The effect of reduced levels of inorganic and organic trace mineral supplementation on performance, carcass traits, and fecal excretion of grow-finish swine

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The effect of reduced levels of inorganic and organic trace mineral supplementation on performance, carcass traits, and fecal excretion of grow-finish swine

by

Matthew Lee Wolfe

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Program of Study:
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CHAPTER 1. INTRODUCTION

Traditionally, diets fed to grow-finish swine have been formulated to contain trace minerals in excess of NRC requirements. High inclusion levels of inorganic trace minerals, such as sulfates, carbonates, and oxides, are considered inexpensive “safety margins”. These account for outdated nutrient requirements, and low absorption and retention of inorganic minerals. Moreover, safety margins are believed to ensure maximum performance and growth, even under stress situations. Maximizing performance has been the main goal for swine producers over the last several decades. Now, more discussion and emphasis is placed on minimizing environmental impact without sacrificing performance.

The environmental impact of swine production targeted by this study is the accumulation of trace minerals in the soil. The increased size and intensity of swine production units has triggered this concern. Copper and zinc are trace minerals that pose the biggest threat and that can accumulate in manure treated soils to levels toxic to plant growth (Barker, 1998). Trace minerals can also accumulate and cause toxicity to certain grazing species, such as sheep (Christie and Beattie, 1989). Pollution through ground water, soil erosion, and water runoff from land that has been repeatedly treated with manure poses a threat to aquatic organisms, including fish (Davis, 1974). For these reasons, the European Union has banned high inclusion levels of several trace minerals, including copper, iron, and zinc in swine diets. The new maximum levels are much lower than traditional inclusion rates. Swine producers in the United States should plan for and expect similar legislation in the future.

It appears the best solution to these concerns is diet modification. Formulating diets closer to a pig’s nutritional needs should minimize nutrient excretion. However, the
bioavailability of certain inorganic salts is still a concern. Kornegay and Harper (1997) proposed that as a percentage of intake, the amount of inorganic Cu, Fe, and Zn digested and retained by the finishing pig is 10 to 20, 5 to 35, and 10 to 20%, respectively. This, along with concerns of soil nutrient accumulation, has sparked an increase in organic trace mineral research (e.g. Bioplex® Products, Alltech Inc., Nicholasville, KY).

The bioavailability of organic or chelated minerals has been reported to be as much as 206% when compared to inorganic minerals in poultry (Wedekind et al., 1992). This is believed to be a result of increased absorption of the trace mineral in the small intestine. Inorganic trace minerals compete for ion transport pathways and are subject to hydroxy-polymerization in the small intestine, which reduces uptake. Organic trace minerals, which are bound to amino acids or proteinates, are more available for uptake for several reasons: 1) hydroxy-polymerization is prevented, allowing the metal to cross the mucus layer; 2) the positive charge of the metal is masked, which speeds its passage through the negatively charged mucus layer; and 3) the metal is protected and does not have to compete with unprotected metal ions for binding sites on mucins, which reduces antagonisms between copper and zinc, for instance (Power, 2006).

Experiments testing the efficacy of organic trace mineral supplementation in poultry have shown promising results (Leeson, 2003; Pierce et al., 2005). Leeson (2003) compared reduced levels of organic (Bioplex®) and inorganic trace mineral supplementation and found the chelated minerals to be at least 30% more bioavailable. Pierce et al. (2005) fed broilers inorganic and organic (Bioplex®) trace minerals at levels as low as 25% of NRC (1998) requirements. Decreases in gain and feed intake were reported in broilers fed decreasing amounts of inorganic trace minerals, but not in those fed organic forms.
Similar experiments have also been conducted in grow-finish swine (Creech et al., 2004; Burkett et al., 2006). Creech et al. (2004) compared reduced levels of organic and inorganic trace mineral (Cu, Fe, and Zn) supplementation in pigs fed from wean to finish. No differences were observed in average daily gain and a decrease in fecal Cu, Fe, and Zn was reported in pigs fed reduced levels of organic trace minerals compared to those fed inorganic forms. Burkett et al. (2006) reported no differences in average daily gain and feed efficiency and a decrease in fecal trace mineral excretion in grow-finish swine fed reduced levels of organic (Bioplex®) Cu, Fe, and Zn compared to swine fed reduced levels of inorganic Cu, Fe, and Zn.

These studies suggest that poultry and swine can be fed reduced levels of organic trace minerals to decrease fecal trace mineral concentrations without sacrificing growth and performance. However, the extremely low inclusion rates (25% of NRC requirements) studied in poultry have not been evaluated in swine. Therefore, the following study focuses on a further reduction in organic (Bioplex®) and inorganic trace mineral supplementation (Cu, Fe, and Zn) and the effects on performance, carcass characteristics, and fecal excretion in grow-finish swine.

**Thesis Organization**

This thesis is organized as a general literature review followed by a paper in the style of the Journal of Animal Science and a general summary of the complete thesis. The review of literature examines the efficacy of replacing inorganic trace minerals with organic forms in swine diets. To accomplish this, an overview of each mineral (Cu, Fe, and Zn) is provided. Lastly, the impact of fecal Cu, Fe, and Zn excretion on the environment is evaluated. The research reported in the paper was conducted by Matthew L. Wolfe under the direction of Dr.
Thomas Baas, Dr. Kenneth Stalder, and Dr. Wendy Powers with the financial support of Alltech, Inc., Nicholasville, Kentucky.
CHAPTER 2. LITERATURE REVIEW

Bioavailability

Many definitions are available for the term bioavailability. Forbes and Erdman (1983) referred to it as the efficiency with which nutrients are absorbed and thus available for storage or use. Fairweather-Tait (1992) defined bioavailability as the proportion of the total mineral in a food utilized for normal body functions. Each of these definitions left out 1 of the 2 important aspects of bioavailability: absorption and utilization. These terms were later used in the same sentence when Ammerman et al. (1995) defined bioavailability as the “degree to which an ingested nutrient in a particular source is absorbed in a form that can be utilized in metabolism by an animal”. Utilization is the process of transport, cellular assimilation, and conversion to a biologically active form (O'Dell, 1984). Another important definition in regards to mineral bioavailability was stated by Dreosti (1993): “Physiochemical factors that reduce uptake of mineral nutrients from the intestinal lumen are the predominant influence on mineral bioavailability”. This statement is highly relevant in the comparison of the bioavailability of inorganic and organic trace minerals.

Organic vs. Inorganic Trace Mineral Supplementation

An increase in the bioavailability of organic trace minerals compared with inorganic forms in poultry is well documented. Wedekind et al. (1992) conducted 5 experiments using male chicks to compare the bioavailability of zinc-methionine with zinc sulfate using 3 different diets: purified crystalline amino acid (AA), semi-purified (soy isolate), and complex (C-SBM) diet. Bioavailability was based on weight gain and tibia zinc. For comparison purposes, the bioavailability for zinc sulfate was set at 100%. The bioavailability
of zinc methionine was found to be 117% (P < 0.05), 177% (P < 0.01), and 206% (P < 0.01) in the AA, soy isolate, and C-SBM diets, respectively.

Cao et al. (2000) evaluated the bioavailability of 8 sources of organic zinc using tissue zinc concentrations following high dietary additions of zinc in both chicks and lambs. No differences were found in bioavailability values among zinc sources in chicks. However, in lambs they reported an increase in the bioavailability of zinc proteinate A compared to zinc sulfate, but not in the other organic sources tested (zinc methionine complex A, zinc methionine complex B, zinc polysaccharide complex, zinc lysine complex, zinc amino acid chelate, zinc proteinate B, and zinc proteinate C).

Guo et al. (2001) conducted 2 experiments using male chicks to evaluate the bioavailability of several organic sources of copper. In experiment 1, bioavailability (based on liver copper concentrations) values were 124, 122, and 111% for copper lysine, copper amino acid chelate, and copper proteinate C, respectively, with copper sulfate set at 100%. The bioavailability values for copper lysine and copper amino acid chelate were greater (P < 0.05) than that of copper sulfate. In experiment 2, bioavailability values were 111, 109, and 105% for copper lysine, copper proteinate A, and copper proteinate B, respectively, with no differences between sources, including copper sulfate.

Two experiments were conducted by Pimentel et al. (1991) to determine the bioavailability of zinc from zinc oxide and zinc methionine in chicks. Zinc source did not affect tibia and zinc concentrations. However, chicks fed zinc methionine had greater pancreas zinc concentrations than those fed zinc oxide.

Leeson (2003) tested the efficacy of feeding reduced levels of organic (Bioplex®) trace minerals (Zn, Mn, Fe, and Cu) to caged broiler chicks. A typically added level of
inorganic (sulfates) trace minerals was compared to the same level of organic trace minerals, as well as reduced levels of organic minerals at 80, 60, 40, and 20%. No differences were found in gain or feed efficiency between treatments. It was estimated that the organic (Bioplex®) trace minerals were at least 30% more bioavailable than the inorganic sulfates.

Pierce et al. (2005) found similar results to those of Lecson (2003). Two-hundred and forty-six broiler chicks were randomly allocated to 7 dietary treatments. Treatments 1, 2, and 3 provided 100, 50, and 25%, respectively, of NRC (1994) requirements for Cu, Zn, and Fe supplied by sulfates. Treatments 4, 5, and 6 provided 100, 50, and 25%, respectively, of NRC (1998) requirements for Cu, Zn, and Fe supplied by organic (Bioplex®) minerals. Treatment 7 contained no added trace minerals. There was a linear decrease (P < 0.01) in gain and feed intake for birds fed decreasing levels of inorganic minerals. However, no differences (P < 0.05) were found in gain and feed intake among the diets containing organic minerals.

Reduced levels of organic trace mineral supplementation have also been studied in swine (Creech et al., 2004; Burkett et al., 2006). Creech et al. (2004) studied performance, mineral status, and mineral excretion of 216 weanling gilts fed various levels of inorganic and organic trace minerals from weaning to market weight. Pigs were fed 1 of 3 diets during the grower phase: 1) control (28, 179, and 318 mg/kg of Cu, Zn, and Fe, respectively); 2) reduced inorganic sulfates (8, 96, and 257 mg/kg of Cu, Zn, and Fe, respectively); and 3) reduced chelated (12, 91, and 351 mg/kg of Cu, Zn, and Fe, respectively). Fifty percent of the trace minerals supplemented in the reduced chelated diet were in organic form, while the remainder were inorganic sulfates. No differences were reported in gain, feed intake, and feed efficiency among treatments during the grower phase. Fecal concentrations of Cu and Zn were lower (P < 0.05) in pigs fed reduced trace minerals compared to the control diet.
during all phases. Fecal Zn concentration during the nursery phase and fecal Cu concentration during the grower phase were lower (P < 0.05) in pigs fed reduced chelated compared with those fed reduced inorganic sulfates.

