

Effects of increasing copper and zinc from two different sources and space allowance on nursery and finishing pig growth performance and carcass characteristics

by

Corey Blaine Carpenter

B.S., California State University, Chico, 2013
M.S., Oklahoma State University, 2015

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

Major Professor
Dr. Joel DeRouchey

Copyright

© Corey Blaine Carpenter 2017.

Abstract

Five experiments using a total of 4,470 pigs were used to determine the effects of dietary Cu and Zn source and finishing pig space allowance. Experiment 1 evaluated increasing dietary Zn from Zn hydroxychloride or ZnSO₄ for finishing pigs. Increasing dietary Zn up to 100 mg/kg Zn maximized ADG and HCW with the greatest response observed during the last 37 d period when ractopamine was included in the diet. Pigs fed diets with Zn hydroxychloride had greater HCW compared to those fed ZnSO₄. Experiment 2 evaluated increasing dietary Cu from either CuSO₄ or a 50:50 blend of CuSO₄:Cu-AA for finishing pigs. Pigs fed Cu from CuSO₄ alone consumed more feed and tended to have poorer feed efficiency than those fed a 50:50 blend of Cu from CuSO₄:Cu-AA. Pigs fed a 50:50 blend of CuSO₄:Cu-AA had improved HCW G:F but ADG was unchanged on a live and HCW basis. Experiments 3 and 4 evaluated increasing dietary Cu from tri-basic copper chloride or a Cu-chelate for nursery pigs. In Exp. 3, increasing Cu from Cu-chelate to 150 mg/kg Cu increased ADG and ending BW. Increasing Cu to 150 mg/kg Cu increased ADFI and improved G:F. Pigs fed Cu from Cu-chelate had greater ADG, ADFI and ending BW than those fed Cu from tri-basic copper chloride. In Exp. 4, increasing Cu to 225 mg/kg Cu increased ADG and ending BW. Because ADFI was unchanged, G:F tended to be improved as Cu level increased. There were no differences detected between Cu sources for growth performance. Experiment 5 was conducted to determine the effects of increasing space allowance by pig removal or gate adjustment during the finishing period. Pigs provided 0.91 m² had increased ADG compared with those allowed 0.63 m² with pigs from pens provided increased space intermediate. Pigs provided 0.91 m² had increased ADFI compared with pigs allowed 0.63 m² and those where a pig was removed; however, pigs from pens where the gate was adjusted were intermediate. As pigs grew to the minimum predicted space requirement and

were subsequently allowed more space, performance was greater than those initially provided 0.61 m² but less than those allowed 0.91 m².

Table of Contents

List of Tables	viii
Acknowledgements.....	ix
Dedication.....	x
Chapter 1 - Effects of increasing zinc from zinc sulfate or zinc hydroxychloride on finishing pig growth performance and carcass characteristics.....	1
Abstract.....	1
Introduction.....	2
Materials and Methods.....	3
General	3
Live Animal Management	4
Harvest and Sample collection.....	4
Chemical Analysis	5
Statistical Analysis.....	5
Results.....	6
Diet Analysis.....	6
Growth Performance and Carcass Characteristics	6
Discussion.....	7
Literature Cited.....	12
Chapter 2 - Effects of increasing copper from either copper sulfate or combinations of copper sulfate and a copper-amino acid complex on finishing pig growth performance and carcass characteristics	20
Abstract.....	20
Introduction.....	21
Materials and Methods.....	22
General	22
Live Animal Management	22
Harvest and Sample Collection.....	23
Chemical Analysis	24
Statistical Analysis.....	24

Results.....	24
Diet Analysis.....	24
Growth Performance and Carcass Characteristics	25
Discussion.....	25
Literature Cited.....	28
Chapter 3 - Effects of increasing copper from tri-basic copper chloride or a copper-chelate on growth performance of nursery pigs.....	36
Abstract.....	36
Introduction.....	37
Materials and Methods.....	38
General	38
Live Animal Management, Exp. 1	39
Live Animal Management, Exp. 2.....	39
Diets and Response Criteria.....	39
Chemical Analysis	40
Statistical Analysis.....	41
Results.....	41
Diet Analysis, Exp. 1 and 2	41
Growth Performance, Exp. 1	42
Growth Performance, Exp. 2	43
Discussion.....	43
Literature Cited.....	46
Chapter 4 - Effects of increasing space allowance by removing a pig or gate adjustment on finishing pig growth performance	54
Abstract.....	54
Introduction.....	55
Materials and Methods.....	56
General	56
Live Animal Management	56
Statistical Analysis.....	56
Growth Performance	57

Discussion.....	58
Literature Cited.....	60

List of Tables

Table 1-1 Diet composition (as-fed basis).....	15
Table 1-2 Chemical zinc analysis of diets (as-fed basis) ¹	17
Table 1-3 Effects of increasing Zn from ZnSO ₄ or Zn hydroxychloride on growth performance of pigs ¹	18
Table 1-4 Effects of increasing Zn from SnSO ₄ or Zn hydroxychloride on carcass characteristics of finishing pigs ¹	19
Table 2-1 Diet composition (as-fed basis).....	31
Table 2-2 Chemical copper analysis of diets (as-fed basis) ¹	33
Table 2-3 Effects of increasing Cu from either CuSO ₄ or combinations of CuSO ₄ and Cu-AA on finishing pig growth performance ¹	34
Table 2-4 Effects of increasing Cu from either CuSO ₄ or combinations of CuSO ₄ and Cu-AA on finishing pig carcass characteristics ¹	35
Table 3-1 Diet composition (as-fed basis) ¹	48
Table 3-2 Chemical analysis of diets (as-fed basis) ¹ (Exp. 1).....	50
Table 3-3 Chemical analysis of diets (as-fed basis) ¹ (Exp. 2).....	51
Table 3-4 Effects of increasing Cu from tri-basic copper chloride or Cu-chelate on growth performance of pigs ¹ (Exp. 1).....	52
Table 3-5 Effects of increasing Cu from tri-basic copper chloride or Cu-chelate on growth performance of pigs ¹ (Exp. 2).....	53
Table 4-1 Space allowance and <i>k</i> -value through the experiment ¹	61
Table 4-2 Diet composition (as-fed basis).....	62
Table 4-3 Effects of increasing space allowance by removing a pig or gate adjustment on finishing pig growth performance.....	63

Acknowledgements

This thesis was made possible through the support of many people. Dr. Joel DeRouche and Dr. Jason Woodworth have provided key mentorship and guidance throughout my time at K-State. Dr. Mike Tokach, Dr. Steve Dritz, and Dr. Bob Goodband have all provided a wealth of knowledge and have largely contributed to my success as a graduate student. These professors have dedicated countless hours away from their personal lives in support of helping me reach my own personal goals and aspirations. Their efforts and mentorship does not go unnoticed and I hold a very high level of respect for the contributions they make to the swine industry on many levels.

Many past and current graduate students have supported me in my time at K-State. Dr. Kyle Coble invested a great deal of time and energy into the process of helping me take the next steps in my post-graduate education. I consider myself lucky to have been part of such a strong and lasting tradition of hardworking and bright groups of people that represent the K-State swine nutrition team over the years. I am thankful for and have given much value to the advice and wisdom from many of the recent previous graduates from the K-State swine nutrition program.

A particular thank you to Dr. James Usry (Micronutrients, Indianapolis, IN) and Dr. Zach Rambo (Zinpro Corporation, Eden Prairie, MN) for your direct support in my research during my time here at K-State. I thoroughly enjoyed working with you and your teams.

Mom and Dad it is because of how I was raised that I have such a passion for pigs and agriculture. Josh, thanks for never “letting me win” in our bouts over the years. Kristi, thanks for your everlasting support in my many endeavors! Grandparents, Aunts, Uncles, Tio’s, Tia’s, extended family and many of my close friends, thank you for the good times! Thanks to Rex and Mitzi Zenger for their moral support during my time in Manhattan!

Dedication

This thesis is dedicated to my grandfather Dale F. Carpenter and father David L. Carpenter. Without them, my passion for pigs and the swine industry as a whole, may not have developed as a child and into my adult years.

Chapter 1 - Effects of increasing zinc from zinc sulfate or zinc hydroxychloride on finishing pig growth performance and carcass characteristics

Abstract

A total of 1,008 pigs (TR4 × Fast Genetics [Saskatoon, SK] × PIC L02; [Hendersonville, TN]; initially 32.1±0.06 kg) were used to determine the effects of Zn source and level on finishing pig growth performance and carcass characteristics. Pigs were allotted to pens based on initial BW with 21 pigs per pen and 8 pens per treatment. Pens were randomly allotted to 1 of 6 dietary treatments arranged as a 2 × 3 factorial with main effects of Zn source (ZnSO₄, Agrium Advance Technology, Loveland, CO or Zn hydroxychloride; IntelliBond-Z; Micronutrients, Indianapolis, IN) and level (50, 100, or 150 mg/kg Zn). All diets were corn-soybean meal-DDGS-based and fed in meal form in 5 phases with 5 mg/kg ractopamine HCl included in the final phase. The trace mineral premix did not contain any supplemental Zn. From d 0 to 66, there were no differences in ADG or ADFI, but G:F decreased (linear, $P = 0.016$) as Zn increased. From d 66 to 103, increasing Zn increased then decreased (quadratic $P < 0.001$) ADG, with the greatest ADG at 100 mg/kg Zn, and tended to increase (quadratic, $P = 0.051$) ADFI. Pigs fed ZnSO₄ or 50 or 100 mg/kg Zn from Zn hydroxychloride had similar G:F, but pigs fed 150 mg/kg added Zn from Zn hydroxychloride had the poorest G:F (Zn source × level interaction $P < 0.001$). Overall d 0 to 103, there were no Zn source × level interactions or Zn source differences observed for ADG or ADFI. Increasing Zn increased then decreased (quadratic, $P = 0.007$) ADG, with the greatest ADG observed in pigs fed 100 mg/kg Zn. For pigs fed ZnSO₄, G:F was relatively unchanged, but in pigs fed Zn hydroxychloride, G:F decreased as Zn increased (Zn

source \times level interaction, $P = 0.019$). Carcass yield (linear, $P = 0.027$) and HCW (quadratic, $P = 0.006$) increased with increasing Zn and pigs fed Zn hydroxychloride had heavier ($P = 0.041$) HCW than those fed Zn from ZnSO₄. Neither Zn source nor level affected back fat depth, loin depth or percentage lean. In conclusion, few Zn source effects were evident; however, providing the current NRC (2012) recommendation of 50 mg/kg Zn in growing-finishing pig diets may not be enough for pigs to reach their full growth potential. Providing 100 mg/kg added Zn above that provided by the major ingredients in this study maximized ADG and HCW with the greatest response observed from ~94 to 127 kg BW.

Keywords: carcass, finishing pig, growth, zinc hydroxychloride, zinc sulfate

Introduction

Zinc is an essential trace mineral required to maintain many biological functions including growth and reproduction in swine (Walker and Black, 2004). The current Zn requirement estimate for 50 to 135 kg pigs is 50 mg/kg (NRC, 2012). Studies used to estimate this requirement determined added Zn concentrations ranging from 45 to 50 mg/kg Zn improved growth and alleviated parakeratotic symptoms of pigs (Luecke et al., 1956, 1957 and Smith et al., 1962). However, today, many U.S. swine nutritionists add 75 to 100 mg/kg Zn to diets to meet the Zn needs of the modern pig while also including a margin of safety (Flohr et al., 2016).

It has been argued that different Zn sources may not impact growth performance in a similar manner. Currently, experiments comparing Zn sources in nursery pigs are more common, but they report inconsistent results. Earlier studies reported Zn-chelates and inorganic sources were equally bioavailable in supporting growth and in restoring or maintaining serum and soft tissue Zn concentrations (Wedekind et al., 1994; Swinkels et al., 1996; Cheng et al., 1998). In regards to organic Zn, Schlegel et al. (2013) reported in a meta-analysis that the bioavailability

of organic Zn ranged from 85 to 117% when compared to inorganic Zn forms. In addition to currently available Zn sources (sulfate, oxide, and chelated), Zn hydroxychloride is an inorganic hydroxyl mineral source made by crystallization and has been shown to be insoluble in water but soluble in 0.4% HCl, 2% citric acid, or neutral ammonium sulfate (Cao et al., 2000; Zhang and Guo. 2006).

To our knowledge, finisher studies comparing the effects of Zn hydroxychloride, a unique hydroxyl inorganic Zn, to other more commonly fed forms of Zn (such as Zn sulfate) have not been published. Thus, the objective of this study was to investigate the effects of increasing Zn from two different sources on growth performance and carcass characteristics of finishing pigs housed in a commercial environment.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. This study was conducted at New Fashion Pork in a commercial research facility near Round Lake, MN. The research barn was an environmentally controlled double-curtain-sided building with completely slatted flooring and deep pits for manure storage. Pigs were stocked to allow 0.69 m² per pig. Each pen was equipped with a 5-hole stainless steel dry self-feeder (Thorp Equipment, Inc., Thorp, WI) and a cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN). All diets were manufactured in a commercial feed mill located in Estherville, IA.

Live Animal Management

A total of 1,008 pigs (TR4 × Fast Genetics [Saskatoon, SK] × PIC L02; [Hendersonville, TN]; initially 32.1 ± 0.06 kg) were used in a 103-d experiment. Pigs were allotted to pen based on initial BW with 21 pigs per pen (mixed sex) and 8 pens per treatment. Pens were randomly allotted to 1 of the 6 dietary treatments arranged as a 2×3 factorial with main effects of Zn source ($ZnSO_4$, Agrium Advance Technology, Loveland, CO or Zn hydroxychloride; IntelliBond-Z; Micronutrients, Indianapolis, IN) and Zn level (50, 100, or 150 mg/kg). All diets were corn- soybean meal-dried distillers grains with solubles-based and fed in meal form in 5 phases (32 to 48, 48 to 63, 63 to 77, 77 to 94, and 94 to 127 kg) with ractopamine HCl included in the final phase (Table 1). The trace mineral premix used did not contain any supplemental Zn. Pigs were weighed and feed disappearance was measured on d 0, 17, 33, 48, 66, 89, and 103 to determine ADG, ADFI, and G:F.

Harvest and Sample collection

On d 89 of the trial, pens were weighed and the 6 heaviest pigs from each pen were removed and transported approximately 563 km to Triumph Foods LLC (St. Joseph, MO) for harvest. Those pigs removed on d 89 were used in growth calculations but not for carcass data. On d 103, the remaining pigs in each pen were weighed, tattooed, and transported to Triumph Foods LLC (St. Joseph, MO) for harvest. Immediately following evisceration, HCW was collected and percentage carcass yield was calculated by dividing HCW by average live weight obtained at the farm before transport to the packing plant. Backfat and loin depth were collected using an optical probe (Fat-O-Meter; SFK Technology A/S, Henlev, Denmark) inserted between the 10th and 11th rib approximately 7 cm from the dorsal midline. Percentage lean was calculated using equations from the National Pork Producers Council (2000).

