th. M. van Diepen, and A. W. Jongbloed. 2006. Effect of graded doses and a high dose of microbial phytase on the digestibility of various minerals in weaner pigs. J. Anim. Sci. 84:1169–1175.

Leeson, S. 2003. A new look at trace mineral nutrition of poultry: Can we reduce environmental burden of poultry manure? In: T. P. Lyons and K. A. Jacques, editors, Nutritional biotechnology in the feed and food industries. Nottingham Univ. Press, Nottingham, UK. p. 125–129.

Leeson, S., and J. D. Summers. 2001. Scott's nutrition of the chicken. 4th ed. University Books, Guelph, ON, Canada.

Liem, A., G. M. Pesti, and H. M. Edwards Jr. 2008. The effect of several organic acids on phytate phosphorus hydrolysis in broiler chicks. Poult. Sci. 87:689–693.

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

Reeves, P. G., L. C. S. DeMars, W. T. Johnson, and H. C. Lukaski. 2005. Dietary copper deficiency reduces iron absorption and duodenal enterocyte hephaestin protein in male and female rats. J. Nutr. 135:92–98.

Richards, J. D., J. Zhao, R. J. Harrell, C. A. Atwell, and J. J. Dibner. 2010. Trace mineral nutrition in poultry and swine. Asian-Australas. J. Anim. Sci. 23:1527–1534.

Sanderson, P. 1986. A new method of analysis of feedingstuffs for the determination of crude oils and fats. In: W. Haresign and O. J. A. Cole, editors, Recent advances in animal nutrition. Butterworths, London, UK. p. 77–81.

Sandström, B. 2001. Micronutrient interactions: Effects on absorption and bioavailability. Br. J. Nutr. 85:S181–S185.

Sauvant, D., J. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials. 2nd ed. Wageningen Academic Publishers, Wageningen, The Netherlands.

Spencer, J. D., G. L. Allee, and T. E. Sauber. 2000. Phosphorus bioavailability and digestibility of normal and genetically modified low-phytate corn for pigs. J. Anim. Sci. 78:675–681.

Stein, H. H., C. T. Kadzere, S. W. Kim, and P. S. Miller. 2008. Influence of dietary phosphorus concentration on the digestibility of phosphorus in monocalcium phosphate by growing pigs. J. Anim. Sci. 86:1861–1867.

Suttle, N. 2010. Mineral nutrition of livetock. 4th ed. CABI, Wallingford, Oxfordshire, OX, UK.

Tran, G., and D. Sauvant. 2004. Chemical data and nutritional value. In: Tables of composition and nutritional value of feed materials. 2nd ed. Wageningen Academic Publishers, Wageningen, The Netherlands. p. 17–24.

Underwood, E. J., and N. F. Suttle. 1999. The mineral nutrition of livestock. 3rd ed. CABI Publishing, New York.

Veum, T. L., M. S. Carlson, C. W. Wu, D. W. Bollinger, and M. R. Ellersieck. 2004. Copper proteinate in weanling pig diets for enhancing growth performance and reducing fecal copper excretion compared with copper sulfate. J. Anim. Sci. 82:1062–1070.

Veum, T. L., D. R. Ledoux, V. Raboy, and D. S. Ertl. 2001. Low-phytic acid corn improves nutrient utilization for growing pigs. J. Anim. Sci. 79:2873–2880.

Yi, G. F., C. A. Atwell, J. A. Hume, J. J. Dibner, C. D. Knight, and J. D. Richards. 2007. Determining the methionine activity of Mintrex organic trace minerals in broiler chickens by using radiolabel tracing or growth assay. Poult. Sci. 86:877–887.

Yu, B., W. Huang, and P. W. Chiou. 2000. Bioavailability of iron from amino acid complex in weanling pigs. Anim. Feed Sci. Technol. 86:39–52.