Burkett et al. (2006) conducted two experiments to study the effects of inorganic, organic and no trace mineral supplementation on phase-fed, grow-finish swine. The first trial consisted of 528 crossbred pigs and 4 dietary treatments: TRT 1) 100% trace mineral supplementation (63, 378, and 157 mg/kg of Cu, Fe and Zn, respectively, for phase 1 from inorganic sources); TRT 2) 100% trace mineral supplementation (21, 277, and 79 mg/kg of Cu, Fe and Zn, respectively, for phase 1 from organic (Bioplex®) sources); TRT 3) 25% reduction from TRT 2; and TRT 4) 50% reduction from TRT 2. Treatment 1 was supplemented with commercially recommended levels of Cu as copper sulfate, Fe as iron sulfate, and Zn (of which 25% was zinc oxide and 75% was zinc sulfate). Treatment 2 contained commercially supplemented levels of Cu, Fe, and Zn from organic sources (Bioplex®). No differences (P < 0.05) were found for average daily gain and carcass characteristics among treatments. Fecal excretion of Cu, Fe, and Zn was highest (P < 0.05) in all 4 collection phases for TRT 1. The second trial consisted of 560 pigs and 4 additional dietary treatments: TRT 5) 75% reduction of TRT 1 from inorganic sources; TRT 6) 50% reduction of TRT 2 from organic (Bioplex®) sources; TRT 7) 75% reduction from TRT 2; and TRT 8) no Cu, Fe, Zn, and Se supplementation. There were no differences in average daily gain and carcass characteristics among the 3 diets containing Cu, Fe, and Zn supplementation. Fecal excretion of Cu was highest (P < 0.05) for pigs fed TRT 5 (inorganic trace minerals).
In summary, many studies have found benefits to replacing inorganic trace minerals with organic forms in both poultry and swine. The work of Leeson (2003) and Pierce et al. (2005) suggest the possibility that gain and feed efficiency can be maintained in broilers by feeding organic trace minerals as low as 25% of NRC (1994) requirements. However, the main advantage is a reduction in fecal excretion because of the increased bioavailability of organic trace minerals.

Copper

Introduction and Function

Copper is needed in swine for hemoglobin synthesis, cellular respiration, cardiac function, bone development, and the activation of several metalloenzymes in many major metabolic pathways (Miller et al., 1979). Copper may also protect body tissues from oxidative stress via the superoxide dismutase enzyme (Arthington et al., 1996). Furthermore, copper is known to promote growth in weanling pigs. The addition of copper at high levels (200 to 250 mg/kg) in weanling pig diets is well documented (Cromwell et al., 1989; Coffey et al., 1994; Apgar et al., 1995; Hill et al., 2000; Veum et al., 2004). The growth promoting action of copper in weanling pigs is believed to be the result of antibacterial properties in the gastrointestinal tract (Fuller et al., 1960; Hawbaker et al., 1961; Bunch et al., 1965). However, recent evidence supports the theory that copper acts systemically in the intestinal tract (Zhou et al., 1994). Regardless, these growth promoting actions are not as apparent in grow-finish swine. Few studies have reported an increase in performance in grow-finish pigs fed pharmacologic additions of copper (Barber et al., 1955), whereas several experiments have shown no differences or a decrease in growth in finishing pigs fed high levels of copper (Wallace et al., 1960; Lillie et al., 1977; Stansbury et al., 1990).
Copper deficiency is characterized by retarded growth (Teague and Carpenter, 1951), anemia (Hart et al., 1930), bone disorders, and cardiovascular disorders (Vadlamudi et al., 1993). Many of the deficiencies associated with copper are due to its important role in the activation of key enzymes, such as cytochrome C oxidase and tyrosinase. Cytochrome C oxidase is essential to the electron transport chain and tyrosinase catalyzes the production of melanin.

The concentration needed for swine to prevent copper deficiency is low. The copper requirement for neonatal pigs is 5 to 6 ppm per day (Okonwo et al., 1979; Hill et al., 1983; NRC, 1998). The requirement for grow-finish swine is 4 ppm per day (NRC, 1998).

Absorption and Transport

Copper is absorbed by both simple diffusion and active transport (Turnland, 1999). Absorption is a function of dietary copper concentration. Pharmacological concentrations induce simple diffusion, whereas lower copper inclusion levels are absorbed by active transport. Absorption takes place in the small intestine, and more specifically, the duodenum. Once absorbed into enterocytes, copper can be transported into the serosal side of the intestine and into blood circulation. Copper is circulated in the pig via albumin, ceruloplasmin, and amino acids. Ceruloplasmin is a glycoprotein that binds the majority of copper in the blood for transport and storage. It is assumed that there are receptors for ceruloplasmin on the cell surface of most major organs within the pig’s body, but it has not been proven (Hill and Spears, 2001).

Nutrient Interactions

The interaction between copper and zinc is well documented (Smith and Larson, 1946; Ritchie et al., 1963; Hill et al., 1983). It is believed that these minerals compete for
absorption in the digestive tract. A diet that is excessive in one of these minerals may result
in a deficiency in the other. Copper status, especially, is highly sensitive to zinc intake. Zinc
intake produces high concentrations of metallothionein in the intestinal mucosa.
Metallothionein binds copper more strongly than zinc. This causes copper absorption to be
very inefficient because copper is sloughed off with mucosal cells (Fischer et al., 1983).

Other factors and elements that inhibit copper absorption and decrease bioavailability
are molybdenum, sulfur, cadmium, silver, lead, and phytates. However, the major contributor
to copper absorption and bioavailability may be copper status of the animal. Increases in
copper status lead to reduced absorption and increased fecal excretion of copper.

Storage

In most animal species, copper is mainly stored in the liver and brain (Miller et al.,
1979). Liver copper concentrations tend to be highest at birth and decrease with age. In the
liver, copper is bound mostly to metallothionein. The liver uses copper to make liver
proteins, such as ceruloplasmin, and excess copper is excreted (Hill and Spears, 2001).

Bioavailability

Variation in bioavailability values of different copper sources in swine is well
documented. Baker and Ammerman (1995) conducted a thorough review and discovered
relative bioavailability values ranging from 0 to 111% for various copper sources in swine.
Cupric sulfate was set as the standard in all trials and appeared to be more bioavailable than
most other copper sources analyzed, such as cupric oxide, cupric carbonate, copper-
molybdenum complex, copper methionine, and copper citrate. Only 3 of the studies that were
reviewed compared the bioavailability of organic copper sources with copper sulfate. Those
studies found bioavailability values of copper methionine (Bunch et al., 1965) and copper molybdenum (Dowdy and Matrone, 1968) to be 107% and 0 to 68%, respectively.

Recent research in swine has focused on the effectiveness of organic copper sources to maintain growth and reduce excretion (Smits and Henman, 2000; Wu et al., 2001; Armstrong et al., 2004; Veum et al., 2004). Few studies have solely researched copper bioavailability in swine. Most of the experiments that have attempted to determine copper bioavailability in swine have used plasma copper levels as their measure (Apgar et al., 1995; Armstrong et al., 2000; Armstrong et al., 2004; Veum et al., 2004). However, it has been suggested that liver copper levels, not plasma copper levels, are a better indicator of copper bioavailability between sources (Lee et al., 1988; Xin et al., 1991). To confirm this point, Kincaid et al. (1986) found the bioavailability of copper proteinate in cattle to be either 147 or 112%, depending on whether liver copper or plasma copper was used. Another problem with copper bioavailability studies is the level of dietary copper utilized. Many researchers have included 200 ppm of copper in the diet. It has been suggested that liver and bile copper concentrations do not provide an accurate means to assess bioavailability in pigs fed adequate to pharmacological concentrations of copper (Armstrong et al., 2000). For these reasons, some of the aforementioned studies will only be reviewed in the following section.

**Organic copper supplementation in swine**

The use of pharmacological concentrations of copper in nursery diets poses a greater environmental concern than the lower inclusion levels seen in grow-finish diets. Consequently, some research has focused on replacing high levels of inorganic copper with lower levels of organic forms in weanling pig diets. Other research has placed emphasis on
the grow-finish phase because it has been estimated to contribute 60 to 70% of the total effluent produced by a typical commercial operation (Lenis and Jongbloed, 1994).

Wu et al. (2001) evaluated mineral excretion in nursery pigs fed reduced levels of organic (Bioplex®) copper. Twenty crossbred barrows were fed 1 of 4 diets: 1) basal diet; 2) basal plus 50 ppm of copper proteinate; 3) basal plus 100 ppm of copper proteinate; and 4) basal plus 250 ppm of copper sulfate. The basal diet contained a trace mineral premix that met or exceeded NRC (1998) requirements. Copper intake, fecal and urinary excretion, and absorption and retention were greater (P < 0.01) for pigs fed copper sulfate compared to all other treatments.

The effectiveness of cupric citrate to increase growth performance and reduce fecal copper excretion in weanling pigs was studied by Armstrong et al. (2004). Two experiments were conducted with the following dietary treatments: 1) control, which consisted of 10 ppm of copper sulfate; 2) 15 ppm of copper citrate; 3) 31 ppm of copper citrate; 4) 62 ppm of copper citrate; 5) 125 ppm of copper citrate; 6) 62 ppm of copper sulfate (experiment 2 only); 7) 125 ppm of copper sulfate (experiment 1 only); and 8) 250 ppm of copper sulfate. In experiment 1, average daily gain, feed intake, and feed efficiency did not differ (P < 0.05) among pigs fed diets containing 125 and 250 ppm of copper sulfate or 125 ppm of copper citrate. In experiment 2, similar results were obtained: no differences (P < 0.05) were reported in average daily gain, feed intake, and feed efficiency for pigs fed diets containing 250 ppm of copper sulfate or 125 ppm of copper citrate. Lastly, fecal copper concentrations were lower (P < 0.05) in pigs consuming 125 ppm copper citrate compared to those consuming 250 ppm copper sulfate. This study confirms that lower inclusion levels of
organic copper sources may be effective in maintaining growth in weanling pigs and in reducing fecal copper concentrations.

Apgar et al. (1995) conducted 2 trials to compare the use of copper lysine complex as a growth promoter in swine. Weanling pigs (n = 176) were fed dietary treatments that included 0, 100, 150, or 200 ppm of supplemental copper from copper sulfate or copper lysine. The basal diet contained 15 ppm of copper. Average daily gain and feed intake increased linearly (P < 0.01) with increasing dietary levels of copper during weeks 1 to 2 and 3 to 5. No differences (P < 0.10) were reported in gain and feed intake between copper sources.

The use of copper proteinate was compared with copper sulfate in weanling pig diets by Veum et al. (2004) in 2 experiments. In experiment 1, weanling pigs (n = 240) were randomly allocated to dietary treatments supplemented with 0, 25, 50, 100, or 200 ppm of copper proteinate; or 250 ppm of copper sulfate. The basal diet contained 16.5 ppm of copper. Overall, pigs fed copper proteinate had increased (P < 0.05) average daily gain compared to those fed copper sulfate. In experiment 2, crossbred barrows (n = 20) were fed dietary treatments supplemented with 0, 50, or 100 ppm of copper proteinate; or 250 ppm of copper sulfate. Barrows fed 50 or 100 ppm copper proteinate had reduced fecal copper excretion concentrations of 77 and 61%, respectively, compared with pigs fed 250 ppm of copper sulfate.

Smits and Henman (2000) evaluated the performance of grow-finish pigs fed diets supplemented with either copper sulfate (150 ppm) or organic (Bioplex®) copper (40 ppm). Similar levels of performance were reported between the 2 dietary treatments (P > 0.05), while fecal copper concentration was reduced (P < 0.01) in those pigs fed organic copper.
The effects of copper citrate and copper sulfate supplementation in grow-finish pigs were compared by Armstrong et al. (2000). Pigs (n = 192) were assigned to 1 of 6 dietary treatments: 1) control, 10 ppm of copper sulfate; 2) 66 ppm of copper sulfate; 3) 225 ppm of copper sulfate; 4) 33 ppm of copper citrate; 5) 66 ppm of copper citrate; and 6) 100 ppm of copper citrate. Pigs fed 66 ppm of copper sulfate tended to grow faster (P < 0.10) than those fed 225 ppm of copper sulfate. However, the authors stated it was difficult to make an accurate assessment on the efficacy of copper citrate relative to copper sulfate based on the data collected.

Stansbury et al. (1990) conducted 4 experiments to determine the effect of copper source and level on performance in nursery and grow-finish pigs. Copper sulfate, inorganic chelated copper, and organic chelated copper were supplemented at levels of 31.25, 62, and 125 ppm. In experiment 1, pigs fed 125 ppm copper, regardless of source, grew faster (P < 0.01) than pigs fed all other treatments. Similar average daily gain was reported between copper sources in the grow-finish phase for all experiments.