Chemical Analysis

Samples of each diet were collected from 6 feeders per phase and combined to make 1 composite sample per treatment and phase. Each sample was then split and ground then sent to Cumberland Valley Analytical Services (Hagerstown, MD) for duplicate analysis of DM (method 930.15; AOAC, 2000), CP (method 990.03; AOAC, 2000), crude fiber (method 978.10; AOAC, 2000), ether extract (method 2003.05; AOAC, 2006), ash (method 942.05; AOAC, 2000), Ca, P, and Zn (method 985.01; AOAC, 2000). Samples of each diet were also analyzed for final Zn concentration at Michigan State University (East Lansing, MI) in the Non-Ruminant Nutrition Lab using a Shimadzu Atomic Absorption Spectrophotometer (AA-7000) (Columbia, MD) and at Ward Laboratories Inc. (Kearney, NE) by a method outlined by AOAC (2012) using an iCAP 6000 series ICP Emission Spectrometer (Thermo Electron Corporation, Marietta, OH). Final Zn concentrations were determined by averaging 4 analyzed values; 2 from Cumberland Valley Analytical Services, 1 from Michigan State University and 1 from Ward Laboratories Inc.

Statistical Analysis

All growth and carcass characteristic data were analyzed as a randomized complete block design using the GLIMMIX procedure of SAS (SAS Inst. Inc. Cary, NC) with pen as the experimental unit. Dietary treatment served as the fixed effect while blocks based on BW were included as a random factor. The main effects of Zn source (ZnSO_4 or IntelliBond-Z) and linear and quadratic effects of Cu level (50, 100, and 150 mg/kg) as well as their interaction were analyzed using polynomial contrast statements. Hot carcass weight was used as a covariate for percentage lean, loin depth, and backfat. Statistical significance was determined at $P < 0.05$ and P -values falling within $P > 0.05$ and $P < 0.10$ were considered marginally significant.

Results

Diet Analysis

The chemical analyses of the complete diets supported the calculated values based on diet formulation (Tables 1 and 2). Total Ca and P concentrations were similar among diets across each dietary phase. Given there was no Zn provided by the trace mineral premix, the Zn concentrations increased as Zn additions increased across dietary treatments as expected.

Growth Performance and Carcass Characteristics

From d 0 to 66 (~32 to 94 kg BW), no Zn source \times level interactions were observed (Table 3). Neither Zn source nor level affected ADG or ADFI; however, increasing Zn decreased (linear, $P = 0.016$) G:F.

From d 66 to 103 (~94 to 127 kg BW), there were no Zn source \times level interactions observed for ADG or ADFI. Average daily gain increased then decreased (quadratic, $P = 0.001$) and ADFI tended to increase then decrease (quadratic, $P = 0.051$) with increasing dietary Zn and was maximized for pigs fed 100 mg/kg. Zinc source did not affect ADG, but pigs fed Zn from Zn hydroxychloride had greater ($P = 0.026$) ADFI than those fed ZnSO₄. A Zn source \times level interaction was observed (linear, $P = 0.001$) for G:F. In pigs fed ZnSO₄, G:F was relatively unchanged; however, in pigs fed Zn hydroxychloride G:F was similar among those fed 50 or 100 mg/kg Zn, but became poorer for those fed 150 mg/kg Zn.

Overall (d 0 to 103; ~32 to 127 kg BW), there were no Zn source \times level interactions observed for ADG or ADFI. Increasing Zn increased then decreased (quadratic, $P = 0.007$) ADG and final BW (quadratic, $P = 0.011$), with the greatest ADG observed for pigs fed 100 mg/kg Zn. There were no differences between pigs fed either Zn source for ADG or final BW. Neither Zn source nor level affected overall ADFI; however, for overall G:F, a Zn source \times level interaction

was observed (linear, $P = 0.019$). For pigs fed $ZnSO_4$, G:F was similar, but in pigs fed Zn hydroxychloride, G:F decreased as Zn increased.

Carcass yield (linear, $P = 0.027$) and HCW (quadratic, $P = 0.006$) increased with increasing added Zn (Table 4). Pigs fed Zn hydroxychloride had heavier ($P = 0.041$) HCW than those fed Zn from $ZnSO_4$. Neither Zn source nor level affected back fat depth, loin depth or percentage lean.

Discussion

The current NRC (2012) requirement estimate for finishing pigs from 50 to 135 kg BW is 50 mg/kg Zn. Since the trace mineral premix used in formulation of all experimental diets was formulated to not contribute any Zn, the lowest level of added Zn was sufficient to meet the NRC (2012) requirement estimates. Gowanlock et al. (2013) concluded that 50% of current NRC (2012) micro-mineral requirement estimate would be adequate to meet growing-finishing pig requirements and that the common practice to incorporate levels of trace minerals that exceed NRC (2012) recommendations for growing-finishing swine diets may not be warranted.

However, our study suggests that there may be growth promoting benefits to supplementing diets with Zn beyond 50 mg/kg. The current study suggests providing 100 mg/kg added Zn to the basal diet maximizes overall BW, ADG and HCW for growing pigs from ~94 to 127 kg of BW.

Some of the earliest experiments evaluated diets with added Zn that ranged from 5 to 61 mg/kg Zn in the diet (Smith et al., 1961, 1962) and determined the Zn requirement to be between 46 and 50 mg/kg. Although many of the earlier studies suggest 50 mg/kg Zn is enough to fully support maintenance and health of pigs, many studies within the last few decades argue that the reduction or elimination of micro-minerals from the diet does not affect pig performance. For example, many studies (Patience and Gills, 1995; Mavromichalis et al., 1999; and Shelton et al.,

2004) have reported eliminating the dietary micro-minerals in the form of the trace mineral premix did not influence pig performance or carcass characteristics. In a study by Shelton et al. (2004) the experiment was ended when pigs reached a mean BW of 109 kg and the experimental diets did not contain ractopamine HCl. Likewise, Patience and Gills (1995) ended their study when pigs reached a mean BW of 107 kg and like Shelton et al. (2004), experimental diets did not contain ractopamine HCl. In our study, ractopamine HCl was included in all diets as pigs grew from ~94 to 127 kg of BW. It was during this period of our study where we observed the greatest magnitude of growth response to increasing Zn, which could help to explain the lack of response in studies prior to ours (Patience and Gills, 1995 and Shelton et al., 2004). Furthermore, dietary variables such as the use of phytase which may liberate a variable amount of bound minerals, combinations of grains used in formulation and micro-mineral contents in grains due to different soils and growing conditions are all unpredictable factors that perhaps make it necessary for nutritionist to provide supplemental micro-minerals in most swine diets. Previous research has argued that the innate Zn provide by the major ingredients used in common swine diets is sufficient to support maximum growth of growing pigs (Wedekind et al., 1994 and Gowanlock et al., 2013). However, other studies have found the innate Zn in major ingredients used in growing pig diets to have limited value to the pig due to the antagonistic behavior of non-hydrolyzed dietary phytate contributed by those major ingredients (Keith and Bell, 1987 and Schlegel et al., 2013). Gowanlock et al. (2013) evaluated levels of Cu, Fe, Mn, and Zn below and up to NRC (1998, 2012) requirement estimates for grower-finisher swine and effects of additional Zn or Fe on growth performance. In their study, they did not observe any growth promoting benefits of adding supplemental levels of dietary Zn to the complete diet.

The results herein suggest it was during the later stages finishing when ractopamine HCl was fed, that the greatest magnitude of improved growth was observed. Recent work has investigated Zn in growing-finishing pig diets and have reported performance benefits of added Zn during the earlier stages of finishing (Paulk et al., 2015). However, the same studies also reported overall growth performance was not affected. Paulk et al (2015) fed a basal diet that contained 55 mg/kg Zn from the trace mineral premix. In their study, an addition of 75 mg/kg of Zn for a total Zn level of 130 mg/kg did not improve overall performance. The findings of the current study suggest 100 mg/kg of Zn maximizes overall BW, ADG, and HCW. However, previous research (Gowanlock et al., 2013 and Paulk et al., 2015) reported carcass characteristics were not influenced by adding more than 55 mg/kg of Zn when fed to pigs in the early finishing period, late finishing period, or throughout the overall finishing period.

In our study, ractopamine HCl was included in all experimental diets from ~94 to 127 kg BW. Some of the most recent work in this area has demonstrated an improvement in both ADG and/or G:F in pigs fed diets containing ractopamine HCl with added Zn from either an inorganic or organic source (Patience et al., 2011; Rambo et al., 2012; Fry et al., 2013). Interestingly, although increased ADG was observed in pigs fed 50 mg/kg Zn from ZnAA with ractopamine HCl, ADG was not improved when an inorganic source was supplemented (Patience et al., 2011; Rambo et al., 2012). Considering the sizable amount of research that has demonstrated growth improvements in pigs fed diets containing added Zn and ractopamine HCl, the mechanisms responsible for the improvements have not been clearly elucidated (Patience et al., 2011; Rambo et al., 2012; Fry et al., 2013). Because Zn was added to all experimental diets in our study, it is not possible to tell if the addition of Zn to ractopamine HCl diets elicited added benefits above that observed from pigs fed ractopamine HCl diets with no added Zn. However, other studies

have tried to determine whether added Zn provides any additional growth benefits beyond that of diets that contained ractopamine HCl only. Paulk et al. (2015) reported ADG and G:F increased in pigs fed ractopamine HCl diets plus 50 mg/kg added Zn from ZnAA compared with those fed ractopamine HCl diets without added Zn, with the ADG response carrying over into the overall data. Fry et al. 2013 determined added Zn (79 mg/kg Zn from the trace mineral premix) may enhance the response to ractopamine HCl diets in some studies; however, the enhancement was not consistent throughout their series of experiments. A notable difference between our studies and those from Paulk et al. (2015) and Fry et al. (2013) is that those studies did not use a premix formulated to be Zn free. It appears results are inconsistent in regards to whether or not added Zn enhances the growth of pigs fed diets that contained ractopamine HCl. Studies support that added dietary Zn at levels above that provided by the trace mineral premix did not enhance the growth response during the time which pigs were fed diets that contained ractopamine HCl (Rambo, 2013 and Gowanlock et al., 2013).

Some studies (Edwards and Baker 1999; Batal et al., 2001; Zhang and Guo 2006) have argued that the relative bioavailability (RBV) is greater for Zn hydroxychloride than for other inorganic Zn sources. Bioavailability of a nutrient is defined as the ratio of the amounts of the standard and test substances required to produce equivalent responses (Littell et al., 1995). Zhang and Guo (2006) provided supplemental levels of Zn in swine diets (initially ~7.5 kg BW) from either tetrabasic Zn chloride (Zn hydroxychloride) or ZnO and reported Zn hydroxychloride was soluble in 0.4% HCl, 2 % citric acid and neutral ammonium citrate whereas ZnO solubility was 94%, 70% and 61% in 0.4% HCl, 2 % citric acid and neutral ammonium, respectively. Although our study didn't measure RBV, we did observe a numerically greater decrease in growth when Zn was provided (above that contributed by the major ingredients) increased from 100 to 150

mg/kg of Zn from Zn hydroxychloride, than for pigs fed ZnSO₄, particularly during the period when ractopamine HCl was fed. It appears that our study may support a greater RBV of Zn hydroxychloride which could have hindered performance when diets contained 150 mg/kg Zn.

Previous research has shown that the Zn concentration contributed from the basal diet by major ingredients appears to be variable and is sometimes higher than what would be expected based on the currently listed innate Zn contribution of some major ingredients (NRC, 2012). Gowanlock et al. (2013) analyzed micro-mineral concentration of their basal diet which did not contain any mineral premix and found the basal diet contributed 35.4, 58.5 and 36.5 mg/kg Zn for diets fed to growing pigs in three dietary phases from 20 to 50, 50 to 80 and 80 to 115 kg BW, respectively. It does appear that the major ingredients used in our diet formulation contributed more Zn than was expected. Nonetheless, our data indicate that providing 100 mg/kg Zn in addition to the dietary innate Zn maximizes overall BW, ADG and HCW.

In conclusion, our results demonstrate there is potential of growth promotion benefits when growing-finishing pig diets are supplemented with Zn above the current NRC (2012) requirement estimate of 50 mg/kg. Additionally, our study suggests little overall growth differences between pigs fed different Zn sources; however, pigs fed diets with Zn hydroxychloride had greater HCW compared to those fed ZnSO₄. These results suggest that providing 100 mg/kg of Zn maximized ADG and HCW with the greatest response observed during the last 37 d period (~94 to 127 kg BW) when 5 mg/kg of ractopamine HCl was included in the diet. This might suggest that the timing of feeding elevated levels of Zn might influence the magnitude of response observed, particularly when ractopamine HCl is fed. As a result, more research should be conducted to determine if timing of feeding different levels or sources of Zn influences the magnitude of growth performance response observed.

Literature Cited

- AOAC. 2000. Official methods of analysis. 17th ed. Assoc. Off. Anal. Chem., Gaithersburg, MD.
- AOAC. 2006. Official methods of analysis. 18th ed. AOAC Int., Washington, DC.
- AOAC. 2012. Official methods of analysis. 19th ed. AOAC Int., Gaithersburg, MD.
- Batal, A. B., Parr, T. M. and Baker, D. H. 2001. Zinc bioavailability in tetrabasic zinc chloride and the dietary zinc requirement of young chicks fed a soy concentrate diet. *Poult. Sci.* 80: 87–91. doi.org/10.1093/ps/80.1.87
- Cao, J., P. R. Henry, C. B. Ammerman, R. D. Miles, R. C. Littell, 2000. Relative bioavailability of basic zinc sulfate and basic zinc chloride for chicks. *J. Appl. Poultry Res.* 9, 513–517. doi.org/10.1093/japr/9.4.513
- Cheng, J., E. T. Kornegay, and T. Schell. 1998. Influence of dietary lysine on the utilization of zinc from zinc sulfate and a zinc-lysine complex by young pigs. *J. Anim. Sci.* 1998. 76:1064–1074. doi:10.2527/1998.7641064x
- Edwards, H. M., III and D. H. Baker. 1999. Bioavailability of zinc in several sources of zinc oxide, zinc sulfate, and zinc metal. *J. Anim. Sci.* 77: 2730–2735. doi:10.2527/1999.77102730x
- Flohr, J.R., J.M. DeRouchey, J.C. Woodworth, M.D. Tokach, R.D. Goodband, and S.S. Dritz. 2016. A Survey of current feeding regimens for vitamins and trace minerals in the US swine industry. *J. Swine Health Prod.* 24:290-303.
- Fry, S., W. Hu, N. Paton, and D. Cook. 2013. Effect of dietary zinc level and source and ractopamine level on performance and carcass traits of finishing pigs. *J. Anim. Sci.* 91(Suppl. 2):O231 (Abstr.).
- Gowanlock, D. W., D. C. Mahan, J. S. Jolliff, S. J. Moeller, and G. M. Hill. 2013. Evaluating the NRC levels of Cu, Fe, Mn, and Zn using organic minerals for grower-finisher swine. *J. Anim. Sci.* 91:5680–5686. doi:10.2527/jas2013-6608
- Keith, M. O., and J. M. Bell. 1987. Effects of canola meal on tissue trace mineral concentrations in growing pigs. *Can. J. Anim. Sci.* 67:133-140. doi: 10.4141/cjas87-015
- Littell, R. C., A. J. Lewis, P. R. Henry. 1995. Statistical evaluation of bioavailability assays. In: Ammerman, C. B., Baker, D. H., Lewis, A.J. (Eds.), *Bioavailability of Nutrients for Animals: Amino acids, Minerals, and Vitamins*. Academic Press, San Diego, CA, pp. 5–33.

- Luecke, R. W., J. A. Hoefler, W. G. Brammell, and F. Thorp, Jr. 1956. Mineral interrelationships in parakeratosis of swine. *J. Anim. Sci.* 15:347–351. doi:10.2527/jas1956.152347x
- Luecke, R. W., J. A. Hoefler, W. G. Brammell, and D. A. Schmidt. 1957. Calcium and zinc in parakeratosis of swine. *J. Anim. Sci.* 16:3–11. doi:10.2527/jas1957.1613
- Mavromichalis, I., J. D. Hancock, I. H. Kim, B. W. Senne, D. H. Kropf, G. A. Kennedy, R. H. Hines, and K. C. Behnke. 1999. Effects of omitting vitamin and trace mineral premixes and (or) reducing inorganic phosphorus addition on growth performance, carcass characteristics, and muscle quality in finishing pigs. *J. Anim. Sci.* 77:2700–2708. doi:10.2527/1999.77102700x
- National Pork Producers Council. 2000. Prediction equations. In: E. Berg, editor, *Pork composition and quality assessment procedures*. Des Moines, IA. p. 19.
- NRC. 1998. *Nutrient requirements of swine*. 10th rev. ed. Natl. Acad. Press, Washington, DC.
- NRC. 2012. *Nutrient requirements of swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC.
- Patience, J. F., and D. Gillis. 1995. Removal of vitamins and trace minerals from finishing diets: Impact on animal performance. In: *Annu. Res. Rep. Prairie Swine Centre*, Saskatoon, SSK, Canada. p. 29–31.
- Patience, J. F., A. Chipman, T. L. Ward, and M.E. Wilson. 2011. Impact of zinc source on grow-finish performance, carcass composition and locomotion score. *J. Anim. Sci.* 89(E-Suppl. 2):178.(Abstr.)
- Paulk, C. B., D. D. Burnett, M. D. Tokach, J. L. Nelssen, S. S. Dritz, J. M. DeRouche, R. D. Goodband, G. M. Hill, K. D. Haydon, and J. M. Gonzalez. 2015. Effect of added zinc in diets with ractopamine hydrochloride on growth performance, carcass characteristics, and ileal mucosal inflammation mRNA expression of finishing pigs. *J. Anim. Sci.* 93:185-196. doi:10.2527/jas2014-8286
- Rambo, Z., A. Schinckel, M. Wilson, T. Ward, and B. Richert. 2012. Effect of supplemental zinc source and ractopamine on grow-finish pig growth performance and carcass characteristics. *J. Anim. Sci.* 90(Suppl. 2):71.(Abstr.)
- Rambo, Z.J., 2013. Effects of supplemental zinc and ractopamine on growth performance, carcass composition, and skeletal muscle synthesis and gene expression in finishing pigs. PhD Diss. Purdue Univ., West Lafayette.
- Schlegel, P., D. Sauvant, and C. Jondreville. 2013. Bioavailability of zinc sources and their interaction with phytates in broilers and piglets. *Animal* 7:47–59. doi:10.1017/S1751731112001000
- Shelton, J. L., L. L. Southern, F. M. LeMieux, T. D. Bidner, and T. G. Page. 2004. Effects of microbial phytase, low calcium and phosphorus, and removing the dietary trace mineral

- premix on carcass traits, pork quality, plasma metabolites, and tissue mineral content in growing-finishing pigs. *J. Anim. Sci.* 82:2630–2639. doi:10.2527/2004.8292630x
- Smith, W. H., M. P. Plumlee and W. M. Beeson. 1961. Zinc requirement of the growing pig fed isolated soybean protein semi-purified rations. *J. Animal Sci.* 20:128-132. doi:10.2527/jas1961.201128x
- Smith, W. H., M. P. Plumlee, and W. M. Beeson. 1962. Effect of source of protein on zinc requirement of the growing pig. *J. Anim. Sci.* 21:399–405. doi:10.2527/jas1962.213399x
- Swinkels, J.W., G.M., E. T. Kornegay, W. Zhou, M. D. Lindemann, K. E. Webb, Jr., and M. W. A. Verstegen. 1996. Effectiveness of zinc amino acid chelate and zinc sulfate in restoring serum and soft tissue zinc concentrations when fed to zinc-depleted pigs. *J. Anim. Sci.* 74:2420-2430. doi:10.2527/1996.74102420x
- Walker, C.F. and R. E. Black. 2004. Zinc and the risk for infectious disease. *Annu. Rev. Nutr.* 24, 235–275. doi: 10.1146/annurev.nutr.23.011702.073054
- Wedekind, K. J., A. J. Lewis, M. A. Giesemann, and P. S. Miller. 1994. Bioavailability of zinc from inorganic and organic sources for pigs fed corn-soybean meal diets. *J. Anim. Sci.* 72:2681-2689. doi:10.2527/1994.72102681x
- Zhang, B. and Y. Guo. 2006. Beneficial effects of tetra basic zinc chloride for weanling pigs and the bioavailability of zinc in tetrabasic form relative to ZnO. *Anim. Feed Sci. Technol.* 135:75-85. doi: org/10.1016/j.anifeedsci.2006.06.006

Table 1-1 Diet composition (as-fed basis)

Item	Phase ¹				
	1	2	3	4	5
Ingredient, %					
Corn	48.08	52.13	55.70	58.31	69.00
Soybean meal (47.5% CP)	19.56	15.69	12.24	9.66	18.66
Corn DDGS ²	30.00	30.00	30.00	30.00	10.00
Monocalcium P (21% P)	0.15	---	---	---	0.30
Limestone	1.35	1.35	1.25	1.25	0.95
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys-HCl	0.35	0.33	0.30	0.28	0.35
L-Thr	---	---	---	---	0.09
L-Trp	0.01	0.01	0.01	---	0.02
HMB ³	---	---	---	---	0.10
Ractopamine HCl ⁴	---	---	---	---	0.03
Vitamin premix ⁵	0.075	0.075	0.075	0.075	0.075
Trace mineral premix ⁶	0.075	0.075	0.075	0.075	0.075
Zn source ^{7,8}	---	---	---	---	---
Total	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) AA, %					
Lys	0.97	0.86	0.76	0.68	0.90
Ile:Lys	71	73	75	77	63
Met:Lys	29	30	33	35	34
Met & Cys:Lys	57	61	65	70	60
Thr:Lys	63	65	67	70	65
Trp:Lys	18.6	18.7	18.6	18.5	18.6
Val:Lys	79	82	86	90	70
Total Lys, %	1.11	0.99	0.88	0.80	1.00
NE, kcal/kg	2,419	2,443	2,464	2,477	2,497
SID Lys:NE, g/Mcal	4.01	3.52	3.08	2.74	3.60
Available P, %	0.41	0.37	0.37	0.36	0.32
Chemical analysis (as-fed basis)⁹					
CP, %	22.0	21.6	20.2	20.3	19.3
Crude fiber, %	4.3	4.3	4.1	4.2	3.2
Ether extract, %	5.3	4.7	5.3	5.6	3.7
Ash, %	5.80	6.21	5.43	5.40	5.21
Ca, %	0.90	0.92	0.91	0.78	0.69

P, % 0.62 0.61 0.54 0.57 0.48

¹Diets were fed in meal form and phase 1, 2, 3, 4 and 5 were fed from approximately (32 to 48, 48 to 63, 63 to 77, 77 to 94, and 94 to 127 kg), respectively.

²Corn distillers dried grains with solubles (Valero Renewables, Welcome, MN).

³Hydroxymethylthio-butanoic acid, Novus International (Saint Charles, MO).

⁴Provided 5 mg/kg of RAC (Paylean, Elanco Animal Health, Greenfield, IN).

⁵Provided per kilogram of diet: 6,174 IU vitamin A, 992 IU vitamin D₃, 40 IU vitamin E, 0.02 mg vitamin B₁₂, 8.8 mg riboflavin, 26.5 mg niacin, 17.6 mg pantothenic acid, 2.65 mg menadione.

⁶Provided per kilogram of diet: 0.30 mg Se from sodium selenite, 162 mg Cu from tri-basic copper chloride, 76 mg Fe from ferrous sulfate, 0.38 mg I from calcium iodate, and 29 mg Mn from manganese sulfate/manganous oxide.

⁷Zinc sulfate, (Agrium Advance Technology, Loveland, CO) added at 50, 100, or 150 mg/kg at the expense of corn.

⁸IntelliBond-Z, Zinc hydroxychloride, (Micronutrients, Indianapolis, IN) added at 50, 100, or 150 mg/kg at the expense of corn.

⁹Six samples of each diet were collected, blended, sub sampled, and analyzed (Cumberland Valley Analytical Services, Hagerstown, MD). Values listed represent the mean for all dietary treatments within a phase for the respective component.

Table 1-2 Chemical zinc analysis of diets (as-fed basis)¹

Item ^{5,6}	Added Zn, mg/kg ²					
	ZnSO ₄ ³			Zn hydroxychloride ⁴		
	50	100	150	50	100	150
Grower (32 – 94 kg)	145	158	173	102	138	179
Finisher (94 – 127 kg)	91	160	213	95	132	188
Overall (32 – 127 kg)	122	159	189	99	136	183

¹Six samples of each diet were collected, blended, sub sampled, and analyzed at Cumberland Valley Analytical Services (Hagerstown, MD), Michigan State University (East Lansing, MI) and Ward Laboratories Inc. (Kearney, NE).

²The trace mineral premix was formulated to contribute no Zn to the complete diet. Values listed represent a weighted average based on feed intake and the chemical Cu analysis for each treatment in each dietary feeding phase.

³Zinc sulfate (Agrium Advance Technology, Loveland, CO).

⁴IntelliBond-Z (Micronutrients, Indianapolis, IN).

⁵Zinc values represent the mean of 4 analytical values; 2 from Cumberland Valley Analytical Services (Hagerstown, MD), 1 from Michigan State University (East Lansing, MI) and 1 from Ward Laboratories Inc. (Kearney, NE).

⁶ Dietary phases 1, 2 and 3 were fed from 32 to 94 kg BW. Dietary phases 4 and 5 were fed from 94 to 127 kg BW.

Table 1-3 Effects of increasing Zn from ZnSO₄ or Zn hydroxychloride on growth performance of pigs¹

Item	ZnSO ₄ mg/kg Zn ²			Zn hydroxychloride mg/kg Zn ³			SEM	Zn source	Probability, <i>P</i> <			
	50	100	150	50	100	150			Zn level		Source × level	
									Linear	Quadratic	Linear	Quadratic
BW, kg												
d 0	32.05	32.05	32.05	32.05	32.04	32.04	0.328	0.899	0.951	0.971	0.951	0.971
d 66	94.17	94.57	94.77	94.24	95.03	93.51	0.618	0.563	0.904	0.166	0.200	0.242
d 103	126.19	128.23	125.99	127.05	129.44	126.45	1.078	0.326	0.703	0.011	0.848	0.766
d 0 to 66												
ADG, kg	0.94	0.94	0.95	0.94	0.95	0.93	0.008	0.436	0.963	0.377	0.312	0.419
ADFI, kg	2.27	2.29	2.33	2.28	2.34	2.29	0.024	0.745	0.145	0.340	0.454	0.150
G:F	0.414	0.413	0.408	0.413	0.405	0.406	0.0027	0.109	0.016	0.629	0.904	0.170
d 66 to 103 ⁴												
ADG, kg	0.93	0.98	0.94	0.96	1.01	0.95	0.018	0.112	0.880	0.001	0.649	0.735
ADFI, kg	2.84	2.94	2.82	2.87	3.01	3.01	0.053	0.026	0.251	0.051	0.163	0.689
G:F	0.329	0.335	0.333	0.334	0.337	0.316	0.0034	0.191	0.017	0.005	0.001	0.156
d 0 to 103												
ADG, kg	0.94	0.96	0.94	0.95	0.97	0.94	0.009	0.555	0.951	0.007	0.376	0.487
ADFI, kg	2.46	2.50	2.49	2.47	2.56	2.53	0.032	0.163	0.168	0.126	0.660	0.603
G:F	0.381	0.383	0.380	0.383	0.379	0.370	0.0024	0.036	0.003	0.257	0.019	0.996

¹A total of 1,008 pigs (TR4 × Fast Genetics [Saskatoon, SK] × PIC L02; [Hendersonville, TN]; initially 32.1 kg) were used in a 103-d growth study with 21 pigs per pen and 8 pens per treatment.

²Zinc sulfate (Agrium Advance Technology, Loveland, CO).

³IntelliBond-Z (Micronutrients, Indianapolis, IN).

⁴On d-73 diets contained 5 mg/kg of ractopamine HCl (Paylean, Elanco Animal Health, Greenfield, IN).

Table 1-4 Effects of increasing Zn from SnSO₄ or Zn hydroxychloride on carcass characteristics of finishing pigs¹

Item							SEM	Zn Source	Probability, <i>P</i> <			
	ZnSO ₄ , mg/kg Zn ²			Zn hydroxychloride, mg/kg Zn ³					Level		Source × level	
	50	100	150	50	100	150			Linear	Quadratic	Linear	Quadratic
Carcass yield, ⁴ %	73.63	74.08	74.53	74.03	74.68	74.36	0.003	0.240	0.027	0.329	0.288	0.327
HCW, kg	92.65	95.04	93.66	94.35	96.90	94.51	0.883	0.041	0.494	0.006	0.618	0.696
Backfat, ⁵ mm	17.6	17.1	17.9	17.4	17.3	17.4	0.40	0.618	0.802	0.343	0.717	0.445
Loin depth, ⁵ mm	62.6	63.5	63.3	63.4	64.0	62.8	0.91	0.727	0.947	0.374	0.464	0.845
Lean, ^{5,6} %	53.75	54.13	53.80	53.96	54.11	53.93	0.264	0.634	0.975	0.254	0.879	0.678

¹A total of 1,008 pigs (TR4 × Fast Genetics [Saskatoon, SK] × PIC L02; [Hendersonville, TN]; initially 32.1 kg) were used in a 103-d growth study with 21 pigs per pen and 8 pens per treatment.

²Zinc sulfate (Agrium Advance Technology, Loveland, CO).

³IntelliBond-Z (Micronutrients, Indianapolis, IN).

⁴Percentage carcass yield was calculated by dividing HCW at the packing plant by live weight at the farm.

⁵Adjusted using HCW as a covariate.

⁶Percentage lean was calculated using equations from the National Pork Producers Council (2000).