The main benefit of utilizing organic copper sources is a reduction in fecal excretion. Most of the previously mentioned studies reported little or no difference in gain or feed efficiency between copper sources. However, many found that copper inclusion levels can be decreased in both nursery and finisher diets when using organic forms. Based on the studies reviewed, this results in lower copper fecal excretion without sacrificing growth and performance.
Zinc

Introduction and Function

The main functions of zinc are: 1) constituent of many enzymes in most major metabolic pathways; 2) immune function; 3) tissue growth and integrity; and 4) growth stimulant at pharmacological concentrations (Hill and Spears, 2001). Zinc is a required component of over 300 enzymes (Vallee and Falchuk, 1993), such as carboxypeptidase A, alcohol dehydrogenase, alkaline phosphatase, and the SOD enzyme. Zinc also plays an important role in the immune system and zinc deficiency can lead to susceptibility to pathogens (Scott and Koski, 2000). Since zinc is a component of DNA and RNA synthetase, zinc is essential for tissue and protein synthesis. Lastly, the addition of zinc at pharmacological concentrations in weanling pig diets is well documented (Hahn and Baker, 1993; Carlson et al., 1999; Hill et al., 2000). Weanling pig diets are commonly supplemented with 2,000 to 3,000 ppm of zinc oxide in the United States to promote growth. The efficacy of using organic sources of zinc at lower concentrations is reviewed in a later section.

Zinc deficiency symptoms in pigs include: parakeratosis (dermatitis), retarded growth (Pond et al., 1964), impaired immune response (Scott and Koski, 2000), impaired reproductive performance (Hoekstra et al., 1967), and a reduction in metallothionein production. Parakeratosis was first reported to be a zinc deficiency in swine by Tucker and Salmon (1955). It is characterized by keratinous lesions/crusts on the pastern, fetlock, knee, hock, tail, ear, shoulder, and/or hip regions of the pig.

The zinc requirement to prevent deficiency in neonatal pigs is 100 ppm per day (NRC, 1998). The requirement for grow-finish swine is 50 to 60 ppm per day (NRC, 1998).
Absorption and Transport

The majority of zinc is absorbed in the small intestine of pigs by a carrier-mediated process, which is more efficient in low zinc intake than in high zinc intake. Thus, it appears that zinc status in the pig plays a major role in zinc absorption. As body zinc levels increase, the efficiency of zinc absorption is increased, and the reverse is also true. Many assumptions have been made relative to zinc absorption in swine, but few are concrete. It has been suggested that passive diffusion occurs at high dietary zinc levels (King and Keen, 1999).

Once absorbed by intestinal mucosal cells, zinc is bound to metallothionein, which exists in the cytosol of intestinal mucosal cells and is also present in liver (Richards and Cousins, 1976). In plasma, zinc is bound to albumin, α-2 macroglobulin, transferrin, immunoglobulin G, and amino acids (Parisi and Vallee, 1969). The majority of zinc in blood is bound to albumin (Smith et al., 1978). Zinc uptake into various tissues and organs is accomplished via a family of zinc transporter proteins: ZnT-1, ZnT-2, ZnT-3, and ZnT-4.

Nutrient Interactions

The most notable nutrient interaction is copper and zinc. These metals have similar chemical and physical properties and compete for mineral binding ligands and uptake in the gastrointestinal tract (Fairweather-Tait, 1992). Copper intake does not appear to have the same effect on zinc absorption as zinc intake has on copper absorption. It has been suggested that high copper intake inhibits zinc absorption, but it is not clear (Fairweather-Tait, 1992). Fairweather-Tait (1992) also stated that iron intake may inhibit zinc absorption.

Many other nutrients and elements interact with zinc. Calcium, phytate, oxalate, fiber, lead, chromium, and cadmium decrease zinc absorption and bioavailability. High calcium intake is known to induce the formation of a Zn-Ca-phytate complex in the upper
gastrointestinal tract and create zinc deficiency in the rat (Davies and Olpin, 1979). Another important factor affecting zinc absorption is zinc status of the animal.

**Storage**

Zinc storage is not well understood and appears to be widely distributed within the pig’s body in the brain, liver, kidney, and other tissues. The liver and kidney are known to release zinc during deficiencies. Zinc stored in the liver is bound to metallothionein and can be mobilized easily (Richards and Cousins, 1976).

**Bioavailability**

Zinc bioavailability studies in swine have used multiple zinc sources as a standard: sulfate, chloride, and oxide. This creates difficulty in comparing studies. The availability of zinc oxide has been reported to be 56% that of zinc sulfate (Hahn and Baker, 1993). Hahn and Baker (1993) conducted 3 trials to evaluate the bioavailability of 3 sources of zinc in weanling pigs: zinc oxide, zinc sulfate, and a zinc-lysine complex. Trial 1 consisted of the following dietary treatments: 1) 0, 250, 500, 1,000, 3,000, and 5,000 ppm of zinc oxide; 2) 1,500 and 2,500 ppm of zinc sulfate; and 3) 1,500 and 2,500 ppm of zinc-lysine complex. Based on response curve slopes, bioavailability values for zinc oxide and the zinc-lysine complex, with respect to zinc sulfate, were 56 and 110%, respectively.

Revy et al. (2002) assessed the bioavailability of zinc sulfate and zinc methionine. Pigs (n = 32) were fed a basal diet, which contained no supplemental zinc, for a 7-day adjustment period. During the 19-day experimental period, pigs were fed 0, 10, 20, or 30 ppm of zinc sulfate or zinc methionine. Gain was not affected by level or source of zinc. Based on alkaline phosphatase activity, bone zinc concentration, plasma zinc concentration, and liver and empty body zinc concentrations, no differences were reported in bioavailability
between zinc sources. Lastly, 27% of zinc intake was retained when measured by means of the balance technique, regardless of level or source.

Schell and Kornegay (1996) evaluated the bioavailability of zinc oxide, zinc methionine, zinc lysine, and zinc sulfate in weaning pigs. Four trials were conducted and pigs were fed 3,000, 2000, or 1,000 ppm of zinc lysine, methionine, oxide, or sulfate, or a control diet containing 105 ppm of zinc. In trials 1 and 2, pigs fed higher zinc concentrations, regardless of source, had increased liver and serum zinc concentrations. Pigs fed zinc sulfate had greater (P < 0.05) liver and serum zinc concentrations than those pigs fed zinc oxide in trials 1 and 2. Based on serum and tissue zinc concentrations, bioavailability values compared to zinc sulfate were lowest for zinc oxide and intermediate for zinc lysine and zinc methionine.

Bioavailability of zinc sulfate and zinc lysine in young pigs was assessed by Cheng et al. (1998). Two trials were conducted with 144 and 96 pigs. Pigs were fed the following diets: 1) basal 1 (B1), 0.8% dietary lysine without added zinc; 2) B1 plus 100 ppm of zinc sulfate; 3) B1 plus 100 ppm of zinc lysine; 4) basal 2 (B2), 1.1% lysine without added zinc; 5) B2 plus 100 ppm of zinc sulfate; and 6) B2 plus 100 ppm of zinc lysine. In trial 1, 100 ppm of zinc sulfate or zinc lysine was added to a 0.95% lysine basal diet. Serum and tissue (liver, kidney, and rib) zinc concentrations were lowest (P < 0.001) for those pigs fed the basal diets with no added zinc. Zinc sulfate and zinc lysine seemed to be equally effective in promoting growth, zinc absorption, and tissue stores of young pigs.

Wedekind et al. (1994) conducted 2 experiments to evaluate the bioavailability of the following sources of zinc: sulfate, methionine, oxide, and lysine. Slope ratio analysis was used to calculate bioavailability values of zinc sources relative to zinc sulfate. Pigs were fed
3 levels of zinc sulfate (0, 7.5, and 15 ppm) to develop a standard curve. Bioavailability of zinc methionine was found to be similar to that of zinc sulfate. However, bioavailability values for zinc lysine and zinc oxide were lower (P < 0.05) than for zinc sulfate.

It appears that bioavailability values of organic zinc sources are similar to that of inorganic sources. However, the results are inconsistent. Some studies have reported lower bioavailability values for organic zinc sources, while others have shown higher values. The majority of research experiments report no differences in bioavailability between organic and inorganic zinc sources.

**Organic zinc supplementation in swine**

The pharmacological addition of zinc in weanling pig diets has warranted research in reducing zinc inclusion using organic forms. One such study by Wu et al. (2001) compared lower inclusions of zinc proteinate with a high addition of zinc oxide. Twenty barrows were fed 1 of 4 dietary treatments: 1) basal, which contained a trace mineral premix that met or exceeded NRC (1998) requirements for zinc; 2) basal plus 200 ppm of zinc proteinate; 3) basal plus 400 ppm of zinc proteinate; and 4) basal plus 2000 ppm of zinc oxide. Average daily gain, feed intake, and fecal zinc concentration were increased in pigs fed zinc oxide compared to those fed zinc proteinate (P < 0.05).

Carlson (2000) compared levels and sources of zinc supplementation in weanling pigs. There were 7 dietary treatments: 1) control (no added zinc); 2) 2000 ppm of zinc oxide; and 3 through 7) 50, 100, 200, 400, and 800 ppm of organic zinc (Bioplex®). For the entire 28-day nursery phase, there were no differences in performance, feed intake, or feed efficiency among treatments. During the first 2 weeks, piglets fed either 50 or 100 ppm organic zinc grew the fastest (P < 0.01).
Two experiments were conducted by Hollis et al. (2005) to evaluate the efficacy of replacing high levels of zinc oxide with lower levels of organic zinc in weanling pig diets. Experiment 1 consisted of the following diets: 1) 2,500 ppm of zinc oxide; 2) 125 ppm of zinc methionine; 3) 250 ppm of zinc methionine; 4) 500 ppm of zinc methionine; and 5) control, which contained 125 ppm of zinc from various inorganic sources. Pigs fed zinc methionine grew faster (P < 0.05) than those fed the control diet. However, pigs fed 2,500 ppm of zinc oxide grew faster than those fed zinc methionine. Experiment 2 compared 5 sources of organic zinc (zinc polysaccharide complex, zinc proteinate, zinc amino acid complex, zinc amino acid chelate, and zinc methionine) supplemented at 500 ppm with inclusion rates of 500 and 2,000 ppm of zinc oxide, as well as a control, which contained 140 ppm of zinc from various inorganic sources. Average daily gain was greatest (P < 0.05) for those pigs consuming 2,000 ppm zinc oxide. The organic sources did not improve gain, feed intake, or feed efficiency beyond that achieved with the control diet.

Carlson et al. (2004) conducted 3 experiments to test the effect of organic zinc supplementation on growth performance, plasma concentrations, and excretion in nursery pigs. For all experiments, the basal diet contained 165 ppm of zinc sulfate. In experiment 1, pigs (n = 306) were supplemented with 0, 125, 250, 375, or 500 ppm of zinc polysaccharide, or 2,000 ppm of zinc oxide. In experiment 2, pigs (n = 98) were supplemented with 0, 50, 100, 200, 400, or 800 ppm of zinc proteinate, or 2,000 ppm of zinc oxide. In experiment 3, pigs (n = 20) were supplemented with 0, 200, or 400 ppm of zinc proteinate, or 2,000 ppm of zinc oxide. For all experiments, there were no overall treatment differences in average daily gain, feed intake, or feed efficiency. In experiments 1 and 3, pigs fed 2,000 ppm of zinc oxide had higher (P < 0.01) fecal zinc concentrations than all other pigs. In summary, no
differences were reported among organic sources of zinc. The authors concluded that feeding lower levels of organic zinc sources to nursery pigs will decrease fecal zinc concentrations without compromising gain and feed efficiency.