Chapter 2 - Effects of increasing copper from either copper sulfate or combinations of copper sulfate and a copper-amino acid complex on finishing pig growth performance and carcass characteristics

Abstract

A total of 1,089 pigs (PIC 280 × 1050; [Hendersonville, TN] initially 37.3±2.8 kg) were used to determine the effects of increasing Cu provided from either CuSO₄ alone or a 50:50 blend of CuSO₄ and Cu-AA on growth performance and carcass characteristics of finishing pigs. Pigs were randomly allotted to 1 of 6 dietary treatments. The 6 dietary treatments consisted of a control diet which contained 17 mg/kg Cu from CuSO₄ from the trace mineral premix, or the control diet with either added CuSO₄ to provide 70 and 130 mg/kg total Cu, or a 50:50 blend of Cu from CuSO₄ and Cu-AA (Availa[®]Cu, Zinpro Corporation, Eden Prairie, MN) to provide 70, 100, and 130 mg/kg total Cu. Experimental diets were corn, soybean meal, DDGS-based and fed in meal form in 5 phases (approximately 37 to 46, 46 to 63, 63 to 77, 77 to 103, and 103 to 129 kg). From d 0 to 43, neither Cu source nor level influenced growth performance. From d 43 to 105, ADFI decreased ($P = 0.037$) for pigs fed the 50:50 blend of added Cu from CuSO₄ and Cu-AA compared to those fed added Cu from CuSO₄ alone. Feed efficiency tended to be improved (linear, $P = 0.056$) as Cu concentration increased. Overall, d 0 to 105, neither Cu level nor source influenced ADG. Pigs fed 70 or 130 mg/kg total added Cu from the 50:50 blend of CuSO₄ and Cu-AA had lower ($P = 0.045$) ADFI but feed efficiency tended to be improved ($P = 0.051$) compared with those fed the same amount of total Cu from only CuSO₄. Due to the decreased ADFI and improved G:F of pigs fed the 50:50 blend of Cu from CuSO₄ and Cu-AA, carcass G:F also improved ($P = 0.033$) compared with those fed added Cu from CuSO₄ alone. In conclusion,

few Cu source effects were observed. Providing a 50:50 blend of CuSO₄ and Cu-AA improved G:F on both a live and HCW basis compared to CuSO₄ alone with no differences in ADG or HCW ADG observed.

Keywords: copper, carcass characteristics, growth performance, swine

Introduction

Studies have shown that increasing Cu regardless of Cu source, has the potential to increase rate of gain and feed intake during the nursery period (Cromwell et al., 1989; Dove, 1995). Additional data support a similar growth response to increasing Cu during the finishing phase of growth (Hastad, 2002; Davis et al., 2002; Coble, 2015).

Previous research suggests there may be a growth benefit for pigs fed added Cu from a Cu-amino acid complex compared with those fed added Cu from CuSO₄ (Coffey et al., 1994; Zhou et al., 1994). Apgar et al. (1995) suggested there was no evidence of a growth benefit between pigs fed added Cu from a Cu-amino acid complex compared with those fed added Cu from CuSO₄. However, another trial did not agree and suggested growing pigs fed added Cu from a Cu-Lys complex tended to have greater ADG and had greater ending BW than those fed added Cu from CuSO₄ (Apgar and Kornegay., 1996). Thus, from the literature there is inconsistency regarding if an organic Cu source will impact growth differently than an inorganic source. Furthermore, to our knowledge there is no published research that has investigated whether a 50:50 blend of added Cu from CuSO₄:Cu-AA will impact growth of finishing pigs differently than those fed Cu from CuSO₄ alone.

Further investigation is warranted to better understand how increasing levels of Cu from either an inorganic or an inorganic:organic Cu blend will impact growing and finishing pig performance. Therefore, the objective of this experiment was to determine the effects of

increasing Cu provided from either CuSO₄ alone or a 50:50 blend of CuSO₄ and Cu-AA on growth performance and carcass characteristics of finishing pigs housed in a commercial environment.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The experiment was conducted in a commercial research facility in southwestern Minnesota. The barn was double-curtain-sided with completely slatted concrete flooring and deep pits for manure storage. The barn contained 42 pens with 25 or 26 pigs (mixed sex) in each, equipped with a 4-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and 1 cup-waterer, providing ad libitum access to feed and water. Pigs were stocked to allow 0.69 m² per pig. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN). All diets were manufactured in a commercial feed mill located in Pipestone, MN.

Live Animal Management

A total of 1,089 pigs (PIC 280 × 1050; [Hendersonville, TN]; initially 37.3±2.8 kg) were used in a 105-d experiment. On d 0 of the experiment, pens of pigs were weighed, blocked by average pig BW, and randomly allotted to 1 of 6 dietary treatments with 7 replicate pens per treatment. All treatments utilized the same basal diet formulation within each phase which contained 17 mg/kg Cu from CuSO₄ provided from the trace mineral premix. The 6 dietary treatments consisted of a control diet with no additional Cu, two diets with added Cu from CuSO₄ to provide either 70 or 130 mg/kg total Cu, and three diets containing a 50:50 blend of Cu

from CuSO₄ and Cu-AA (Availa-Cu[®], Zinpro Corporation, Eden Prairie, MN) to provide either 70, 100, or 130 mg/kg total Cu.

Experimental diets were corn-soybean meal, corn DDGS-based and were fed in meal form in 5 phases (approximately 37 to 46, 46 to 63, 63 to 77, 77 to 103, and 103 to 129 kg; Table 1). For diets that contained added Cu above that provided from the trace mineral premix, Cu was added at the expense of corn. Nutrient values for the ingredients were based on the NRC (2012). Pigs were weighed and feed disappearance was measured approximately every 2 weeks to calculate ADG, ADFI, G:F, HCW ADG and G:F. .

Harvest and Sample Collection

On d 79 of the trial, pens were weighed and the 3 heaviest pigs from each pen were removed and transported 95 km to JBS USA (Worthington, MN) for harvest. These pigs were used in calculation of pen growth performance, but not carcass characteristics. On d 105, final pen weights were recorded and feed disappearance was measured. The remaining pigs in the barn were individually tattooed with a pen identification number to allow individual carcass measurements to be recorded, and transported to JBS USA (Worthington, MN) for harvest. Carcass yield was calculated using HCW at the plant divided by average individual live weight at the farm. Standard carcass measurements of backfat (BF), and loin depth (LD), were measured with an optical probe [Fat-O-Meter (SFK, Herlev, Denmark)] inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 centimeters from the dorsal midline. Pen was the experimental unit with carcass as the observational unit. Percentage lean was calculated using equations from the National Pork Producers Council (2000).

Chemical Analysis

Complete diet samples were collected from a minimum of 6 feeders per phase and combined to make 1 composite sample per treatment within phase. Each sample was then split, ground and then sent to Minnesota Valley Testing Laboratories (New Ulm, MN) for analysis of DM (method 930.15, AOAC, 2000), CP (method 990.03; AOAC, 2000), ash (method 942.05; AOAC, 2000), Ca, P, and Cu concentrations (method 985.01; AOAC, 2000) (Tables 2, 3 and 4). For the copper analysis, a total of 2 individual samples were analyzed 1 or 2 times for each diet within each phase at Minnesota Valley Testing Laboratories (New Ulm, MN).

Statistical Analysis

Data were analyzed as a randomized complete block design using PROC GLIMMIX (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. Percentage lean, loin depth, and backfat were adjusted to a common hot carcass weight for evaluation. Effects of Cu source (70 and 130 mg/kg Cu, within source) and linear and quadratic effects of Cu level (17, 70, 100 and 130 mg/kg Cu, across source) were analyzed. All polynomial contrasts were determined using PROC IML (SAS Institute, Inc., Cary, NC). Significant results were defined as $P \leq 0.05$ and marginally significant as $P > 0.05$ and ≤ 0.10 .

Results

Diet Analysis

The chemical analyses of the complete diets supported the calculated values based on diet formulation (Tables 1 & 2).

Growth Performance and Carcass Characteristics

From d 0 to 43 (~37 to 77 kg BW), neither Cu source nor level influenced growth performance (Table 3). From d 43 to 105 (~77 to 129 kg BW), ADFI was decreased ($P = 0.037$) for pigs fed the 50:50 blend of added Cu from CuSO₄ and Cu-AA compared to those fed added Cu from CuSO₄ alone. Feed efficiency tended to be improved (linear, $P = 0.056$) as level of Cu increased.

Overall, d 0 to 105 (~37 to 129 kg BW), neither Cu level nor source influenced ADG. Pigs fed 70 and 130 mg/kg total added Cu from the 50:50 blend of CuSO₄ and Cu-AA had lower ($P = 0.045$) ADFI, but feed efficiency marginally improved ($P = 0.051$) compared with those fed the same amount of added Cu from only CuSO₄. Carcass G:F also improved ($P = 0.033$; Table 4) compared with those fed added Cu from CuSO₄ alone; however, Cu source nor level influenced any other carcass parameter.

Discussion

The current NRC (2012) requirement estimate for finishing pigs from ~50 to 135 kg BW is 3.0 – 3.5 mg/kg Cu. Flohr et al. (2016) reported that swine nutritionists typically formulate swine diets to contain levels of Cu above the requirement estimate of NRC (2012). This may be because previous research has shown that feeding high concentrations of Cu has been associated with improved growth performance (Hastad, 2002; Davis et al., 2002; Coble, 2015).

Previous studies suggest that increasing Cu improves growth performance during the early finishing period, but not in the late finishing period. Coble (2015) fed finishing pigs (initially ~25 kg) diets containing added Cu from either tri-basic copper chloride or CuSO₄ at 0, 75, or 150 mg/kg added Cu. In their study, increasing added Cu increased ADG and ADFI but no changes in feed efficiency were observed. Hot carcass weight and loin depth also increased as

added Cu increased. Interestingly, in the present data we did not observe any differences in ADG, ADFI or carcass characteristics with increasing added dietary Cu which is in direct contrast with the findings from Coble (2015). Hastad (2002) fed diets to growing pigs that were formulated to contain increasing levels of Cu from CuSO_4 or tri-basic copper chloride and reported pigs provided increasing levels of Cu regardless of source had improved growth performance until an average BW of 61 kg was reached, with no benefit thereafter. A key contrast between our study and previous studies (Hastad, 2002; Coble, 2015) is that each of those experiments suggest the growth benefit to increasing added Cu is observed in early finishing. Hastad (2002) and Coble (2015) both reported pigs fed increasing levels of Cu regardless of source, had increased ADFI and ADG during the early finishing period. In our study, increasing Cu during the early finishing period did not affect growth performance regardless of Cu source. Interestingly, in contrast to our study and previous research (Hastad, 2002; Coble, 2015), Davis et al. (2002) reported that pigs fed 125 mg/kg added Cu from CuSO_4 had improved growth performance in both the early (32 to 68 kg) and late (68 to 106 kg) finishing periods. Additionally, Zhao et al. (2014) showed that in late finishing, (98 to 101 kg) increasing Cu from $\text{Cu}(\text{HMTB}_a)_2$ increased ADG and tended to increase ADG for pigs (101 to 119 kg) with only marginal changes in G:F during the last phase of finishing. Overall, pigs (32 to 119 kg) fed increasing Cu from $\text{Cu}(\text{HMTB}_a)_2$ had increased ADG and improved G:F with no evidence for differences in feed intake or ending BW. Similar to our study, Davis et al. (2002) and Zhao et al. (2014) support that there may be a performance benefit to increasing added Cu in late finishing.

It has been reported in the literature that CuSO_4 has typically been the most commonly used Cu source in swine diets (Cromwell et al., 1998; Miles et al., 1998). The current body of literature lacks information regarding the comparison between feeding increasing levels of Cu

from a single source or a 50:50 blend of two different Cu sources. Studies have compared the effects of other dietary sources of Cu fed to grow-finishing pigs (Apgar and Kornegay 1996; Hastad, 2002; Coble, 2015). Apgar and Kornegay (1996) fed a control diet (36 mg/kg Cu from CuSO₄) or diets that contained 200 mg/kg added Cu from either CuSO₄ or a Cu-Lys complex to growing pigs (initially 70 kg). The authors reported pigs fed diets containing Cu from the Cu-Lys complex tended to have greater ADG than those fed Cu from CuSO₄. Hastad et al. (2002) fed pigs diets that contained 50, 100 or 200 mg/kg Cu from tri-basic copper chloride or CuSO₄ and reported ADG tended to be greater and ADFI was greater for those fed Cu from CuSO₄ compared with those fed Cu from tri-basic copper chloride. Coble (2015) fed pigs diets that contained 0, 75, or 150 mg/kg Cu from either tri-basic copper chloride or CuSO₄ and reported growth performance and carcass characteristics were similar for pigs fed increasing Cu from either source. In our study, ADG and G:F were unchanged; however, pigs fed increasing levels of Cu from CuSO₄ during the late finishing period consumed more feed but had poorer feed efficiency on both a live and HCW basis than those fed a 50:50 blend of Cu from Cu-AA and CuSO₄. The differences in ADFI between pigs fed CuSO₄ compared with those fed the 50:50 blend appear to be driven by the unexpected reduction in feed intake for those fed 130 mg/kg Cu from the 50:50 blend. This was unexpected because increased ADFI has been associated with feeding high levels of dietary Cu and is a performance response that has been repeated and well demonstrated in the literature (Hastad, 2002; Davis et al., 2002; Coble, 2015).

In addition to the research that has been done regarding the sulfate, chloride and AA-complex forms of Cu, Cu-chelates in growing pigs diets is a similar area where research has been done (Stansbury et al., 1990; Zhao et al., 2014). Stansbury et al. (1990) conducted four experiments in order to determine if any differences in growth could be found between pigs fed

diets containing CuSO₄ compared with those fed diets containing Cu-chelates. Interestingly, those series of experiments showed that pigs provided Cu in the form of a chelate did not have greater performance compared with those fed Cu from CuSO₄. In a more recent study, Zhao et al. (2014) fed diets to pigs containing dietary levels of Cu ranging from 4 to 160 mg/kg Cu from either CuSO₄ or a Cu-chelate [Cu(HMTB_a)₂]. They reported pigs fed 80 mg/kg Cu from Cu(HMTB_a)₂ had greater HCW and tended to have greater ADG than those provided 6 or 160 mg/kg Cu from CuSO₄. Because HCW and ADG was greater for pigs fed diets containing 80 mg/kg Cu from Cu(HMTB_a)₂ compared with those fed 160 mg/kg Cu from CuSO₄ this suggests pig growth may be dependent on Cu source. It appears in their study that ADG was mostly responsible for the performance differences Cu source whereas in our study, the performance differences for Cu source appear to be feed intake driven.

In conclusion, providing a 50:50 blend of CuSO₄ and Cu-AA improved G:F on both a live and HCW basis with no differences in ADG or HCW ADG. Pigs fed Cu from CuSO₄ alone had greater ADFI and tended to have poorer feed efficiency compared to the blend of Cu sources. Copper source did not impact ADG or carcass characteristics.

Literature Cited

- AOAC. 2000. Official methods of analysis. 17th ed. Assoc. Off. Anal. Chem., Gaithersburg, MD.
- Apgar, G. A., E. T Kornegay, M. D. Lindemann, and D. R. Notter. 1995. Evaluation of copper sulfate and a copper lysine complex as growth promoters in weanling swine. *J. Anim. Sci.* 73:2640-2646. doi:10.2527/1995.7392640x
- Apgar, G. A. and E. T Kornegay. 1996. Mineral balance of finishing pigs fed copper sulfate or a copper lysine complex at growth-stimulating levels. *J. Anim. Sci.* 74:1594-1600. doi:10.2527/1996.7471594x
- Coble, K. F. 2015. Influence of dietary fiber and copper on growth performance and carcass characteristics of finishing pigs and utilizing linear programming to determine pig flow. PhD Diss. Kansa state University, Manhattan

- Coffey, R. D., G. L. Cromwell, and H. J. Monegue. 1994. Efficacy of a copper-lysine complex as a growth promotant for weanling pigs. *J. Anim. Sci.* 72:2880-2886.
doi:10.2527/1994.72112880x
- Cromwell, G. L., T. S. Stahly and H. J. Monegue. 1989. Effects of source and level of copper on performance and liver copper stores in weanling pigs. *J. Anim. Sci.* 67:2996-3002.
doi:10.2527/jas1989.67112996x
- Cromwell, G. T., M. D. Lindemann, H. K. Monegue, D. D. Hall, and D. E. Orr. 1998. Tribasic copper chloride and copper sulfate as copper sources for weanling pigs. *J. Anim. Sci.* 76:118-123. doi:10.2527/1998.761118x
- Davis, M. E., C. V. Maxwell, D. C. Brown, B. Z. de Rodas, Z. B. Johnson, E. B. Kegley, D. H. Hellwig, and R. A. Dvorak. 2002. Effect of dietary mannan oligosaccharides and(or) pharmacological additions of copper sulfate on growth performance and immunocompetence of weanling and growing/finishing pigs. *J. Anim. Sci.* 80:2887-2894.
doi:10.2527/2002.80112887x
- Dove, C. R. 1995. The effect of copper level on nutrient utilization of weanling pigs. *J. Anim. Sci.* 73:166-171. doi:10.2527/1995.731166x
- Flohr, J.R., J.M. DeRouchey, J.C. Woodworth, M.D. Tokach, R.D. Goodband, and S.S. Dritz. 2016. A Survey of current feeding regimens for vitamins and trace minerals in the US swine industry. *J. Swine Health Prod.* 24:290-303.
- Hastad, C. W. 2002. Phosphorus requirements of grow-finish pigs reared in commercial environments. MS Thesis. Kansas State University, Manhattan.
- Miles, R.D., S. F. O'Keefe, P. R. Henry, C. B. Ammerman, and X. G. Luo. 1998. The effect of dietary supplementation with copper sulfate or tribasic copper chloride on broiler performance, relative copper bioavailability, and dietary prooxidant activity. *Poult. Sci.* 77:416-425. doi:10.1093/ps/77.3.416
- National Pork Producers Council. 2000. Prediction equations. In: E. Berg, editor, *Pork composition and quality assessment procedures*. Des Moines, IA. p. 19.
- NRC. 2012. *Nutrient requirements of swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC
- Stansbury, W. F., L. F. Tribble, and D. E. Orr, Jr. 1990. Effect of chelated copper sources on performance of nursery and growing pigs. *J. Anim. Sci.* 68:1318-1322.
doi:10.2527/1990.6851318x

- Zhao, J., G. Allee, G. Gerlemann, L. Ma, M. I. Gracia, D. Parker, & R. J. Harrell .2014. Effects of a chelated copper as growth promoter on performance and carcass traits in pigs. *Asian-Australas. J. Anim. Sci.* 27:965-973. doi: 10.5713/ajas.2013.13416
- Zhou, **W.**, E. T. Kornegay, H. van Leer, J.W.G.M. Swinkels, E. **A.** Wong, and M. D. Lindemann. 1994. The role of feed consumption and feed efficiency in copper-stimulated growth. *J. Anim. Sci.* 72:2385-2394. doi:10.2527/1994.7292385x

Table 2-1 Diet composition (as-fed basis)

Item	Phase ^{1,2}				
	1	2	3	4	5
Ingredient, %					
Corn	56.04	61.33	65.87	69.32	79.48
Soybean meal (46.0 % CP)	21.61	16.52	11.97	8.52	8.39
Corn DDGS ³	20.00	20.00	20.00	20.00	10.00
Calcium carbonate	1.25	1.20	1.18	1.15	1.13
Monocalcium P (21.5% P)	0.15	---	---	---	0.09
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys-HCL	0.36	0.37	0.39	0.39	0.32
DL-Met	0.01	---	---	---	---
L-Thr	0.05	0.04	0.05	0.06	0.07
L-Trp	---	0.01	0.02	0.02	0.02
Optiphos 2000 ⁴	0.01	0.01	0.01	0.01	0.01
Trace mineral premix ⁵	0.10	0.10	0.10	0.10	0.10
Vitamin premix ⁶	0.08	0.08	0.08	0.08	0.05
Cu Source ^{7,8}	---	---	---	---	---
Total	100.00	100.00	100.00	100.00	100.00
Calculated analysis					
Standardized ileal digestible (SID) AA, %					
Lys	1.02	0.91	0.82	0.74	0.65
Ile:Lys	63	62	60	59	59
Met:Lys	29	29	30	31	30
Met & Cys:Lys	55	56	57	59	59
Thr:Lys	61	61	61	63	65
Trp:Lys	18.4	18.5	18.5	18.5	18.5
Val:Lys	70	70	70	70	70
Total Lys, %	1.18	1.06	0.96	0.87	0.76
NE, kcal/kg	2,431	2,466	2,494	2,515	2,547
SID Lys:NE, g/Mcal	4.20	3.69	3.29	2.94	2.55
Available P, %	0.29	0.26	0.25	0.25	0.22
Chemical analysis (as-fed basis) ⁹					
DM, %	86.14	86.03	86.04	86.00	85.96
CP, %	20.38	18.77	16.10	14.35	13.63
Ash, %	4.40	3.92	3.54	3.43	3.30

Ca, %	0.61	0.53	0.53	0.55	0.58
P, %	0.51	0.46	0.40	0.38	0.37

¹Phase 1, 2, 3, 4 and 5 were fed from approximately 37 to 46, 46 to 63, 63 to 77, 77 to 103, and 103 to 129 kg.

²Dietary treatments which contained a combination of CuSO₄ and Cu-AA were formed by adding 18, 33, or 48 mg/kg of additional Cu from CuSO₄ combined with 35, 50 or 65 mg/kg of Cu from Cu-AA, respectively at the expense of corn. Dietary treatments which contained only CuSO₄ were formed by adding either 0, 53 or 113 mg/kg of Cu from CuSO₄, at the expense of corn. The trace mineral premix was formulated to contribute 17 mg/kg of Cu from CuSO₄.

³Corn distillers dried grains with solubles (Valero Renewables, Aurora, MN).

⁴An assumed available P release value of 0.10 was used in formulation.

⁵Supplied: Zinc 110 g, Iron 110 g, Manganese 33 g, Copper 17 g, Iodine 0.33 g, and Selenium 0.30 g per kg of premix.

⁶Supplied: Vitamin A 7,054,720 I.U., Vitamin D3 1,102,300 I.U., Vitamin E 35,274 I.U., Vitamin B12 26, Riboflavin (B2) 6,173 mg, Niacin 39,683 mg, d-Pantothenic acid 22,046 mg, Menidione 3,527 mg per kg of premix.

⁷ Copper sulfate (CuSO₄; Prince Agri Products, Quincy, IL).

⁸Availa®Cu, (Zinpro Corporation, Eden Prairie, MN).

⁹ Multiple samples of each diet were collected, blended and sub sampled before being analyzed at Minnesota Valley Testing Laboratory (New Ulm, MN). Values listed represent the mean for all dietary treatments within a phase for the respective component.

Table 2-2 Chemical copper analysis of diets (as-fed basis)¹

Item ⁶	Added Cu ² , mg/kg					
	Control	CuSO ₄ ³		CuSO ₄ /Cu-AA ^{4,5}		
	17	70	130	70	100	130
Grower (37 – 77 kg)	43	73	95	97	87	112
Finisher (77 – 129 kg)	31	86	123	89	117	139
Overall (37 – 129 kg)	36	82	114	93	107	130

¹Multiple samples of each diet were collected, blended and sub sampled before being analyzed at Minnesota Valley Testing Laboratory (New Ulm, MN).

²The trace mineral premix was formulated to contribute 17 mg/kg of Cu from CuSO₄ to the complete basal diet. “Added Cu” within a dietary phase indicates the sum of Cu added from the premix and as an ingredient used in formulation. Values listed represent a weighted average based on feed intake and the chemical Cu analysis for each treatment in each dietary feeding phase.

³Copper sulfate (CuSO₄) (Prince Agri Products, Quincy, IL)

⁴Availa® Cu (Zinpro Corporation, Eden Prairie, MN)

⁵Copper concentration was achieved by a 50:50 inclusion of each Cu source.

⁶Dietary phases 1, 2 and 3 were fed from 37 to 77 kg BW. Dietary phases 4 and 5 were fed from 77 to 129 kg BW.

Table 2-3 Effects of increasing Cu from either CuSO₄ or combinations of CuSO₄ and Cu-AA on finishing pig growth performance¹

Item	Control ²	CuSO ₄ ³ , mg/kg		CuSO ₄ ³ /Cu-AA ⁴ , mg/kg			SEM	Probability, <i>P</i> <		
		70	130	70	100	130		Cu Source ⁵	level	
	17	70	130	70	100	130			Linear	Quadratic
BW, kg										
d 0	37.2	37.2	37.3	37.2	37.4	37.2	1.12	0.848	0.748	0.867
d 43	76.9	77.2	77.9	77.5	78.1	77.3	1.70	0.880	0.292	0.559
d 105	127.7	129.4	129.7	129.0	130.5	128.3	1.82	0.467	0.247	0.235
d 0 to 43										
ADG, kg	0.92	0.93	0.94	0.94	0.95	0.93	0.016	0.936	0.264	0.408
ADFI, kg	2.14	2.16	2.19	2.17	2.21	2.13	0.039	0.321	0.186	0.142
G:F	0.432	0.429	0.429	0.433	0.428	0.437	0.0041	0.170	0.964	0.512
d 43 to 105										
ADG, kg	0.83	0.85	0.85	0.85	0.85	0.83	0.013	0.400	0.455	0.334
ADFI, kg	2.64	2.68	2.67	2.64	2.64	2.56	0.034	0.037	0.603	0.349
G:F	0.315	0.317	0.319	0.320	0.321	0.325	0.0031	0.110	0.056	0.811
d 0 to 105										
ADG, kg	0.87	0.88	0.89	0.89	0.89	0.87	0.010	0.573	0.249	0.264
ADFI, kg	2.43	2.46	2.47	2.44	2.46	2.38	0.029	0.045	0.916	0.208
G:F	0.358	0.359	0.360	0.363	0.362	0.368	0.0030	0.051	0.125	0.914

¹A total of 1,089 pigs (280 × 1050 PIC; Hendersonville, TN; initially 37.3±2.8 kg) were used with 25 or 26 pigs per pen and 7 pens per treatment in a 105-d growth study.

²The trace mineral premix was formulated to contribute 17 mg/kg of Cu from CuSO₄ to the complete basal diet. All values listed as “Added Cu” represent the sum of Cu added from the premix and as an ingredient used in formulation.

³Copper Sulfate (CuSO₄; Prince Agri. Products, Quincy, IL)

⁴Availa[®] Cu (Zinpro Corporation, Eden Prairie, MN)

⁵Main effect of Cu source (70 and 130 mg/kg, within source).

Table 2-4 Effects of increasing Cu from either CuSO₄ or combinations of CuSO₄ and Cu-AA on finishing pig carcass characteristics¹

Item	Probability, <i>P</i> <									
	Control ²	CuSO ₄ ³ , mg/kg		CuSO ₄ ³ /Cu-AA ⁴ , mg/kg			SEM	Cu Source ⁵	Cu level	
		17	70	130	70	100			130	Linear
Yield, %	72.36	72.57	71.91	72.66	72.61	72.44	0.333	0.329	0.796	0.179
HCW, kg	93.04	93.84	93.89	93.72	94.73	92.92	1.353	0.547	0.493	0.247
Backfat, ⁶ mm.	17.3	17.4	17.4	17.5	17.2	17.1	0.36	0.836	0.687	0.770
Loin depth, ⁶ mm.	63.6	63.5	63.1	63.9	63.3	65.2	1.06	0.201	0.790	0.617
Lean, ⁶ %	55.91	55.84	55.82	55.81	55.98	56.22	0.264	0.363	0.605	0.581
HCW ADG ⁷ , kg	0.620	0.628	0.628	0.627	0.635	0.619	0.0079	0.552	0.519	0.229
HCW G:F	0.259	0.260	0.259	0.264	0.263	0.266	0.0025	0.033	0.213	0.589

¹A total of 1,089 pigs (280 × 1050 PIC; Hendersonville, TN initially 37.3±2.8 kg) were used with 25 or 26 pigs per pen and 7 pens per treatment in a 105-d growth study.

²The trace mineral premix was formulated to contribute 17 mg/kg of Cu from CuSO₄ to the complete basal diet. All values listed as “Added Cu” represent the sum of Cu added from the premix and as an ingredient used in formulation.

³Copper Sulfate (CuSO₄; Prince Agri. Products., Quincy, IL)

⁴Availa[®] Cu (Zinpro Corporation, Eden Prairie, MN)

⁵Main effect of Cu source (70 and 130 mg/kg, within source)

⁶Hot carcass weight was used as a covariate. Percentage lean was calculated using equations from the National Pork Producers Council (2000).

⁷An initial HCW was established using an assumed initial percentage yield of 75%.

Chapter 3 - Effects of increasing copper from tri-basic copper chloride or a copper-chelate on growth performance of nursery pigs

Abstract

A total of 2,117 pigs were used in two 35-d growth experiments to determine the effects of increasing added Cu from tri-basic copper chloride or a Cu-chelate on nursery pig growth performance. In Exp. 1, a total of 1,452 pigs [Group 1; 350 barrows (DNA 200 × 400; initially 5.9 ± 0.17 kg)] and [Group 2; 1,102 pigs (PIC 1050 × 280; initially 6.0 ± 0.26 kg)] were weaned at approximately 21 d of age. In Exp. 2, a total of 665 pigs [Group 3; 350 barrows (DNA 200 × 400; initially 6.4 ± 0.19 kg)] and [Group 4; 315 barrows and gilts (DNA 241 × 600; initially 5.2 ± 0.49 kg)] were weaned at approximately 21 d of age. Pigs in groups 1, 2, and 3 were fed a common starter diet for 7 d and pigs in group 4 were fed a common diet for 5 d after weaning before starting experiments. On d 0 of each experiment, pens of pigs were allotted by BW to 1 of 7 dietary treatments arranged as a 2×3 factorial plus one control diet, with main effects of Cu source (IntelliBond-C; Micronutrients, Indianapolis, IN or Mintrex-Cu; Novus, St. Charles, MO) and Cu level. Copper levels were 50, 100 or 150 mg/kg in Exp. 1 and 75, 150 or 225 mg/kg in Exp. 2. Diets were corn-soybean meal-based and fed in meal form in 2 phases (d 0 to 14 and 14 to 35). In Exp. 1 from d 0 to 35, there was a Cu source × level interaction (linear, $P < 0.05$) for ADG and d 35 BW where the rate of improvement with increasing Cu was greater in pigs fed Cu-chelate diets compared to those fed TBCC diets. Increasing added Cu increased (linear, $P = 0.001$) ADFI and improved G:F. Although Cu source did not influence G:F, pigs fed Cu from a Cu-chelate had greater ($P \leq 0.007$) ADG and ADFI than those fed Cu from tri-basic copper chloride. In Exp. 2 from d 0 to 35, there were no Cu source × level interactions observed.