Burkett et al. (2006) conducted 2 experiments to study the effect of inorganic, organic, and no trace mineral supplementation on performance, carcass characteristics, and fecal excretion in phase-fed, grow-finish swine. Pigs were fed various levels of organic and inorganic trace mineral supplementation. Inorganic forms of Cu, Fe, and Zn (of which 25% was zinc oxide and 75% was zinc sulfate) were compared to organic forms (Bioplex®). No differences were reported in average daily gain and carcass characteristics among treatments in experiment 1. Pigs fed inorganic zinc (TRT 1) had the highest fecal zinc concentrations, while pigs fed organic zinc (TRT 4) had the lowest fecal zinc concentrations (P < 0.05). In experiment 2, pigs fed organic zinc (TRT 6) had the highest fecal zinc concentrations (P < 0.05). No differences were found in gain or carcass characteristics among pigs consuming the diets that contained trace mineral supplementation. Pigs receiving no supplemental zinc (TRT 8) displayed symptoms of parakeratosis.

Creech et al. (2004) conducted a study to evaluate performance, mineral status, and mineral excretion of 216 weanling gilts fed various levels of inorganic and organic trace minerals from weaning to market weight. Pigs were fed 1 of 3 diets: control, reduced sulfates, or reduced chelates. No differences were reported in gain, feed intake, and feed efficiency among treatments during the growing phase. Pigs fed the control diet had higher (P < 0.01) plasma zinc concentrations than those fed the reduced diets during the nursery phase, growing phase, and in the gilt-developer phase (trial 3 only). However, in trials 1 and 2, no differences were reported in plasma zinc concentration among treatments during the
gilt-developer phase. Fecal zinc concentrations were higher (P < 0.01) at all sampling times in pigs fed control diets than in pigs fed diets with reduced sulfates or chelates. Pigs consuming the reduced inorganic diet had higher (P < 0.01) fecal zinc concentrations than those consuming the reduced organic diet during the nursery phase.

Based on the studies reviewed, it is difficult to assess the efficacy of replacing inorganic forms of zinc with organic forms in nursery pig diets. Studies comparing high inclusion levels of inorganic zinc with lower levels of organic zinc in nursery pigs have produced conflicting results. Some experiments report no differences in gain and feed efficiency, while others show an increase in performance in pigs fed inorganic zinc. In grow-finish swine, it appears that reduced supplemental levels of organic zinc can be used to reduce fecal zinc concentrations without sacrificing growth and performance.

**Iron**

**Introduction and Function**

Iron is the most abundant of the trace elements in the animal body (Henry and Miller, 1995). It is estimated that 40% of the iron in animal tissue is in the form of heme (Kratzer and Vohra, 1986). Obviously, one of the main functions of iron is oxygen transport in heme. Also, iron plays a major role in oxygen storage within myoglobin. Other functions include: transport of electrons in electron transport chain, immune function (Osborne and Davis, 1968), and lipid metabolism through cytochrome b5 and P-450 (Hill and Spears, 2001).

Several other enzymes contain iron, such as tryptophan dioxygenase, phenylalanine hydroxylanse, and xanthine dehydrogenase.

Deficiencies of iron in swine are generally limited to nursing pigs. This is due mainly to low iron concentration in sow milk and low iron stores of newborn pigs. Regardless, iron
deficiency is the most commonly known mineral deficiency in swine (Hill and Spears, 2001). Iron deficient nursing pigs will exhibit loss of appetite, labored breathing, and ultimately, death. Iron deficiency is also known to alter certain immune responses (Kuvibidla and Surendra, 2002) and decrease growth (Pickett et al., 1960).

The iron requirement for neonatal pigs is 100 ppm per day (NRC, 1998). This recommendation is based mainly on early experiments conducted by Pickett et al. (1960). They tested the efficacy of feeding diets containing 60 ppm of supplemented iron to pigs weaned at 10 to 14 d of age and reported decreased growth. The requirement for grow-finish swine is 50 to 60 ppm/d (NRC, 1998).

**Absorption and Transport**

Iron absorption is well understood and researched in humans and rats, but not in pigs. Rats serve as a poor model because they continually accumulate iron, unlike pigs. It was originally proposed that only enough iron to meet the pig’s needs was absorbed (Hahn et al., 1943). Now, it is clear that iron absorption in mammals increases as iron stores decrease and as erythropoiesis increases, which is the development of mature red blood cells (Hill and Spears, 2001).

Iron is commonly absorbed in the protonated (Fe$^{3+}$) state. In the pig, absorption takes place in the small intestine and mainly in the duodenum and jejunum through ferrous iron receptors. Iron is transported across mucosal cells by diffusion or by the use of amino acids, such as cysteine, ornithine, lysine, or histidine (Hill and Spears, 2001).

The major protein in plasma involved in iron transport is transferrin (McKnight et al., 1980). Iron must be converted into the Fe$^{3+}$ state to bind to transferrin. This is accomplished by enzymes that have ferroxidase activity, such as ceruloplasmin. Once in the Fe$^{3+}$ state and
bound to transferrin, iron can be transported to other organs within the pig’s body. Transferrin receptors are located on the plasma membrane of cells and are responsible for transportation of iron (as well as other minerals) into the cell.

**Nutrient Interactions**

It appears that certain amino acids and/or peptides may influence iron absorption as the iron contained in soy products is considered unavailable (Hill and Spears, 2001). Animal proteins, on the other hand, increase iron absorption. Also, iron is known to impair zinc absorption (Solomans and Jacob, 1981). Ferrous iron (Fe$^{2+}$) inhibits zinc absorption more than ferric iron (Fe$^{3+}$). Lastly, excess copper in diets is known to deplete iron reserves in the liver of piglets and, therefore, excess iron is recommended in weanling pig diets (Bradley et al., 1983).

**Storage**

Iron is stored primarily as ferritin, which is a globular protein found mainly in liver (Hill and Spears, 2001). Serum ferritin levels are directly correlated with iron status of the pig. Storage of iron can also be found in hemosiderin and is more pronounced as iron stores increase. Release of iron from hemosiderin is much slower than from ferritin. Iron from ferritin can be readily released for hemoglobin synthesis or other needs.

**Bioavailability**

Henry and Miller (1995) presented an extensive review of iron bioavailability studies in swine. With most experiments using ferrous sulfate as the standard, bioavailability values ranged from 8 to 192% for iron sources such as ferric citrate, ferric choline citrate, ferric carbonate, ferric sulfate, ferric oxide, iron EDTA, iron-methionine, and iron-proteinate. Ferric oxide was found to have low bioavailability compared to iron sulfate. Ferric carbonate
was the most variable in terms of bioavailability values reported. Most of the studies reviewed by Henry and Miller (1995) used hemoglobin regeneration as the response criterion.

Some research trials have focused on the bioavailability of organic zinc sources (Anderson et al., 1974; Brady et al., 1978; Spears et al., 1992; Lewis et al., 1995). Anderson et al. (1974) studied the bioavailability of several sources of iron, including EDTA (ethylenediaminetetraacetic acid), which is a chelating agent. Miniature pigs \( (n = 56) \) were fed the following dietary treatments: 1) no added Fe (basal diet contained 8 ppm); 2) ferrous sulfate; 3) catalytically reduced iron; 4) electrolytic iron powder; 5) sodium iron pyrophosphate; 6) ferripolyphosphate powder; and 7) disodium iron EDTA. Diets 2 through 7 provided 64 to 69 ppm of supplemental iron. Body weight gain was lower in pigs fed diets 1 and 5 compared to those consuming diets 2, 6, and 7. The efficiency with which iron was incorporated into hemoglobin ranged from 27 to 30\% in pigs fed diets 2, 6, and 7 and was higher than in pigs consuming all other diets. Bioavailability values (based on pigs fed diet 2 as 100\%) were 97, 90, and 70\% for diets 7, 6, and 4, respectively.

Five experiments were conducted by Brady et al. (1978) to evaluate the efficacy of feeding an organic iron source to sows in lactation and late gestation. In experiment 1, sows \( (n = 12) \) were fed either a control diet, which supplied 60 ppm of iron, or were supplemented with 3,000 ppm of organic iron (iron proteinate). After 2 weeks of lactation, mean hemoglobin among piglets farrowed from iron proteinate-fed sows was 8.5 g/dl compared to 5.9 for other piglets. Iron content in sow milk was increased and nearly doubled by the second week of lactation among sows fed iron proteinate. In experiment 2, sows \( (n = 18) \) were fed the same dietary treatments as experiment 1. Once again, milk iron content was
increased in sows fed iron proteinate. Also, piglets farrowed from sows fed iron proteinate had greater iron blood concentration. It was concluded that the drastic increases in piglet hemoglobin were not solely accounted for by differences in sow milk. The authors hypothesized that another route of iron transfer was via the sow’s feces.

Other studies have produced conflicting results in bioavailability values of organic iron sources (Spears et al., 1992; Lewis et al., 1995). Spears et al. (1992) reported iron methionine to have a bioavailability value of 183% compared to iron sulfate in nursing pigs. On the contrary, Lewis et al. (1995) found iron methionine 68 to 81% as bioavailable as iron sulfate in weanling pigs. The aforementioned studies suggest the need for further research in the area of organic iron bioavailability.

**Organic iron supplementation in swine**

The use of organic iron sources has not been a focus of research mainly because iron accumulation in manure and soil is not a major concern. This is due to 2 reasons: 1) iron is not added to swine diets in large quantities for growth promotion, reproductive performance, etc.; and 2) toxicity levels for iron are higher in humans, grazing animals, and aquatic life than those for copper and zinc. Instead, research of organic iron sources is limited to those studies that test the efficacy of feeding several minerals in organic form. These studies indicate that a reduction in fecal iron concentration can be achieved in swine by using organic iron forms.

Burkett et al. (2006) conducted 2 experiments to compare inorganic and organic trace mineral supplementation in grow-finish swine. Pigs were fed graded levels of organic (Bioplex®) and inorganic (sulfate) iron. No differences were reported in gain or carcass characteristics among treatments in experiment 1. Pigs fed diets containing organic trace
mineral supplementation had the lowest (P < 0.05) fecal iron concentration during phases 1, 2, 3, and overall compared to pigs fed the control diet (TRT 1). In experiment 2, no differences were reported among treatments for fecal iron concentration during phase 1 and overall.

Creech et al. (2004) fed gilts 1 of 3 diets from weaning to development: control, reduced inorganic trace minerals, and reduced organic trace minerals. No differences were found in gain, feed intake, and feed efficiency among treatments. Hemoglobin concentration was lower (P < 0.05) for pigs fed reduced levels of inorganic minerals compared to those fed reduced levels of organic minerals during the nursery phase. There were no differences in hemoglobin concentration among treatments during the grow-finish and gilt-developer phases. Fecal iron concentration tended to be lower (P < 0.10) in pigs fed the reduced organic diet compared to those fed the reduced inorganic diet during the nursery phase. During the growing and gilt-developer phases, pigs consuming the control diet excreted more (P < 0.01) iron than pigs consuming all other diets.

**Manure Loading**

Swine production units have been under scrutiny for the past several years due to negative public perception and the potential risks involved with air, water, and soil quality. One such risk is manure loading or the accumulation of nutrients, such as trace minerals, in the soil after repeated and concentrated manure application. This has drawn increased attention for obvious reasons. Copper and zinc, for instance, are known to remain bound to soil and do not migrate except during soil erosion (Ferket et al., 2002). Headon (1992) showed that a 500-sow, farrow-to-finish operation producing 20 pigs per sow per year produces a comparable amount of effluent as a town of 25,000 people. More specifically,
much attention is focused on the grow-finish segment of pig production. This phase contributes 60 to 70% of the total effluent produced from a typical commercial operation (Lenis and Jongbloed, 1994). Large swine operations must have access to large areas of land to safely spread manure and avoid over-application.