Increasing Cu increased ADG (linear, $P = 0.048$) and final BW (linear, $P = 0.019$). The increase in ADG combined with no differences ADFI resulted in a tendency for improved G:F (linear, $P = 0.052$). In summary, these results suggest that increasing dietary Cu from tri-basic copper chloride or a Cu-chelate improved overall ADG and d 35 BW in nursery pigs and Cu source has the potential to influence nursery pig performance.

Keywords: nursery pig, growth, tri-basic copper chloride, copper-chelate

Introduction

The NRC (2012) reports a nutrient requirement estimate of 6 mg/kg of Cu for pigs weighing less than 11 kg BW and suggests that the Cu requirement decreases to 5 mg/kg for pigs between 11 and 135 kg BW. However, according to Flohr et al. (2016), many U.S. swine nutritionists formulate nursery pig diets to contain between 11 and 250 mg/kg Cu. This is likely because previous data have demonstrated increased growth performance of pigs to be associated with feeding high concentrations of Cu through 250 mg/kg (Dove, 1995; Cromwell et al., 1998; Hill et al., 2000).

Research has shown that different inorganic Cu sources ranging from 11 to 327 mg/kg in the diet influence nursery pig growth performance similarly (Cromwell et al., 1998; Shelton et al., 2011; Huang et al 2015). Tri-basic copper chloride is an inorganic mineral source, which is non-hygroscopic and has low solubility in water, but is highly soluble in acidic conditions (Miles et al., 1998). Organic Cu sources are argued to be more bioavailable to the young pig due to their chemical structure compared to inorganic sources. Mintrex-Cu is an organic form of Cu [Cu(HMTBa)₂] which has been shown to be more bioavailable to the pig because of decreased binding activity with other dietary constituents, therefore suggesting that lower concentrations are required compared with inorganic Cu (Zhao et al., 2009).

To our knowledge there are no published data that directly compare the effects of increasing added Cu from TBCC or a Cu-chelate on growth performance of nursery pigs. Therefore, our studies were designed to investigate the effects of increasing Cu from either TBCC or a Cu-chelate on growth performance of nursery pigs.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used for these studies. Four groups of pigs were used in two experiments with groups 1 and 2 combined to represent Exp. 1, and groups 3 and 4 combined to represent Exp. 2. Groups 1 and 3 pigs were housed at the Kansas State University Segregated Early Weaning Facility in Manhattan, KS. Group 2 pigs were housed in a commercial research facility in southwestern Minnesota. Group 4 pigs were housed at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The research facilities were environmentally controlled. For groups 1 and 3, each pen (1.2 × 1.2 m) had tri-bar flooring and contained one 4-hole dry self-feeder and one cup waterer to provide ad libitum access to feed and water. For group 2, each pen (3.7 × 2.3 m) had plastic slatted flooring and contained one 6-hole dry self-feeder and one pan waterer to provide ad libitum access to feed and water. For group 4, each pen (1.2 × 1.5 m) had tri-bar flooring and contained one 4-hole dry self-feeder and one nipple waterer to provide ad libitum access to feed and water. Dietary treatments for groups 1, 3, and 4 were manufactured at the O.H. Kruse Feed Mill in Manhattan, KS. Group 2 dietary treatments were manufactured in a commercial feed mill located in Pipestone, MN.

Live Animal Management, Exp. 1

In group 1, 350 barrows (DNA 200 × 400; initially 5.9±0.17 kg) were weaned at approximately 21 d of age and allotted to pen based on initial BW with 5 pigs per pen and 10 replicate pens per treatment. In group 2, 1,102 pigs (PIC 1050 × 280; initially 6.0±0.26 kg) were weaned and randomly placed over 2 consecutive days with 24 to 27 pigs per pen and 3 replicate pens per treatment for each day. Group 1 and 2 pigs were fed a common starter diet for 7 d after weaning before beginning the experiment.

Live Animal Management, Exp. 2

In group 3, 350 barrows (DNA 200 × 400; initially 6.4±0.19 kg) were weaned at approximately 21 d of age and allotted to pens based on initial BW with 5 pigs per pen and 10 replicate pens per treatment. In group 4, 315 barrows and gilts (DNA 241 × 600; initially 5.2 ±0.49 kg) were weaned and allotted to pens based on initial BW and age. Age block 1 consisted of 4 replicate pens per treatment and pigs ranged in age from 16 to 20 d. Age block 2 consisted of 5 replicate pens per treatment and pigs ranged in age from 21 to 24 d. Group 3 and 4 pigs were fed a common starter diet for 7 and 5 d, respectively, after weaning.

Diets and Response Criteria

On d 0 of each experiment, pens were allotted by BW to 1 of 7 dietary treatments arranged as a 2 × 3 factorial plus a control diet, with main effects of Cu source (Tri-basic Copper Chloride, TBCC, IntelliBond-C; Micronutrients, Indianapolis, IN or Copper-methionine chelate, Cu-chelate, Mintrex-Cu; Novus, St. Charles, MO) and Cu level. Copper levels were 50, 100 or 150 mg/kg in Exp. 1 and 75, 150, and 225 mg/kg in Exp. 2. Diets were corn-soybean meal-based and fed in meal form in 2 phases (d 0 to 14 and 14 to 35; Table 1). The trace mineral premix added to all diets provided complete diets with 17 mg/kg Cu from CuSO₄. The Met activity

contributed by the Cu-chelate was considered in all diet formulation. For each group, pigs and feeders were weighed on d 0, 7, 14, 21, 28, and 35 to calculate ADG, ADFI, and G:F.

Chemical Analysis

Complete diet samples for each group were collected from a minimum of 6 feeders and combined to make 1 composite sample per treatment and phase. Samples were then split, ground and sent to a commercial analytical lab for chemical analysis.

For Exp. 1, group 1 samples were sent to University of Missouri-Columbia Agriculture Chemical Laboratories (Columbia, MO) for analysis of DM (method 934.01; AOAC, 2006) CP (method 984.13; AOAC, 2006) crude fiber (method 978.10; AOAC; AOCS Ba 6a-05; 2006), ether extract (method 920.39; AOAC, 2006) ash (method 942.05; AOAC, 2006) and Cu (method 980.02; AOAC, 2006) concentrations and Ward Laboratories Inc. (Kearney, NE) for analysis of Ca, P and Cu concentrations analysis by a method outlined by AOAC (2012) using an iCAP 6000 series ICP Emission Spectrometer (Thermo Electron Corporation, Marietta, OH). Group 1 Cu concentrations were determined by averaging the analyzed values from each lab. Group 2 samples were sent to Midwest Laboratories (Omaha, NE) for duplicate analysis of DM (method 930.15; AOAC, 2000) CP (method 990.03; AOAC, 2000) crude fiber (method 978.10; AOAC; AOCS Ba 6a-05; 2006), ether extract (method 945.16; AOAC, 2000) ash (method 942.05; AOAC, 2006) and Cu (method 985.01; AOAC, 2000) concentrations. For Exp. 1, final nutrient concentrations represent the combined average of the chemical analyses of diets across pig groups 1 and 2.

For Exp. 2, groups 3 and 4 samples were sent to Cumberland Valley Analytical Services (Hagerstown, MD) for analysis of DM (method 930.15; AOAC, 2000), CP (method 990.03; AOAC, 2000), ether extract (method 2003.05; AOAC, 2006) ash (method 942.05; AOAC,

2000), Ca, P and Cu (method 985.01; AOAC, 2000) concentrations and at Ward Laboratories Inc. (Kearney, NE) Copper concentrations were analyzed by a method outlined by AOAC (2012) using an iCAP 6000 series ICP Emission Spectrometer (Thermo Electron Corporation, Marietta, OH). Copper concentrations were determined by averaging 3 individual analyzed values, 2 from Cumberland Valley and 1 from Ward Labs. In group 4, nutrient concentrations were determined by averaging 2 analyzed values. For Exp. 2, final nutrient concentrations represent the combined average of the chemical analyses of diets across pig groups 3 and 4.

Statistical Analysis

Data were combined across groups 1 and 2 for Exp. 1 and groups 3 and 4 for Exp. 2 and each experiment was analyzed as a randomized incomplete block design using PROC GLIMMIX (SAS Institute, Inc., Cary, NC) with pen as the experimental unit and dietary treatment as the fixed effect. For Exp. 1, the random effect of block within group was used in the model. For Exp. 2, the random effects of block and block within group were used in the model. The main effects of source (TBCC or Cu-chelate) and linear, quadratic and cubic effects of Cu level (0, 50, 100, 150 or 0, 75, 150, 225 mg/kg Cu for Exp. 1 and 2, respectively) as well as their interaction were analyzed using polynomial contrast statements. Results were considered significant with $P < 0.05$ and marginally significant when $P < 0.10$ and ≥ 0.05).

Results

Diet Analysis, Exp. 1 and 2

The chemical analyses of the complete diets were similar to the intended formulation (Tables 2 and 3) and Cu additions increased across dietary treatments.

Growth Performance, Exp. 1

From d 0 to 14 (6.0 to 9.8 kg), there were no Cu source \times level interactions observed. Increasing added Cu increased (linear, $P \leq 0.003$; Table 4) ADG and ADFI, which tended to improve (linear, $P = 0.057$) G:F. Although Cu source did not influence G:F, pigs fed added Cu from Cu-chelate tended to have greater ($P = 0.081$) ADG and ($P = 0.053$) ADFI than those fed added Cu from TBCC.

From d 14 to 35 (9.8 to 22.6 kg), there was a source \times level interaction (linear, $P = 0.011$) for ADG as ADG increased linearly with each increasing level of Cu from Cu-chelate; however, pigs fed Cu from TBCC only had increased ADG at 150 mg/kg. Increasing added Cu increased (cubic, $P = 0.020$) ADG with the greatest response initially from 0 to 50 mg/kg Cu with a marginal increase in ADG from 50 to 100 mg/kg and a further increase in ADG observed when Cu increased from 100 to 150 mg/kg. Increasing added Cu increased (linear, $P = 0.001$) ADFI and improved (linear, $P = 0.001$) G:F. Similar to performance from d 0 to 14, Cu source did not influence G:F; however, pigs fed Cu from Cu-chelate had greater ($P \leq 0.009$) ADG and ADFI than those fed Cu from TBCC.

Overall d 0 to 35 (6.0 to 22.6 kg), a Cu source \times level interaction was observed (linear, $P = 0.042$) for ADG where the rate of improvement with increasing Cu was greater in pigs fed Cu-chelate diets compared to those fed TBCC diets. Despite the interaction, increasing added Cu increased (linear, $P = 0.001$) ADG, ADFI, and G:F. Although Cu source did not influence G:F; pigs fed Cu from Cu-chelate had greater ($P \leq 0.007$) ADG and ADFI than those fed Cu from TBCC.

Growth Performance, Exp. 2

From d 0 to 14 (5.8 to 9.4 kg), a tendency for a source \times level interaction (quadratic, $P = 0.086$; Table 5) was observed for ADG with maximum ADG at 150 mg/kg Cu from the Cu-chelate, but at 225 mg/kg for pigs fed TBCC. Despite this interaction, increasing Cu increased (linear, $P \leq 0.004$) ADG and ADFI with no changes in G:F. Copper source did not impact performance.

From d 14 to 35 (9.4 to 21.6 kg), there were no Cu source \times level interactions observed. Neither Cu source nor level influenced ADG or ADFI; however, increasing Cu improved (linear, $P = 0.021$) G:F.

Overall d 0 to 35 (5.8 to 21.6), there were no Cu source \times level interactions observed. Increasing Cu increased ADG (linear, $P = 0.048$) and final BW (linear, $P = 0.019$). The increase in ADG combined with no differences ADFI resulted in a tendency for improved G:F (linear, $P = 0.052$) with increasing Cu, but no Cu source effect was observed.

Discussion

While research has been conducted comparing Cu sources in swine diets, it is our understanding that there is no other published research that has directly compared the effects of increasing Cu from TBCC to a Cu-chelate (Mintrex-Cu) on nursery pig performance. Much of the research in the current body of literature have compared increasing Cu from CuSO_4 alone, or comparing CuSO_4 to TBCC. Huang et al. (2015) fed diets to nursery pigs that contained increasing Cu (14 to 273 mg/kg) and similar to our Exp. 2, they reported that there were no differences in growth among pigs fed Cu from either TBCC or CuSO_4 . Huang et al. (2015) hypothesized that it may be due to the short duration of their 10 d study that a response to Cu source was not observed. Cromwell et al. (1998) conducted three experiments and fed diets to

nursery pigs (7.9 to 17.7 kg) that contained 13 (control), 100, 150, or 200 mg/kg added Cu from either TBCC or CuSO₄. In their experiments, they reported that pigs fed diets containing different Cu sources had similar growth performance and pigs fed 200 mg/kg Cu from CuSO₄ had improved performance compared to those fed no added Cu. Alternatively to the aforementioned studies, Ma et al. (2015) completed a multi-trial meta-analysis to evaluate the effect of dose-responses of Cu from either Cu(HMTBa)₂ (Mintrex-Cu) or CuSO₄ on nursery pig growth performance. The authors reported that only from d 14 to 21 post-weaning (21 d weaning age) was the ADG response curve significantly different for pigs fed Cu(HMTBa)₂ compared with those fed CuSO₄. In addition, the authors found similar ADFI responses among Cu sources. These studies generally conclude that increasing added Cu improves growth performance; however, consistent with the conclusions from the experiments for the study herein, it appears there is variation in the literature around whether or not nursery pig growth performance is dependent on Cu source.

Several studies have shown that adding growth promoting levels of Cu improves nursery pig growth performance (Dove, 1995; Cromwell et al., 1998; Hill et al., 2000). Dove (1995) fed diets to nursery pigs that contained either 15 or 250 mg/kg added Cu from CuSO₄ and reported pigs provided diets containing 250 mg/kg added Cu had greater growth performance than those fed diets containing 15 mg.kg Cu. These findings are similar to those from Cromwell et al. (1998) who reported pigs fed 13 mg/kg added Cu had poorer growth than those fed 200 mg/kg Cu from CuSO₄. A regional study completed by Hill et al. (2000) confirmed those previous findings in that pigs fed high added Cu (250 mg/kg) had greater ADG and G:F than those fed diets without added Cu. More recently, Bikker et al. (2016) fed pigs (~7 to ~37 kg) increasing Cu (15, 80, 120 and 160 mg/kg Cu) from CuSO₄ in barley-wheat-based diets with 20% corn. In their

study, increasing added Cu from 15 to 160 mg/kg Cu increased ADG and ADFI for growing pigs.

Each of our experiments agree that increasing added Cu increased overall ADG and BW. It appears the typical improved ADFI response to increasing added Cu helps to explain the growth response in Exp. 1, in that increasing added Cu in the early (6.0 to 9.8 kg), late (9.8 to 22.6 kg) and overall (6.0 to 22.6 kg) nursery periods of the study increased both ADG, ADFI and improved G:F. Others have found similar responses in previous studies with nursery pigs (Dove, 1995; Shelton et al., 2011; Bikker et al., 2016). For Exp. 2, ADFI increased only in the first 14 d (5.8 to 9.4 kg) of the experiment for pigs fed increasing added Cu, with no differences in feed intake for pigs fed increasing added Cu in the late (9.4 to 21.6 kg) or overall (9.4 to 21.6) nursery periods. As a result, in Exp. 2, increasing added Cu increased ADG in the early nursery period but not the late nursery period in Exp. 2. However, in each period, the magnitude of growth improvement to increasing Cu was numerically similar. In the early and late nursery period, the ADG advantage was 22 and 18 g/d, respectively, compared to the pigs fed the control diet. It appears that the ADG response to increasing Cu was more difficult to detect in the late nursery period. Interestingly, there were no differences in feed intake during the late nursery period, however G:F improved and d 35 BW was increased by increasing added Cu. This may help support that while not significant, there may be potential for a growth advantage to increasing added Cu during the late nursery period.