The impacts of long-term application of swine manure have been researched (Christie and Beattie, 1989; Mueller et al., 1994; Kornegay and Harper, 1997). Christie and Beattie (1989) analyzed copper and zinc concentrations on plots of land applied with 3 rates (50, 100, and 200 m$^3$/ha/yr) of swine manure over a 17-year period. Copper (> 80 ppm) and zinc (50 ppm) were significantly increased on land applied with the highest rate of pig slurry after 17 years. Herbage concentrations for the highest application rate reached 10 and 44 mg/kg for copper and zinc, respectively, which could be toxic to sheep. However, yields were not decreased for any of the application rates over the 17-year period.

Mueller et al. (1994) studied the influence of applying manure from a swine lagoon on a particular field for a 3-year period. Swine effluent was applied at a rate to fulfill the nitrogen requirement of the soil. They reported approximately a four-fold increase in zinc and a three-fold increase in copper after 3 years.

Kornegay and Harper (1997) studied the effects of applying copper-rich swine manure to plots of land for a 16-yr period. Pigs were fed 255 ppm of copper sulfate and the manure was applied at an annual rate of 80 ton/acre. Three different soil types were tested: silt loam, sandy loam, and clay loam. The authors reported 9.0, 19.6, and 3.6-fold increases in extractable copper for silt loam, sandy loam, and clay loam soils, respectively. Increases for extractable zinc ranged from 2.1 to 2.6-fold for the 3 soil types. However, copper and zinc concentrations were not increased in the grain grown and yields were not decreased.
The effect of swine slurry application on alfalfa production and soil nutrient concentration was evaluated by Lloveras et al. (2004). The 2-year study consisted of 2 different locations and 4 treatments: 1) annual winter application of 25 m$^3$/ha of swine slurry manure, 2) annual winter application of 50 m$^3$/ha of swine slurry manure, 3) annual fertilization of 32.75 kg/ha of P and 125 kg/ha of K, and 4) control (no manure or fertilizer). Application of swine manure in the winter at either rate did not decrease yield. The application of slurry (both rates) increased plant concentration of copper in both locations, whereas the concentration of zinc only increased at 1 location. It was suggested that applying moderate amounts of swine slurry over a 2-year period will not increase trace minerals in the soil at a level toxic to plant growth.

Lopez Alonso et al. (2000) evaluated the liver concentrations of cattle grazing on manure treated pasture in Spain. The authors found hepatic copper and zinc concentrations in cattle to be higher in areas with elevated levels of these minerals in the soil. Furthermore, the density of young pigs (piglets and growing-finishing pigs), leading to increased swine manure application in those particular areas, influenced copper, but not zinc accumulation in calves. Lastly, in areas with the highest pig densities, more than 20% of the cattle analyzed had liver copper concentration that exceeded the potentially toxic concentration of 150 mg/kg of live weight.

Jondreville et al. (2002) and Revy et al. (2003) calculated the number of years before the concentration of copper and zinc would reach toxic levels (100 and 300 mg/kg of copper and zinc, respectively) in soil based on current swine manure application practices. Calculations were made for 3 different inclusion rates of copper (4, 35, and 100 ppm) and zinc (60, 100, and 150) in grow-finish swine diets. Jondreville et al. (2002) reported that
feeding 4 ppm of copper to grow-finish swine will produce manure copper concentrations that will only accumulate to toxic levels in soil after 647 years of application. However, feeding 100 ppm of copper to grow-finish swine may result in toxic copper levels after 16 years. Revy et al. (2003) reported that feeding 60 ppm of zinc to grow-finish swine will produce manure zinc concentrations that will only accumulate to toxic levels in soil after 270 years of application. Feeding 150 ppm of zinc, on the other hand, may result in toxic zinc levels after 55 years. Based on these findings, traditional practices of trace mineral supplementation should be reviewed and/or revised.

The aforementioned concerns have led to increased restriction of trace mineral supplementation in several countries. The European Union has set maximum levels (mg/kg) of Fe, Cu, and Zn in pig diets at 750, 25, and 150, respectively.

In summary, soil build-up of trace minerals can occur over long periods of repeated swine manure application. Studies have shown that copper and zinc can accumulate to levels that are toxic to grazing animals and plants. An acceptable rate of application and/or maximum time period to prevent trace mineral accumulation has not been established.
CHAPTER 3. THE EFFECT OF REDUCED LEVELS OF INORGANIC AND ORGANIC TRACE MINERAL SUPPLEMENTATION ON PERFORMANCE, CARCASS TRAITS, AND FECAL EXCRETION OF GROW-FINISH SWINE

A paper to be published in the Journal of Animal Science


ABSTRACT

An experiment was conducted to compare the effect of 2 levels of inorganic and 2 levels of organic (Bioplex, Alltech Inc., Nicholasville, KY) trace mineral (Cu, Fe, and Zn) supplementation on performance, carcass characteristics, and mineral excretion of grow-finish swine. Crossbred barrows and gilts (n = 559; 24.89 ± 0.42 kg) were blocked by weight, penned by sex, and randomly assigned to 1 of 4 dietary treatments. A basal diet was utilized for all 4 dietary phases and treatments and contained inorganic forms of Cu, Fe, and Zn at concentrations of 6, 71, and 30 mg/kg, respectively, for phase 1 (as-fed basis). Treatment 1 was supplemented (amount added to the basal diet) with Cu as CuSO4, Fe as FeSO4, and Zn (25% was ZnO and 75% was ZnSO4) at concentrations of 20, 24, and 33 mg/kg, respectively,
for phase 1 (as-fed basis). Treatment 2 was supplemented with organic sources of Cu, Fe, and Zn at concentrations of 3, 15, and 15 mg/kg, respectively, for phase 1 (as-fed basis).

Supplemental levels of Cu, Fe, and Zn from treatment 1 and treatment 2 were reduced by 60% for treatment 3 and treatment 4, respectively. Estimates of 10th rib backfat and loin muscle area were obtained using real-time ultrasound on all pigs prior to harvest (BW = 114 kg). Pigs fed treatment 1 consumed more feed per day than those fed treatment 3 (P = 0.003). There were no treatment differences for ADG, G:F, backfat, loin muscle area, lean efficiency, and carcass percent lean (P = 0.10, 0.15, 0.31, 0.71, 0.38, and 0.54, respectively). Pigs fed inorganic trace minerals excreted more (P < 0.05) Cu than those fed organic forms during the entire grow-finish period. No treatment differences were found in fecal Fe concentrations (P = 0.56). A gradient reduction (P < 0.05) was observed in fecal Zn concentrations in pigs fed treatments 1, 2, 3, and 4, respectively, during phase 4 and for the entire grow-finish period. Signs of parakeratosis were observed in 0.0, 0.7, 8.9, and 3.6% of pigs fed treatments 1, 2, 3, and 4, respectively. In conclusion, organic trace minerals can be supplemented in place of inorganic forms in grow-finish swine diets to reduce fecal mineral concentrations. And, both inorganic and organic trace minerals can be fed at reduced levels to decrease fecal trace mineral concentrations without affecting growth, feed efficiency and carcass characteristics. However, under increased levels of stress, mineral deficiency symptoms may occur more frequently.

Key Words: [Fecal excretion, Growth, Pigs, Trace minerals]

INTRODUCTION

Traditionally, diets fed to grow-finish swine have been formulated to contain excess trace minerals above NRC requirements to account for low absorption and retention of
inorganic metals, to maximize performance (Carlson et al., 1999; Hill et al., 2000), and to provide a safety margin in times of stress. Trace minerals, such as Cu and Zn, fed at levels exceeding animal requirements are excreted and can build up in soils and reach levels which are toxic to plant growth (Tucker, 1997). Other concerns with intense manure application include toxicity to grazing animals (Lopez Alonso et al., 2000) and aquatic species (Besser, 2001) through ground water, soil erosion, and water runoff.

A potential solution to these environmental concerns is the utilization of chelated or organic trace minerals. The bioavailability of organic trace minerals has been reported to be as much as 206% when compared to inorganic trace minerals in poultry (Wedekind et al., 1992). Experiments examining the effect of organic trace mineral supplementation in grow-finish swine have reported a reduction in fecal trace mineral concentrations without sacrificing growth and feed efficiency (Creech et al., 2004; Burkett et al., 2006). In addition, experiments evaluating the effect of feeding reduced levels of inorganic or organic trace minerals to swine have reported little or no difference in growth and feed efficiency (Creech et al., 2004; van Heugten et al., 2004; Burkett et al., 2006). These studies have all resulted in significant reductions in fecal trace mineral concentrations. Lower inclusion levels of trace minerals in grow-finish swine diets may further reduce fecal excretion. The current study was conducted to evaluate the effect of reducing organic and inorganic forms of Cu, Fe, and Zn on growth, feed efficiency, carcass traits, and fecal trace mineral concentrations of grow-finish swine.
MATERIALS AND METHODS

Experimental Design

Experimental procedures for this study were approved by the Iowa State University Institutional Animal Care and Use Committee. Crossbred barrows and gilts (n = 559; 24.89 ± 0.42 kg) were blocked by weight, penned by sex, and randomly assigned to 4 dietary treatments. Pigs were housed in 2 adjacent, environmentally controlled buildings with slatted flooring over deep pit manure storage. All pigs were provided ad libitum access to feed and water throughout the grow-finish period. Each pen (2.4 x 3.6 m) had a 2-nipple hanging drinker and a 2-hole self feeder. There were 10 to 12 pigs per pen and 12 pens per treatment. The experiment included 26 pens of barrows and 22 pens of gilts. Treatments 1 and 3 each had 6 pens of each sex, while treatments 2 and 4 each had 5 pens of gilts and 7 pens of barrows. Unhealthy or injured pigs were documented and removed from test.

A 4-phase feeding program was utilized for all pigs according to the following regimen: Phase 1 (24 to 37 kg); phase 2 (37 to 55 kg); phase 3 (55 to 82 kg); and phase 4 (82 to 114 kg). Four dietary treatments were formulated using a complete basal diet, which is presented in Table 1. The basal diet contained Cu as CuSO₄, Fe as FeSO₄, and Zn (25% was ZnO and 75% was ZnSO₄) at concentrations of 6, 71, and 30 mg/kg, respectively, for phase 1 (as-fed basis). Two different levels of Cu, Fe, and Zn were supplemented from either organic (Bioplex, Alltech Inc., Nicholasville, KY) or inorganic sources to form 4 dietary treatments (Table 2). Treatment 1 (TRT 1) was supplemented (amount added to the basal diet) with Cu as CuSO₄, Fe as FeSO₄, and Zn (25% was ZnO and 75% was ZnSO₄) at concentrations of 20, 24, and 33 mg/kg, respectively, for phase 1 (as-fed basis). Treatment 2 (TRT 2) was supplemented (amount added to the basal diet) with Cu, Fe, and Zn from organic sources at
concentrations of 3, 15, and 15 mg/kg, respectively, for phase 1 (as-fed basis). Supplemental levels of Cu, Fe, and Zn from TRT 1 and TRT 2 were reduced by 60% for treatment 3 (TRT 3) and treatment 4 (TRT 4), respectively. Samples of all diets were analyzed (Dairy One Inc., Ithaca, NY) for trace mineral (Table 2) and dry matter content.

**Measurements**

Pigs were removed from test at a mean body weight of 114 kg. Backfat thickness (BF) and loin muscle area (LMA) were measured at the 10th rib by a National Swine Improvement Federation-certified technician using an Aloka 500V ultrasound machine equipped with a 12.5 cm, 3.5 MHz linear array transducer (Corometrics Medical Systems, Inc., Wallingford, CT). Fat-free lean equations (NPPC, 2000) were utilized to estimate kilograms of lean (KL) at market weight and at trial entry:

\[
\text{Market weight lean (kg)} = 0.3782 \times \text{sex (barrow = 1; gilt = 2)} - 2.9488 \times \text{BF (cm)} + 0.3817 \times \text{LMA (cm}^2) + 0.291 \times \text{off-test weight (kg)} - 0.2424
\]

\[
\text{Trial entry lean (kg)} = 0.188 \times \text{on-test weight (kg)} - 1.644
\]

Lean gain on test (LGOT) was calculated by subtracting the estimate of trial entry lean from market weight lean and dividing by days on test. Percent lean on a live basis (PLL) and on a carcass basis (PLC) were computed from ultrasonic measurements (NPPC, 2000). Feed disappearance and BW were measured every 2 wk to determine ADG, ADFI, G:F, and efficiency of lean gain (LE), which was calculated by dividing market weight lean (pen basis) by feed intake (pen basis).

Fecal grab samples were collected from at least 70% of the pigs within every pen during each of the 4 dietary phases. Feed samples of the 4 dietary treatments were collected after each feed delivery. Feed and fecal samples were dried in an oven (Lab Line
Instruments, Inc., Melrose Park, IL) at 55°C for 48 h. Feed and fecal samples were then ground in a sample mill (Cyclotec Sample Mill, Model 1093, Foss Tecator, Hoganas, Sweden) to pass a 1-mm screen. Fecal samples were pooled by pen on an equal weight basis before analysis of Cu, Fe, and Zn concentrations.

Feed and fecal samples were analyzed by Dairy One Inc. (Ithaca, NY) for trace mineral and dry matter content. A Thermo Jarrell Ash IRIS Advantage HX Inductively Coupled Plasma (ICP) Radial Spectrometer (Thermo Electron Corporation, Waltham, MA) was utilized to evaluate trace mineral concentrations. Dry matter content was analyzed by Near Infrared Reflectance Spectroscopy (NIRS) (AOAC, 1995).

An indigestible marker (Celite, World Minerals Inc., Santa Barbara, CA) was included in all diets at 1%. The amount of acid insoluble ash (AIA) in both the feed and excreta samples was determined by utilizing the procedure outlined by Vogtmann et al. (1975). Acid insoluble ash was used in the following formula to determine period feces excretion:

\[
\text{Period feces excretion} = \frac{\text{feed (AIA)} \times \text{period feed consumption}}{\text{feces (AIA)}}
\]

Apparent digestibility values for Cu, Fe, and Zn during each collection phase were calculated according to the procedures outlined by Dove (1995):

\[
\text{Apparent nutrient digestibility} = 100 \times \frac{\text{total period intake} - \text{period feces excretion}}{\text{total period intake}}
\]

**Statistical Analyses**

Data were analyzed as a general randomized complete block design using the PROC MIXED procedure in SAS (SAS, 2003). Pen was the experimental unit in all analyses. The initial model for performance and carcass traits included fixed effects of barn, treatment, and
sex, and all 2- and 3-way main effect interactions. Pen nested within barn, sex, and treatment were included as random effects. Off-test weight was a covariate for the analyses of BF and LMA. On-test weight was a covariate for the analyses of ADG, LGOT, ADFI, G:F, and LE. The initial model for fecal analyses included fixed effects of barn, treatment, sex, and phase, and all 2- and 3-way main effect interactions. Average daily feed intake was a covariate in the analyses of fecal Cu, Fe, and Zn concentrations. Interactions of main effects found to be non-significant were eliminated from the final models. Least squares means were compared using the PDIFF option in SAS when a fixed effect was a significant source of variation. The number of pigs exhibiting mineral deficiency symptoms was analyzed using Fisher’s Exact Test in SAS. Statistical significance was declared at P < 0.05 and trends were reported at an alpha level between 0.05 and 0.10.

RESULTS AND DISCUSSION

Performance

Pigs fed TRT 1 consumed more feed per day than pigs fed TRT 3 (P = 0.003) (Table 3). Pigs consuming TRT 1 tended to eat more feed per day than those consuming TRT 2 and TRT 4 (P = 0.055 and 0.054, respectively). These results are in agreement with Burkett et al. (2006), who found that grow-finish swine fed total dietary concentrations of 23, 263, and 64 mg/kg of inorganic Cu, Fe, and Zn, respectively, consumed more (P < 0.05) feed, but did not grow faster than those pigs fed 10, 251, and 81 mg/kg of the same minerals in organic form. However, in another trial, Burkett et al. (2006) found that pigs fed the highest inclusion level of inorganic Cu, Fe, and Zn (63, 378, and 157 mg/kg, respectively) consumed less feed than those pigs fed reduced levels of the same trace minerals in organic form. In spite of the variation reported in ADFI, no treatment differences were found for ADG (P = 0.10). Other
studies testing the efficacy of feeding reduced levels of organic or inorganic trace minerals to grow-finish swine have found no difference in ADG and ADFI. van Huegten et al. (2004) found no differences in ADG and ADFI between grow-finish swine fed normal (17, 506, and 181 mg/kg of Cu, Fe, and Zn, respectively) and reduced (12, 389, and 80 mg/kg of Cu, Fe, and Zn, respectively) levels of inorganic trace minerals. Creech et al. (2004) compared pigs fed a control diet (28, 179, and 318 mg/kg of Cu, Zn, and Fe, respectively, during the grower phase) from weaning to market weight with those fed reduced levels of inorganic (8, 96, and 257 mg/kg of Cu, Zn, and Fe, respectively, during the grower phase) and organic trace minerals (12, 91, and 351 mg/kg of Cu, Zn, and Fe, respectively, during the grower phase). No treatment differences were reported by Creech et al. (2004) for ADG, ADFI, and G:F. No differences between treatments were observed in the present study for G:F (P = 0.15).

Reductions in ADFI and ADG for pigs fed the lowest inorganic (TRT 3) and organic (TRT 4) trace mineral concentrations may be a sign of Zn deficiency. Based on NRC (1998) requirements, Zn was the most limiting of the 3 trace minerals fed at reduced levels. Analyzed concentrations of Zn were below NRC (1998) requirements for treatments 2, 3, and 4 during phases 1 and 2. Signs of parakeratosis were observed in 0, 0.7, 8.9, and 3.6% of pigs fed treatments 1, 2, 3, and 4, respectively. The majority of the symptoms documented were noticed during phase 4. The number of pigs exhibiting signs of parakeratosis was greater for TRT 3 when compared to TRT 1 and TRT 2 (P < 0.01), but did not differ from TRT 4 (P = 0.06). Parakeratosis, reduced appetite, and retarded growth are all signs of Zn deficiency (Liptrap et al., 1970). Liptrap et al. (1970) reported that grow-finish barrows and gilts fed 53 or 80 mg/kg of Zn grew faster and consumed more feed than those fed 22 mg/kg of Zn, which is in agreement with the results of the current study.
Differences observed in ADG, ADFI, and G:F between sexes were in agreement with Burkett et al. (2006). Barrows grew faster, consumed more feed, and were less efficient than gilts (P < 0.01).

**Carcass Characteristics**

There were no treatment differences for LGOT, LMA, BF, LE, KL, PLL, and PLC (P = 0.06, 0.71, 0.31, 0.38, 0.39, 0.54, and 0.63, respectively) (Table 3). These results are in agreement with those of Burkett et al. (2006) who found no differences in LMA, BF, LE, KL, PLL, and PLC between pigs fed several different levels of inorganic and organic Cu, Fe, and Zn. van Heugten et al. (2004) reported no differences in fat depth, loin depth, and percent lean between pigs fed normal or reduced levels of inorganic Cu, Fe, Zn, and Mn. It appears that replacing inorganic trace minerals with organic forms has little or no impact on carcass characteristics. Furthermore, feeding reduced levels of either inorganic or organic trace minerals to grow-finish swine has no influence on carcass characteristics. No trace mineral supplementation has also been previously shown to have no effect on BF or LMA (Burkett et al., 2006).

Sex differences in carcass traits were in agreement with those found by Burkett et al. (2006). Gilts were heavier muscled, leaner, and had a greater percent lean (P < 0.01).

**Fecal Excretion**

Pigs fed TRT 1 (inorganic trace minerals) excreted the greatest (P < 0.01) amount of fecal Cu during each of the 4 collection phases (Table 4). Pigs fed TRT 3 (inorganic) excreted more (P < 0.05) fecal Cu than TRT 2 (organic) and TRT 4 (organic) during phases 1, 3, 4, and overall. Pigs fed TRT 2 excreted greater (P < 0.05) concentrations of fecal Cu compared to those fed TRT 4 during phases 3, 4, and overall. These results are in agreement
with those of Burkett et al. (2006), who, in 2 trials, reported a reduction in fecal Cu excretion in grow-finish swine fed organic Cu at concentrations of 21 and 12 mg/kg compared with those fed inorganic Cu at concentrations of 63 and 23 mg/kg, respectively. Burkett et al. (2006) found that feeding reduced levels of organic or inorganic Cu to grow-finish swine resulted in a reduction of fecal Cu concentrations. Similar results were found by van Heugten et al. (2004), who reported a 36% decrease in fecal Cu concentrations in grow-finish swine fed 12 mg/kg of inorganic Cu compared with those fed 17 mg/kg of inorganic Cu. Creech et al. (2004) reported a decrease in fecal Cu concentrations in growing pigs supplemented with 5 mg/kg of chelated Cu compared with those supplemented with 5 mg/kg of inorganic Cu.

Apparent digestibility values for Cu were lowest (P < 0.05) for pigs fed TRT 3 compared to all other treatments during phase 3 and for the entire grow-finish period (Table 4). These results agree with those of Burkett et al. (2006), who reported lower apparent digestibility values for Cu in grow-finish swine fed 63 or 23 mg/kg of inorganic Cu compared with those fed 10 to 21 mg/kg of organic Cu.

No differences were found in fecal Fe concentrations (P = 0.56) between treatments (Table 5). Burkett et al. (2006) reported no differences in fecal Fe excretion in grow-finish swine fed 251 to 321 mg/kg of organic Fe compared with those fed 263 mg/kg of inorganic Fe. However, in another trial, Burkett et al. (2006) reported a gradient reduction in fecal Fe concentrations in grow-finish swine fed decreasing levels of inorganic and organic Fe. van Heugten et al. (2004) reported a 34% reduction in fecal Fe concentrations in grow-finish swine fed 389 mg/kg of inorganic Fe compared with those fed 506 mg/kg of Fe from the same source. Creech et al. (2004) reported a reduction (P < 0.10) in fecal Fe concentrations during the nursery phase, but not the growing phase, in pigs supplemented with 25 mg/kg of
organic Fe compared with those supplemented with 25 mg/kg of inorganic Fe. However, in the current study, analyzed dietary Fe concentrations were greater and more inconsistent than formulated concentrations, which likely impacted fecal Fe concentrations. One possible explanation for an increase in reported analyzed Fe concentrations in the feed includes Fe contamination from sources such as dicalcium phosphate or calcium carbonate. In addition, the analytical error of the procedures used to measure Fe concentrations in the feed and feces was estimated to be 4%. No treatment differences were found in Fe apparent digestibility (P = 0.16) in the current study (Table 5).

A gradient reduction was observed in fecal Zn concentrations in pigs fed treatments 1, 2, 3, and 4, respectively, during phase 4 and for the entire grow-finish period (Table 6). These results are in agreement with those of Burkett et al. (2006), who reported the same occurrence in grow-finish swine fed decreasing levels of inorganic and organic Zn. van Heugten et al. (2004) reported a 68% reduction in fecal Zn concentrations in grow-finish swine fed 80 mg/kg of inorganic Zn compared with those fed 181 mg/kg of Zn from the same source. Creech et al. (2004) reported a reduction (P < 0.01) in fecal Zn excretion in nursery pigs supplemented with 25 mg/kg of organic Zn compared with those supplemented with 25 mg/kg of inorganic Zn.