The study herein is unique in that the added Cu sources used for the study herein have not been deeply compared with each other. Thus, it is difficult to provide a potential explanation as to why we did not observe a late (9.4 to 21.6 kg) or overall nursery (5.8 to 21.6 kg) ADFI response for increasing added Cu in Exp. 2. Experiments 1 and 2 for the study herein agree that

increasing added Cu in both the late and overall periods positively influences feed efficiency. Due to a relatively small amount of research, not much is known about the growth stimulation mechanisms for TBCC and Cu-chelates. However, some studies report the feed efficiency responses may be related to; disruption of bacterial cell membranes resulting in Cu ion penetration and bacterial cell toxicity (Pang and Applegate. 2007). More research is warranted to better understand the modes of actions behind why Cu positively influences performance of nursery pigs.

In summary, these results suggest that increasing TBCC or Cu-chelate has the potential to affect both phase 1 and 2 nursery growth phases and subsequently improves d 35 BW. From our data, it also appears pigs provided Cu from Cu-chelate may have greater ADG, ADFI and d 35 BW than those provided Cu from TBCC; however, the studies herein do provide conflicting results on whether or not nursery pig growth performance is dependent on Cu source.

Literature Cited

- AOAC. 2000. Official methods of analysis. 17th ed. Assoc. Off. Anal. Chem., Gaithersburg, MD.
- AOAC. 2006. Official methods of analysis. 18th ed. AOAC Int., Washington, DC.
- AOAC. 2012. Official methods of analysis. 19th ed. AOAC Int., Gaithersburg, MD.
- Bikker, P., A. W. Jongbloed, J. van Baal. 2016. Dose-dependent effects of copper supplementation of nursery diets on growth performance and fecal consistency in weaned pigs. *J. Anim. Sci.* 94:181-186. doi:10.2527/jas2015-9874
- Cromwell, G. T., M. D. Lindemann, H. K. Monegue, D. D. Hall, and D. E. Orr. 1998. Tribasic copper chloride and copper sulfate as copper sources for weanling pigs. *J. Anim. Sci.* 76:118-123. doi:10.2527/1998.761118x
- Dove, C. R. 1995. The effect of Cu level on nutrient utilization of weanling pigs. *J. Anim. Sci.* 73:166-171. doi:10.2527/1995.731166x

- Flohr, J.R., J.M. DeRouchey, J.C. Woodworth, M.D. Tokach, R.D. Goodband, and S.S. Dritz. 2016. A Survey of current feeding regimens for vitamins and trace minerals in the US swine industry. *J. Swine Health Prod.* 24:290-303.
- Hill, G. M., G. L. Cromwell, T. D. Crenshaw, C. R. Dove, R. C. Ewan, D. A. Knabe, A. J. Lewis, G. W. Libal, D. C. Mahan, G. C. Shurson, L. L. Southern, and T. L. Veum. 2000. Growth promotion effects and plasma changes from feeding high dietary concentrations of zinc and copper to weanling pigs (regional study). *J. Anim. Sci.* 78:1010–1016. doi:10.2527/2000.7841010x
- Huang, Y. L., M. S. Ashwell, R. S. Fry, K. E. Lloyd, W. L. Flowers, and J. W. Spears. 2015. Effect of dietary copper amount and source on copper metabolism and oxidative stress of weanling pigs in short-term feeding. *J. Anim. Sci.* 93:2948–2955. doi:10.2527/jas.2014-8082
- Ma, Y. L., G. I. Zanton, J. Zhao, K. Wedekind, J. Escobar, & M. Vazquez-Añón. 2015. Multitrial analysis of the effects of copper level and source on performance in nursery pigs. *J. Anim. Sci.* 93:606-614. doi:10.2527/jas2014-7796
- Miles, R. D., S. F. O’Keefe, P. R. Henry, C. B. Ammerman, and X. G. Luo. 1998. The effect of dietary supplementation with copper sulfate or tribasic copper chloride on broiler performance, relative copper bioavailability, and prooxidant activity. *Poult. Sci.* 77:416–425. doi:10.1093/ps/77.3.416
- NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.
- Pang, Y. and T. Applegate. 2007. Effects of dietary copper supplementation and copper source on digesta pH, calcium, zinc, and copper complex size in the gastrointestinal tract of the broiler chicken. *Poult. Sci.* 86:531-537. doi:10.1093/ps/86.3.531
- Shelton, N. W., M. D. Tokach, J. L. Nelssen, R. D. Goodband, S. S. Dritz, J. M. DeRouchey, and G. M. Hill. 2011. Effects of copper sulfate, tri-basic copper chloride, and zinc oxide on weanling pig performance. *J. Anim. Sci.* 89:2440–2451. doi:10.2527/jas.2010-3432
- Zhao, J., R. J. Harrell, G. Allee, B. Hinson, P. Winkelbauer, C. Atwell, J. D. Richards, and M. Vazquez-Anon. 2009. Effect of an organic copper source on growth performance and tissue copper concentration in nursery pigs. *J. Anim. Sci.* 87(Suppl. 3):60 (Abstr.).

Table 3-1 Diet composition (as-fed basis)¹

Item	Phase	
	1	2
Ingredient, %		
Corn	48.47	57.30
Soybean meal ²	27.68	33.73
Dried whey	10.00	---
Liquid fat ³	5.00	5.00
Limestone	0.85	0.85
Monocalcium P (21.5% P)	1.60	1.70
Salt	0.30	0.35
L-Lys-HCl	0.33	0.33
L-Thr	0.15	0.16
HMB ⁴	0.22	0.18
HP-300 ⁵	5.00	---
Vitamin premix ⁶	0.15	0.15
Trace mineral premix ⁷	0.25	0.25
Cu source ^{8,9}	---	---
Total	100.00	100.00
Calculated analysis		
Standardized ileal digestible (SID) AA, %		
Lys	1.30	1.25
Ile:Lys	63	62
Met: Lys	36	35
Met + Cys: Lys	58	58
Thr: Lys	65	65
Trp: Lys	18.4	18.4
Val: Lys	67	67
NE, kcal/kg	2,645	2,615
SID Lys:NE, g/Mcal	4.91	4.78
CP, %	21.7	21.3
Ca, %	0.85	0.80
P, %	0.78	0.75
Available P, %	0.49	0.44

¹In each experiment, phase 1 and 2 were fed from (Exp. 1; 6.0 to 9.8 and 9.8 to 22.6 kg) and (Exp. 2; 5.8 to 9.4 and 9.4 to 21.6 kg), respectively. Dietary treatments were formed by adding 50, 100 or 150 mg/kg Cu (Exp. 1) or 75, 150, or 225 mg/kg of Cu (Exp. 2) from either

tri-basic copper chloride or Cu-chelate at the expense of corn. The trace mineral premix was formulated to contribute 17 mg/kg of Cu to the complete diet for each experiment.

²Exp. 1 and 2 (47.7% CP).

³Exp. 2 and Group 1 (choice white grease) and group 2 (beef tallow).

⁴Hydroxymethylthio-butanoic acid, Novus International (Saint Charles, MO).

⁵HP-300, Hamlet Protein, Findlay, OH, formulated with 3.25% SID Lys.

⁶Provided per kilogram of diet: 8,818 IU vitamin A, 2,205 IU vitamin D₃, 44.1 IU vitamin E, 0.04 mg vitamin B₁₂, 8.3 mg riboflavin, 82.7 mg niacin, 27.6 mg pantothenic acid, 4.4 mg menidione.

⁷Provided per kilogram of diet: 17 mg Cu from copper sulfate, 0.3 mg I from Ca iodate, 110 mg Fe from ferrous sulfate, 33 mg Mg from manganese sulfate, 0.3 mg Se from sodium selenite, 110 mg Zn from zinc sulfate.

⁸Mintrex Cu[®], copper methionine hydroxy analogue (Novus, International, St. Charles, MO).

⁹IntelliBond-C[®], tri-basic copper chloride (Micronutrients, Indianapolis, IN).

Table 3-2 Chemical analysis of diets (as-fed basis)¹ (Exp. 1)

Item	Phase 1							Phase 2						
	Added Cu, mg/kg													
	Control	TBCC ²			Cu-chelate ³			Control	TBCC ²			Cu-chelate ³		
	0	50	100	150	50	100	150	0	50	100	150	50	100	150
DM, % ⁴	87.5	87.2	86.8	86.7	86.6	86.6	86.8	86.7	86.4	85.8	85.6	86.2	86.1	85.7
CP, % ⁴	21.9	21.0	20.6	20.9	20.8	20.8	20.8	19.2	20.4	19.9	21.9	18.9	19.6	21.2
Crude fiber, % ⁴	1.9	2.0	1.5	1.6	2.0	2.1	2.1	2.6	2.4	2.1	2.4	1.9	2.0	2.0
Ether extract, % ⁴	7.1	6.8	7.2	6.9	6.6	7.6	6.9	6.7	6.5	6.3	5.3	6.3	5.6	5.6
Ash, % ⁴	5.7	5.7	5.6	6.0	5.9	5.8	5.9	5.4	5.4	5.3	5.7	5.4	5.7	5.6
Ca, %	0.85	0.78	0.77	0.82	0.75	0.86	0.76	0.75	0.97	1.00	0.76	1.01	0.87	0.91
P, %	0.76	0.74	0.68	0.79	0.73	0.83	0.78	0.62	0.72	0.79	0.77	0.81	0.66	0.88
Cu, mg/kg ⁵	40	88	140	145	104	155	204	40	75	119	174	100	135	230

¹Multiple samples of each diet were collected, blended and sub sampled, and analyzed (Missouri Agricultural Experimentation Lab, Colombia, MO, Ward Laboratories, Kearney, NE and Midwest Labs, Omaha, NE). All values represent the combined average of the chemical analyses of diets for the experiment.

²IntelliBond-C[®], tri-basic copper chloride (Micronutrients, Indianapolis, IN).

³Mintrex Cu[®], copper methionine hydroxy analogue (St. Charles, MO).

⁴Group 1; 1 analytical value from 2 individual samples was determined. Values for phase 2 represent 1 mean analytical value from 4 individual samples. Group 2; 1 analytical value from a single sample was determined.

⁵Group 1; 1 analytical value from 2 individual samples was determined. Group 2; 1 analytical value from a single sample analyzed in duplicate.

Table 3-3 Chemical analysis of diets (as-fed basis)¹ (Exp. 2)

Item	Phase 1							Phase 2						
	Added Cu, mg/kg													
	Control	TBCC ²			Cu-chelate ³			Control	TBCC ²			Cu-chelate ³		
	0	75	150	225	75	150	225	0	75	150	225	75	150	225
DM, % ⁴	88.9	88.1	88.9	89.0	89.0	89.0	88.9	88.9	88.4	88.2	88.6	88.4	88.6	88.6
CP, % ⁴	24.1	24.3	24.3	24.5	24.7	24.8	24.0	24.3	23.8	24.3	32.9	24.4	24.0	23.4
Crude fiber, % ⁴	2.5	2.5	2.4	2.5	2.8	2.7	2.6	2.6	3.0	2.7	2.6	2.5	2.5	2.3
Ether extract, % ⁴	6.0	6.7	6.4	7.2	6.9	6.8	7.3	7.3	7.1	7.0	7.0	7.3	7.1	6.6
Ash, % ⁴	6.6	6.6	6.6	6.8	6.5	6.4	6.4	5.9	6.1	6.0	7.2	5.7	5.7	5.3
Ca, % ⁴	1.06	0.97	1.01	1.01	0.94	0.95	1.03	1.02	0.93	0.93	1.01	0.93	0.99	0.93
P, % ⁴	0.86	0.85	0.84	0.89	0.84	0.88	0.88	0.82	0.81	0.82	0.84	0.79	0.84	0.76
Cu, mg/kg ⁵	24	86	179	248	134	227	316	28	90	144	246	114	177	283

¹For each group of pigs, multiple samples of each diet were collected, blended and sub-sampled, and analyzed (Cumberland Valley Analytical Services, Hagerstown, MD and Ward Laboratories, Kearney, NE). All values represent the combined average of the chemical analyses of diets for the experiment.

²IntelliBond-C[®], TBCC (Micronutrients, Indianapolis, IN).

³Mintrex-Cu[®], copper methionine hydroxy analogue (St. Charles, MO).

⁴Group 1 and 2; 1 analytical value from 2 individual samples was determined.

⁵Group 1; 1 analytical value from 3 individual samples was determined. Group 2; 1 analytical value from 2 individual samples was determined.

Table 3-4 Effects of increasing Cu from tri-basic copper chloride or Cu-chelate on growth performance of pigs¹ (Exp. 1)

Item	Added Cu, mg/kg								Probability, <i>P</i> <				
	Control	TBCC ²			Cu-chelate ³			SEM	Cu Source	Cu level		Source × level	
	0	50	100	150	50	100	150			Linear	Quadratic	Linear	Quadratic
BW, kg													
d 0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	0.05	0.112	0.998	0.613	0.372	0.402
d 14	9.6	9.5	9.7	9.9	9.8	9.9	10.0	0.17	0.030	0.001	0.941	0.462	0.318
d 35	21.5	22.3	22.4	22.8	22.6	23.0	23.4	0.25	0.001	0.001	0.031	0.019	0.384
d 0 to 14													
ADG, g	251	251	266	274	268	271	281	10.2	0.081	0.001	0.953	0.780	0.377
ADFI, g	356	353	373	374	373	373	388	14.5	0.053	0.003	0.917	0.511	0.718
G:F	0.709	0.713	0.714	0.737	0.721	0.726	0.728	0.0122	0.678	0.057	0.794	0.650	0.265
d 14 to 35													
ADG ⁴ , g	567	602	602	614	612	621	635	6.8	0.001	0.001	0.004	0.011	0.568
ADFI, g	841	870	861	882	888	894	901	13.6	0.009	0.001	0.159	0.167	0.222
G:F	0.675	0.693	0.7	0.698	0.692	0.696	0.707	0.0084	0.800	0.001	0.216	0.471	0.417
d 0 to 35													
ADG, g	440	461	467	477	474	480	493	5.9	0.001	0.001	0.027	0.042	0.334
ADFI, g	646	662	665	678	682	684	694	9.7	0.007	0.001	0.279	0.211	0.277
G:F	0.681	0.696	0.703	0.705	0.698	0.702	0.711	0.0062	0.632	0.001	0.179	0.540	0.669

¹A total of 1,452 pigs [Group 1; 350 barrows (DNA 200 × 400; initially 5.9 kg)] and [Group 2; 1,102 pigs (PIC 1050 × 280; initially 6.0 kg)] were used in two 35-d growth studies. Data were combined across the 2 groups with 5 pigs per pen and 10 replications per treatment in group 1; and 24 to 27 pigs per pen and 6 replications per treatment in group 2. The treatment design was the same across both groups of pigs. The trace mineral premix was formulated to contribute 17 mg/kg of Cu to the complete diet.