Apparent digestibility values for Zn were greater (P < 0.01) for pigs fed TRT 2 compared with those fed TRT 1 during the entire grow-finish period (Table 6). Greater Zn apparent digestibility values were observed in pigs fed TRT 3 compared with those fed TRT 1 and TRT 4 (P < 0.01) during the entire grow-finish period. Burkett et al. (2006) reported greater apparent digestibility values for Zn in grow-finish swine fed 277, 259, or 303 mg/kg of organic Zn compared with those fed 378 mg/kg of inorganic Zn. In contrast, Swinkels et
al. (1996) observed no differences in Zn bioavailability (based on serum and soft tissue Zn concentrations) between weanling pigs supplemented with 45 mg/kg of ZnSO₄ and those supplemented with 45 mg/kg of Zn amino acid chelate. Based on the findings of this study and others, we were unable to determine if there is a significant difference in Zn bioavailability in swine between inorganic and organic sources.

No differences were observed between sexes for fecal mineral concentrations or apparent digestibility values (P < 0.05).

Another alternative that may reduce fecal trace mineral concentrations in the grow-finish phase, which was not a focus of this study, is trace mineral withdrawal prior to slaughter. Removing supplemental mineral premixes from finishing diets 30 d prior to slaughter has been shown to have no effect on gain or feed intake (McGlone, 2000). Shaw et al. (2002) removed trace mineral premixes 28 d prior to slaughter and reported no differences in ADG, ADFI, G:F, and carcass traits, while reducing fecal Cu, Fe, Zn, and Mn concentrations.

In conclusion, reducing trace mineral concentrations in grow-finish swine diets, as well as replacing inorganic trace minerals with organic forms, both appear to be effective methods to decrease fecal mineral concentrations.

**IMPLICATIONS**

Organic trace minerals can be supplemented in place of inorganic forms in grow-finish swine diets to reduce fecal concentrations of these nutrients. Both organic and inorganic trace minerals can be fed to grow-finish swine at reduced levels to decrease fecal trace mineral concentrations without adversely affecting growth, feed efficiency, and carcass characteristics. However, the pigs in the current study underwent minimal health challenges
in an environmentally controlled building. Under increased levels of stress due to health or environmental conditions, mineral deficiency symptoms may occur more frequently and become more detrimental in pigs fed reduced levels of trace minerals.

**LITERATURE CITED**


Table 1. Composition (as-fed basis) of the basal diet in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on performance, carcass characteristics and fecal excretion of grow-finish swine (24 to 114 kg BW)

<table>
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<th>Ingredient composition</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24 to 37 kg</td>
<td>37 to 55 kg</td>
<td>55 to 82 kg</td>
<td>82 to 114 kg</td>
</tr>
<tr>
<td>Ground yellow dent corn, %</td>
<td>67.25</td>
<td>69.50</td>
<td>73.50</td>
<td>78.75</td>
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<tr>
<td>Soybean meal (47.5%), %</td>
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<td>21.00</td>
<td>15.75</td>
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<tr>
<td>Trace mineral mix, %</td>
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<td>3.00</td>
<td>2.50</td>
<td>2.50</td>
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<tr>
<td>Choice white grease, %</td>
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<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
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<td>Celite, %</td>
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<td>1.00</td>
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</table>

Formulated content

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<tr>
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<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude fat, %</td>
<td>4.91</td>
<td>4.98</td>
<td>5.09</td>
<td>5.25</td>
</tr>
<tr>
<td>Crude fiber, %</td>
<td>2.77</td>
<td>2.75</td>
<td>2.73</td>
<td>2.69</td>
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<td>Lysine, %</td>
<td>1.12</td>
<td>1.05</td>
<td>0.93</td>
<td>0.79</td>
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<td>Available lysine, %</td>
<td>0.94</td>
<td>0.88</td>
<td>0.78</td>
<td>0.65</td>
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<tr>
<td>Tryptophan, %</td>
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<td>0.21</td>
<td>0.19</td>
<td>0.15</td>
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<td>Threonine, %</td>
<td>0.75</td>
<td>0.71</td>
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<tr>
<td>Methionine, %</td>
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<td>0.31</td>
<td>0.29</td>
<td>0.27</td>
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<tr>
<td>Ash, %</td>
<td>5.03</td>
<td>4.93</td>
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<td>NaCl, %</td>
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<td>0.52</td>
<td>0.45</td>
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Analyzed content

<table>
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<tr>
<th></th>
<th>24 to 37 kg</th>
<th>37 to 55 kg</th>
<th>55 to 82 kg</th>
<th>82 to 114 kg</th>
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<tbody>
<tr>
<td>DM, %</td>
<td>85.58</td>
<td>85.11</td>
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<tr>
<td>CP, %</td>
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<td>15.74</td>
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<td>Ca, %</td>
<td>0.86</td>
<td>0.66</td>
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<td>P, %</td>
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<td>0.58</td>
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<td>Na, %</td>
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<td>0.18</td>
<td>0.19</td>
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<tr>
<td>Cu, ppm</td>
<td>6.47</td>
<td>6.17</td>
<td>5.70</td>
<td>5.02</td>
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<td>Fe, ppm</td>
<td>71.15</td>
<td>68.94</td>
<td>63.35</td>
<td>58.21</td>
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<td>Zn, ppm</td>
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<td>19.50</td>
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<td>Mo, ppm</td>
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<td>ME, kcal/kg</td>
<td>3410.00</td>
<td>3370.00</td>
<td>3350.00</td>
<td>3330.00</td>
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</tbody>
</table>

1Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW.

2Inorganic trace minerals were supplemented from a commercially available trace mineral premix which contained Cu as CuSO₄, Fe as FeSO₄, and Zn (25% was ZnO and 75% was ZnSO₄).

3Celite diatomaceous earth was added as an indigestible marker (World Minerals Inc., Santa Barbara, CA).
Table 2. Supplemental and total analyzed diet concentrations (as fed) of Cu, Fe, and Zn in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on performance, carcass characteristics and fecal excretion of grow-finish swine (24 to 114 kg BW).

<table>
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<tr>
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<th>Treatment&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Phase&lt;sup&gt;1&lt;/sup&gt;</th>
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<th>3</th>
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<sup>1</sup>Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW.

<sup>2</sup>Treatments 1 and 3 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO<sub>4</sub>, Fe as FeSO<sub>4</sub>, and Zn (25% as ZnO and 75% as ZnSO<sub>4</sub>)); Treatments 2 and 4 - Cu, Fe, and Zn supplemented from organic sources. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively, for phase 1. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).

<sup>3</sup>Supplemental concentrations (amount added to the basal diet) for treatments 1 and 3 were in inorganic form, while supplemental levels for treatments 2 and 4 were in organic form.

<sup>4</sup>Total analyzed dietary concentrations (basal diet plus supplemental levels).

<sup>5</sup>NRC – values were extrapolated using a polynomial function of the requirement in NRC (1998) based on the average weight for the phase and the requirement reported for that phase.
Table 3. Least squares means (on a pen basis) for performance and carcass traits in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on performance, carcass characteristics and fecal excretion of grow-finish swine (24 to 114 kg BW)\(^1\)

<table>
<thead>
<tr>
<th>Traits(^3)</th>
<th>Treatment(^2)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMA, cm(^2)</td>
<td></td>
<td>41.93</td>
<td>42.31</td>
<td>41.81</td>
<td>42.55</td>
<td>0.500</td>
</tr>
<tr>
<td>BF, mm</td>
<td></td>
<td>22.43</td>
<td>21.44</td>
<td>21.59</td>
<td>21.93</td>
<td>0.400</td>
</tr>
<tr>
<td>ADG, kg/day</td>
<td></td>
<td>0.93</td>
<td>0.91</td>
<td>0.90</td>
<td>0.90</td>
<td>0.010</td>
</tr>
<tr>
<td>LGO, kg/day</td>
<td></td>
<td>0.42</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.004</td>
</tr>
<tr>
<td>ADFI, kg/day</td>
<td></td>
<td>2.49(^a)</td>
<td>2.44(^{ab})</td>
<td>2.41(^b)</td>
<td>2.44(^{ab})</td>
<td>0.019</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
<td>0.003</td>
</tr>
<tr>
<td>G:F</td>
<td></td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
<td>0.37</td>
<td>0.003</td>
</tr>
<tr>
<td>KL, kg</td>
<td></td>
<td>42.72</td>
<td>43.57</td>
<td>43.06</td>
<td>43.22</td>
<td>0.300</td>
</tr>
<tr>
<td>PLL, %</td>
<td></td>
<td>37.65</td>
<td>38.04</td>
<td>37.83</td>
<td>38.02</td>
<td>0.210</td>
</tr>
<tr>
<td>PLC, %</td>
<td></td>
<td>50.93</td>
<td>51.36</td>
<td>51.11</td>
<td>51.39</td>
<td>0.280</td>
</tr>
</tbody>
</table>

\(^a\)Within a row, means without a common superscript letter differ (P < 0.05).
\(^1\)Means reported for all performance traits only reflect pigs that remained in the experiment for the entire test period.
\(^2\)Treatment 1 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO\(_4\), Fe as FeSO\(_4\), and Zn (25% as ZnO and 75% as ZnSO\(_4\)) at concentrations of 20, 24, and 33 mg/kg, respectively; Treatment 2 - Cu, Fe, and Zn supplemented from organic sources at concentrations of 3, 15, and 15 mg/kg, respectively; Treatment 3 - 60% reduction in micromineral concentration from treatment 1; Treatment 4 - 60% reduction in micromineral concentration from treatment 2. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).
\(^3\)LMA = loin muscle area, BF = tenth-rib backfat, ADG = average daily gain, LGO = lean gain on test, ADFI = average daily feed intake, LE = lean efficiency, G:F = feed efficiency, KL = kilograms of lean, PLL = percent lean live, PLC = percent lean carcass.
Table 4. Least squares means (±SE) for fecal Cu concentration (DM basis) and apparent digestibility in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on grow-finish swine (24 to 114 kg BW)

<table>
<thead>
<tr>
<th>Trait</th>
<th>Treatment</th>
<th>Phase</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Cu, mg/kg</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>64±9</td>
<td>71±5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>79±9</td>
<td>63±5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>56±9</td>
<td>67±5</td>
</tr>
<tr>
<td>Apparent digestibility, %</td>
<td>1</td>
<td>6±8</td>
<td>9±8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10±8</td>
<td>9±8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16±8</td>
<td>5±8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7±8</td>
<td>-29±8</td>
</tr>
</tbody>
</table>

Within a column, means without a common superscript letter differ (P < 0.05).

1Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW. The number of days on feed for each phase was as follows: Phase 1: Barn 1 = 24 days, Barn 2 = 23 days; Phase 2: Barn 1 and 2 = 17 days; Phase 3: Barn 1 = 25 days, Barn 2 = 24 days; Phase 4: Barn 1 = 22 to 36 days, Barn 2 = 23 to 39 days.

2Treatment 1 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO₄, Fe as FeSO₄, and Zn (25% as ZnO and 75% as ZnSO₄)) at concentrations of 20, 24, and 33 mg/kg, respectively; Treatment 2 - Cu, Fe, and Zn supplemented from organic sources at concentrations of 3, 15, and 15 mg/kg, respectively; Treatment 3 - 60% reduction in micromineral concentration from treatment 1; Treatment 4 - 60% reduction in micromineral concentration from treatment 2. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).
Table 5. Least squares means (±SE) for fecal Fe concentration (DM basis) and apparent digestibility in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on grow-finish swine (24 to 114 kg BW)

<table>
<thead>
<tr>
<th>Trait</th>
<th>Treatment</th>
<th>Phase</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Fecal Fe, mg/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1354&lt;sup&gt;b&lt;/sup&gt; ± 98</td>
<td>1165&lt;sup&gt;b&lt;/sup&gt; ± 71</td>
<td>1099 ± 64</td>
</tr>
<tr>
<td>2</td>
<td>1399&lt;sup&gt;ab&lt;/sup&gt; ± 99</td>
<td>1058&lt;sup&gt;bc&lt;/sup&gt; ± 56</td>
<td>1130 ± 58</td>
</tr>
<tr>
<td>3</td>
<td>1519&lt;sup&gt;a&lt;/sup&gt; ± 99</td>
<td>1015&lt;sup&gt;c&lt;/sup&gt; ± 56</td>
<td>1140 ± 57</td>
</tr>
<tr>
<td>4</td>
<td>1269&lt;sup&gt;b&lt;/sup&gt; ± 99</td>
<td>1312&lt;sup&gt;a&lt;/sup&gt; ± 55</td>
<td>1070 ± 60</td>
</tr>
<tr>
<td>Apparent digestibility, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
<td>22&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>15 ± 4</td>
</tr>
<tr>
<td>2</td>
<td>21&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>16&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>19 ± 4</td>
</tr>
<tr>
<td>3</td>
<td>4&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
<td>15&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>4</td>
<td>21&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>3&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
<td>18 ± 4</td>
</tr>
</tbody>
</table>

<sup>abc</sup>Within a column, means without a common superscript letter differ (P < 0.05).

<sup>1</sup>Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW. The number of days on feed for each phase was as follows: Phase 1: Barn 1 – 24 days, Barn 2 – 23 days; Phase 2: Barn 1 and 2 – 17 days; Phase 3: Barn 1 – 25 days, Barn 2 – 24 days; Phase 4: Barn 1 – 22 to 36 days, Barn 2 – 23 to 39 days.

<sup>2</sup>Treatment 1 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO₄, Fe as FeSO₄, and Zn (25% as ZnO and 75% as ZnSO₄)) at concentrations of 20, 24, and 33 mg/kg, respectively; Treatment 2 - Cu, Fe, and Zn supplemented from organic sources at concentrations of 3, 15, and 15 mg/kg, respectively; Treatment 3 - 60% reduction in micromineral concentration from treatment 1; Treatment 4 - 60% reduction in micromineral concentration from treatment 2. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).
Table 6. Least squares means (±SE) for fecal Zn concentration (DM basis) and apparent digestibility in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on grow-finish swine (24 to 114 kg BW)

<table>
<thead>
<tr>
<th>Trait</th>
<th>Treatment&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Phase</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Fecal Zn, mg/kg</td>
<td>307&lt;sup&gt;a&lt;/sup&gt; ± 14</td>
<td>305&lt;sup&gt;a&lt;/sup&gt; ± 8</td>
<td>318&lt;sup&gt;a&lt;/sup&gt; ± 9</td>
</tr>
<tr>
<td></td>
<td>255&lt;sup&gt;b&lt;/sup&gt; ± 15</td>
<td>250&lt;sup&gt;b&lt;/sup&gt; ± 8</td>
<td>264&lt;sup&gt;b&lt;/sup&gt; ± 9</td>
</tr>
<tr>
<td></td>
<td>218&lt;sup&gt;c&lt;/sup&gt; ± 15</td>
<td>213&lt;sup&gt;c&lt;/sup&gt; ± 8</td>
<td>280&lt;sup&gt;c&lt;/sup&gt; ± 8</td>
</tr>
<tr>
<td></td>
<td>215&lt;sup&gt;d&lt;/sup&gt; ± 15</td>
<td>215&lt;sup&gt;d&lt;/sup&gt; ± 8</td>
<td>206&lt;sup&gt;d&lt;/sup&gt; ± 9</td>
</tr>
<tr>
<td>Apparent digestibility, %</td>
<td>27&lt;sup&gt;ab&lt;/sup&gt; ± 4</td>
<td>16&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
<td>28&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
</tr>
<tr>
<td></td>
<td>27&lt;sup&gt;ab&lt;/sup&gt; ± 4</td>
<td>35&lt;sup&gt;c&lt;/sup&gt; ± 4</td>
<td>46&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
</tr>
<tr>
<td></td>
<td>38&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>35&lt;sup&gt;a&lt;/sup&gt; ± 4</td>
<td>37&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
</tr>
<tr>
<td></td>
<td>26&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
<td>34&lt;sup&gt;d&lt;/sup&gt; ± 4</td>
<td>30&lt;sup&gt;b&lt;/sup&gt; ± 4</td>
</tr>
</tbody>
</table>

<sup>abc</sup>Within a column, means without a common superscript letter differ (P < 0.05).

<sup>1</sup>Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW. The number of days on feed for each phase was as follows: Phase 1: Barn 1 – 24 days, Barn 2 – 23 days; Phase 2: Barn 1 and 2 – 17 days; Phase 3: Barn 1 – 25 days, Barn 2 – 24 days; Phase 4: Barn 1 – 22 to 36 days, Barn 2 – 23 to 39 days.

<sup>2</sup>Treatment 1 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO<sub>4</sub>, Fe as FeSO<sub>4</sub>, and Zn (25% as ZnO and 75% as ZnSO<sub>4</sub>)) at concentrations of 20, 24, and 33 mg/kg, respectively; Treatment 2 - Cu, Fe, and Zn supplemented from organic sources at concentrations of 3, 15, and 15 mg/kg, respectively; Treatment 3 - 60% reduction in micromineral concentration from treatment 1; Treatment 4 - 60% reduction in micromineral concentration from treatment 2. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).
Table 7. Least squares means (±SE) for fecal dry matter content (%) and fecal mass (kg) in a study comparing the effect of reduced levels of inorganic and organic trace mineral (Cu, Fe, and Zn) supplementation on grow-finish swine (24 to 114 kg BW)

<table>
<thead>
<tr>
<th>Trait</th>
<th>Treatment(^1)</th>
<th>Phase(^1)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal dry matter (%)</td>
<td></td>
<td>1</td>
<td>25.7(^{ab}) ± 0.3</td>
<td>27.3 ± 0.3</td>
<td>28.0(^{bc}) ± 0.3</td>
<td>29.1 ± 0.3</td>
<td>27.51(^{ab}) ± 0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>25.4(^{b}) ± 0.3</td>
<td>27.2 ± 0.3</td>
<td>28.7(^{b}) ± 0.3</td>
<td>29.2 ± 0.3</td>
<td>27.60(^{b}) ± 0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>26.3(^{a}) ± 0.3</td>
<td>27.8 ± 0.3</td>
<td>28.9(^{a}) ± 0.3</td>
<td>29.8 ± 0.3</td>
<td>28.20(^{a}) ± 0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>24.9(^{ab}) ± 0.3</td>
<td>27.6 ± 0.3</td>
<td>28.1(^{ab}) ± 0.3</td>
<td>29.0 ± 0.3</td>
<td>27.47(^{ab}) ± 0.16</td>
</tr>
<tr>
<td>Fecal mass (kg, DM basis)(^3)</td>
<td></td>
<td>1</td>
<td>0.239 ± 0.012</td>
<td>0.382(^{a}) ± 0.012</td>
<td>0.386(^{a}) ± 0.012</td>
<td>0.404(^{ab}) ± 0.012</td>
<td>0.353(^{a}) ± 0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.262 ± 0.012</td>
<td>0.367(^{b}) ± 0.012</td>
<td>0.346(^{b}) ± 0.012</td>
<td>0.378(^{bc}) ± 0.012</td>
<td>0.339(^{bc}) ± 0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.255 ± 0.012</td>
<td>0.323(^{a}) ± 0.012</td>
<td>0.361(^{ab}) ± 0.012</td>
<td>0.362(^{c}) ± 0.012</td>
<td>0.326(^{bc}) ± 0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.241 ± 0.012</td>
<td>0.353(^{ab}) ± 0.012</td>
<td>0.361(^{ab}) ± 0.012</td>
<td>0.411(^{a}) ± 0.012</td>
<td>0.342(^{ab}) ± 0.006</td>
</tr>
</tbody>
</table>

\(^{a,b,c}\)Within a column, means without a common superscript letter differ (P < 0.05).

\(^1\)Phase 1 - diet fed from 24-37 kg BW; Phase 2 - diet fed from 37-55 kg BW; Phase 3 - diet fed from 55-82 kg BW; Phase 4 - diet fed from 82-114 kg BW. The number of days on feed for each phase was as follows: Phase 1: Barn 1 – 24 days, Barn 2 – 23 days; Phase 2: Barn 1 and 2 – 17 days; Phase 3: Barn 1 – 25 days, Barn 2 – 24 days; Phase 4: Barn 1 – 22 to 36 days, Barn 2 – 23 to 39 days.

\(^2\)Treatment 1 - Cu, Fe, and Zn supplemented from inorganic sources (Cu as CuSO\(_4\), Fe as FeSO\(_4\), and Zn (25% as ZnO and 75% as ZnSO\(_4\))) at concentrations of 20, 24, and 33 mg/kg, respectively; Treatment 2 - Cu, Fe, and Zn supplemented from organic sources at concentrations of 3, 15, and 15 mg/kg, respectively; Treatment 3 - 60% reduction in micromineral concentration from treatment 1; Treatment 4 - 60% reduction in micromineral concentration from treatment 2. The basal diet contained Cu, Fe, and Zn from inorganic sources at concentrations of 6, 71, and 30 mg/kg, respectively. All organic minerals were Bioplex products (Alltech Inc., Nicholasville, KY).

\(^3\)Fecal mass is presented as kg/pig/d.
CHAPTER 4. GENERAL SUMMARY

Minimizing the environmental impact from swine production will continue to increase in priority. One potentially negative impact is that of soil nutrient accumulation. Long-term manure application can cause nutrients, such as trace minerals, to build-up in the soil, especially if high levels of these nutrients are included in the diet. The obvious solution to this concern would be to decrease added levels of trace minerals, such as Cu, Fe, and Zn, in pig diets. For instance, the European Union has already banned high inclusion levels of several trace minerals. However, another resolution could be through the use of organic forms of trace minerals. Organic or chelated minerals have been suggested due to increased bioavailability, which allows producers to lower inclusion levels of trace minerals in the diet, resulting in a reduction in fecal mineral excretion.

The objective of this thesis was to determine if feeding reduced levels of organic or inorganic forms of Cu, Fe, Zn to grow-finish swine impacted performance, carcass traits, or fecal excretion. To accomplish this, four dietary treatments were formulated.

No treatment differences were noted in growth, feed efficiency, and carcass characteristics. Pigs fed the highest concentration of inorganic trace minerals consumed more feed than all other treatments. Pigs fed organic trace minerals excreted less copper than those pigs fed inorganic trace minerals. Pigs fed the lowest levels of trace minerals, in either organic or inorganic form, excreted less zinc than those pigs fed higher levels of trace minerals. No treatment differences were reported in fecal iron concentrations.

The results from this study suggest that organic trace minerals can be supplemented in place of inorganic forms in grow-finish swine diets to reduce fecal mineral concentrations. And, both organic and inorganic trace minerals can be fed to grow-finish swine at reduced
levels to decrease fecal trace mineral concentrations without adversely affecting growth, feed efficiency, and carcass traits. However, it should be noted that the pigs in this study were extremely healthy and were housed in a temperature controlled environment.

Zinc deficiency symptoms were noticed in 8.9 and 3.6% of pigs fed the lowest concentrations of trace minerals from inorganic and organic sources, respectively. Under increased levels of stress, mineral deficiency symptoms may occur more frequently. Future studies should focus on the inclusion of reduced levels of inorganic and organic trace minerals in diets fed to health and/or environmentally challenged, grow-finish swine.
CHAPTER 5. REFERENCES CITED


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Thank you also to my graduate committee for their guidance and encouragement during my years at Iowa State University. A special thanks to Dr. Wendy Powers and Dr. Theodore Bailey for providing their expertise and experience in each of their respective fields.

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