²Intellibond-C[®], tri-basic copper chloride (Micronutrients, Indianapolis, IN).

³Mintrex Cu[®], copper methionine hydroxy analogue (St. Charles, MO).

⁴Cu level (cubic, *P* = 0.020)

Table 3-5 Effects of increasing Cu from tri-basic copper chloride or Cu-chelate on growth performance of pigs¹ (Exp. 2)

Item	Added Cu, mg/kg							SEM	Probability, <i>P</i> <				
	Control	TBCC ²			Cu-chelate ³				Cu Source	Cu level		Source × level	
	0	75	150	225	75	150	225			Linear	Quadratic	Linear	Quadratic
BW, kg													
d 0	5.8	5.8	5.8	5.8	5.8	5.8	5.8	0.60	0.960	0.974	0.964	0.956	0.965
d 14	9.1	9.1	9.4	9.6	9.3	9.6	9.5	1.01	0.431	0.002	0.886	0.502	0.108
d 35	21.1	21.0	21.7	22.0	21.6	22.2	21.8	2.77	0.315	0.019	0.624	0.619	0.130
d 0 to 14													
ADG, g	239	235	254	266	249	269	259	32.1	0.289	0.004	0.854	0.631	0.086
ADFI, g	315	307	343	350	334	340	341	20.8	0.456	0.001	0.921	0.203	0.139
G:F	0.756	0.765	0.743	0.757	0.740	0.785	0.752	0.0527	0.738	0.899	0.817	0.486	0.567
d 14 to 35													
ADG, g	567	561	585	590	572	589	580	88.8	0.852	0.143	0.957	0.564	0.431
ADFI, g	852	845	858	870	861	868	837	125.0	0.872	0.831	0.702	0.181	0.147
G:F	0.663	0.663	0.682	0.679	0.661	0.679	0.687	0.0106	0.913	0.021	0.812	0.551	0.497
d 0 to 35													
ADG, g	436	430	452	459	441	459	451	66.4	0.712	0.048	0.976	0.560	0.296
ADFI, g	637	629	651	660	647	654	637	83.7	0.939	0.305	0.808	0.150	0.144
G:F	0.681	0.683	0.692	0.694	0.677	0.700	0.701	0.0168	0.710	0.052	0.882	0.418	0.812

¹A total of 665 pigs [Group 3; 350 barrows (DNA 200 × 400; initially 6.4 kg)] and [Group 4; 315 pigs (DNA 241 × 600; initially 5.2 kg)] were used in two 35-d growth studies. Data were combined across the 2 groups with 5 pigs per pen and 10 replications per treatment in group 3 and 5 pigs per pen and 9 replications per treatment in group 4. The treatment design was the same across both groups of pigs. The trace mineral premix was formulated to contribute 17 mg/kg of Cu to the complete diet.

²Intellibond-C[®], tri-basic copper chloride (Micronutrients, Indianapolis, IN).

³Mintrex Cu[®], copper methionine hydroxy analogue (St. Charles, MO).

Chapter 4 - Effects of increasing space allowance by removing a pig or gate adjustment on finishing pig growth performance

Abstract

A total of 256 pigs (PIC 327 × 1050; Hendersonville, TN; initially 55.9±0.43 kg) were used in a 71-d growth study to determine the effects of increasing space allowance and pig removal on pig growth performance. Pens of pigs were blocked by BW and allotted to 1 of 4 space allowance treatments, initially with 8 pigs per pen and 8 pens per treatment. Treatments included pens with 0.91 m² per pig or 0.63 m² per pig for the entire study. Two additional treatments initially provided 0.63 m² per pig, but either a gate was adjusted on d 28, 45, and 62 or the heaviest pig in the pen was removed from the pen on d 28 and 45 to provide more space to keep pigs in accordance with their predicted minimum space requirement [$(m^2) = 0.0336 \times BW (kg)^{0.67}$]. From d 0 to 14 (56 to 69 kg), there was no effect of stocking density observed for ADG, ADFI, and G:F. From d 14 to 28 (69 to 83 kg), pigs provided 0.91 m² had increased ($P < 0.05$) ADG, ADFI and G:F compared with those allowed 0.63 m². On d 28 (83 kg), either the heaviest pig was removed or the gate was adjusted to provided pigs 0.72 m². Pigs provided 0.91 m² tended to be heavier ($P = 0.081$) on d 28 and had increased ADFI ($P = 0.025$) compared with those provided 0.63 m² or those that had the heaviest pig removed. From d 45 to 62 (98 to 116 kg), pigs provided 0.91 m² were heavier ($P < 0.001$) than all others, while pigs provided 0.63 m² had reduced ADFI compared to all other treatments. From d 62 to 71 (116 to 124 kg), pigs provided 0.91 m² had greater ($P < 0.05$) ADG and ADFI than those provided 0.63 m² with space adjustment treatments intermediate. Overall d 0 to 71 (66 to 124 kg), pigs provided 0.91 m² had increased ($P = 0.001$) ADG compared with those allowed 0.63 m² with pigs provided increased space intermediate. Based on a k value of 0.0336, no differences in performance were expected before a BW of approximately 83 kg. In summary, pigs with 0.91 m² grew faster and consumed more feed than pigs restricted in space. As pigs reached the critical k value, gate adjustments and pig removals affected growth similarly. As pigs grew to the minimum predicted space requirement and were subsequently allowed more space, performance was greater than those provided 0.61 m² but less than those allowed 0.91 m². Thus, the industry accepted minimum

space prediction equation [$m^2 = 0.0336 \times BW \text{ (kg)}^{0.67}$] may not fully explain the effects of space on pig performance across multiple body weight ranges.

Key Words: finishing pig, growth, k value, pig removal, space allowance

Introduction

Facility space is the second largest cost of pig production and efficient space usage is important for profitable pork production. A common allometric expression has been used to describe the relationship between floor space and pig BW. Gonyou et al. (2006) used the allometric expression $A = k \cdot BW^{0.67}$, where A is area allowed per pig (m^2), k is a coefficient, and BW is pig weight (kg). This converts BW into a 2-dimensional concept, to describe floor space allowance in order to predict productivity. Using the k value, 0.0336, the equation should indicate when crowding begins to limit growth. Pig growth should not be decreased until their BW reaches the point where there is inadequate space to maintain maximal growth rate, (i.e., $k < 0.0336$); Gonyou et al., 2006). However, some studies (Gonyou et al., 2006; Thomas et al., 2015; Flohr et al., 2016) demonstrated growth reductions due to inadequate space may start to occur before pigs reach the critical k value.

Removing the heaviest pig(s) from the pen roughly 2 wk before marketing all the pigs in a pen (topping) is a common production practice that has been implemented by the commercial swine industry. Many studies have shown that the removal of the heaviest pig(s) before the entire pen is marketed results in an increased growth rate and space allowance for the remaining pigs in pen (Woodworth et al., 2000; DeDecker et al., 2005; Flohr et al., 2016).

Surprisingly, pig removal from pens has not been evaluated to better understand if the growth improvements are due to the change in social dynamic from removing the heaviest pig or simply the increased space in the pen from removing the heaviest pig. Thus, the objective of our study was to determine whether the increase in growth rate that occurs when pigs are removed from pens during marketing is due to increasing space allowance by pig removal or gate adjustment during the finishing period.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The research barn was an environmentally controlled solid sided building with completely slatted flooring and deep pits for manure storage. Pens were 2.43×3.05 m, equipped with adjustable gates to allow different space allowances per pig and contained a 2-hole 71×25 cm (length \times width) single sided stainless steel dry self-feeder (Farmweld, Teutopolis, IL) and a cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN). All diets were manufactured at the Kansas State University O.H. Kruse Feed Mill, Manhattan, KS.

Live Animal Management

A total of 256 pigs (PIC 327 \times 1050; Hendersonville, TN; initially 55.9 ± 0.43 kg) were used in a 71-d growth study. Pens of pigs were blocked by BW and allotted to 1 of 4 space allowance treatments, initially with 8 pigs per pen (4 barrows and 4 gilts) and 8 pens per treatment. Treatments included pens with 0.91 m^2 per pig or 0.63 m^2 per pig for the entire study. Two additional treatments initially provided 0.63 m^2 per pig, but either a gate was adjusted on d 28, 45, and 62 providing 0.72 , 0.81 , and 0.91 m^2 respectively, or the heaviest pig in the pen was removed on d 28 and 45 providing 0.72 and 0.84 m^2 , respectively (Table 1). The space adjustments and pig removals were made to keep the pigs above their predicted minimum space requirement [$(\text{m}^2) = 0.0336 \times \text{BW (kg)}^{0.67}$], where 0.0336 is the k value. If a pig died or was removed from a pen during the experiment, pen size was adjusted to maintain the correct space allowance per pig. Pigs were fed a common corn-soybean-meal-based diet offered in 3 phases (Table 2). Diets were formulated to meet or exceed the pigs' nutrient requirement estimates (NRC, 2012) and the 3 phases were fed from approximately 56 to 83, 83 to 98, and 98 to 124 kg BW (Table 2). Pens of pigs and feeders were weighed on d 0, 14, 28, 45, 62, and 71 to calculate ADG, ADFI, and G:F.

Statistical Analysis

Data were analyzed as a randomized block design with space allowance treatment as a fixed effect and block as a random effect using the MIXED procedure of SAS (SAS Institute,

Inc., Cary, NC), and pen served as the experimental unit. Treatment means were separated using the DIFFS option from the LSMEANS statement of SAS. Statistical significance was determined at $P < 0.05$ and P -values falling within $P > 0.05$ and $P < 0.10$ were considered marginally significant.

RESULTS

Growth Performance

From d 0 to 14 (56 to 69 kg), there was no effect of stocking density observed for ADG, ADFI, and G:F (Table 3) as anticipated. However, from d 14 to 28 (69 to 83 kg), pigs provided 0.91 m² had increased ADFI ($P = 0.041$) and ADG ($P = 0.002$) compared with those allowed 0.63 m², which resulted in improved G:F ($P = 0.021$). These observations suggest space restriction started to influence growth rate between 69 to 83 kg BW. Based on a k value of 0.0336, no differences in pig performance were expected before a BW of approximately 80 kg.

On d 28, floor space was increased to 0.72 m² per pig by either adjusting the gate or removing the heaviest pig which kept those pigs in the increased space allowance treatments above the critical k value coefficient (0.0336). From d 28 to 45 (83 to 98 kg), pigs provided 0.63 m² or increased space allowance by removal of the heaviest pig, had decreased ($P = 0.025$) ADFI compared to pigs provided 0.91 m² with pigs from pens where the gate was adjusted intermediate. There was no effect on ADG, but pigs provided 0.63 m² had numerically lower ADG compared with those provided 0.91 m².

On d 45, floor space was increased by adjusting the gate or removing the heaviest pig to 0.81 m² or 0.84 m² per pig, respectively. This adjustment kept those pigs in the increased space allowance treatments above the critical k value coefficient (0.0336). From d 45 to 62 (98 to 116 kg), ADFI was decreased ($P = 0.001$) for pigs provided 0.63 m² compared to all other treatments. During this period, increasing space allowance by either adjusting the gate or removing the heaviest pig resulted in performance like pigs allowed 0.91 m².

On d 62 (116 kg), because the critical k value was reached sooner for pigs in the gate adjustment treatment than for the pig removal treatment (based on the actual m²), gates were adjusted to reach the desired k value; however, a pig was not removed from the pig removal treatment.

From d 62 to 71 (116 to 124 kg), pigs provided 0.91 m² were heavier ($P = 0.001$) than those provided 0.61 m² or that had the heaviest pig removed with the gate adjustment treatment

intermediate. Average daily gain decreased ($P = 0.008$) when pigs were allowed 0.63 m^2 compared to all other treatments, which is likely due to the decreased ($P = 0.001$) ADFI as G:F was not affected.

For the overall study, (d 0 to 71; 66 to 124 kg), pigs provided 0.91 m^2 had increased ($P = 0.001$) ADG compared with those allowed 0.63 m^2 with pigs from pens provided increased space intermediate. Pigs provided 0.91 m^2 had increased ($P = 0.001$) ADFI compared with pigs allowed 0.63 m^2 and those where a pig was removed; however, pigs from pens where the gate was adjusted were intermediate.

Discussion

In this study, pigs were stocked to keep space allowance from being-growth limiting (0.91 m^2 per pig), or to be growth limiting (0.63 m^2 per pig) throughout the entire study. Two additional treatments were initially non-growth limiting ($0.63 \text{ m}^2/\text{pig}$) on d 0, but as the pigs grew, either the gate was adjusted or the heaviest pig was removed to keep the remaining pigs in the pen above the predicted space requirement which theoretically should have not limited growth. The space allowances were predicted using the equation developed by Gonyou et al. (2006) [$\text{m}^2 = 0.0336 \times \text{BW (kg)}^{0.67}$].

Gonyou et al. (2006) proposed the floor space prediction equation [$\text{m}^2 = 0.0336 \times \text{BW (kg)}^{0.67}$] and suggested a predicted optimal threshold for which growth should not be constrained until the k value [$k = \text{m}^2/\text{BW(kg)}^{0.67}$] drops below the critical k coefficient ($k = 0.0336$). In their study, Gonyou et al. (2006) reported that ADFI was decreased when pigs were stocked below a critical k value of 0.0336, which is also supported by the study herein. More recently, two studies (Flohr et al., 2016; Thomas et al., 2015) have applied these equations in both research and commercial environments and found reductions in performance due to inadequate space allowance at lighter body weights than previously predicted (Gonyou et al., 2006). These results were confirmed in the present study.

Over the last two decades, several studies have observed an increase in growth rate following the removal of heavyweight pig(s) from a group (Woodworth et al., 2000; DeDecker et al., 2005; Jacela et al., 2009). These authors reported that removal of heavy weight pigs resulted in the remaining pigs having increased ADG compared to those from intact pens where pigs were not removed (Woodworth et al., 2000; DeDecker et al., 2005; Jacela et al., 2009). Similar results were found in our study where removing a pig from the pen increased growth rate of pigs

compared to pigs stocked at 0.63 m². Interestingly, in our study, it appears the remaining pigs in pens that had the heaviest pig(s) removed over time did not maintain similar performance to those stocked at 0.91 m². Our results also indicate that the pigs remaining in pens that had the heaviest pigs removed over time had similar ADG and ADFI compared to those from intact pens where space was increased by adjusting the gating. Thus, the increased growth rate of remaining pigs after the heaviest pigs are marketed appears to be due to increased space allowance rather than any potential in social hierarchy.

Recently, Flohr et al. (2016) evaluated the effects of initial stocking density and marketing removal strategies on the growth of pigs remaining in the pen until market. One of the objectives in the study by Flohr et al. (2016) was to determine if pigs managed to be kept above the critical k coefficient perform like those that are unrestricted throughout finishing. During the first growth period of their study, pigs provided 0.91 m² (unrestricted) had greater ADG and ADFI than those provided 0.65 m², regardless of removal strategy with G:F unchanged. Based on the predicted reduction in ADG by Gonyou et al. (2006), Flohr et al (2016) should have observed a 1.4% reduction in ADG; however, their observed reduction in growth was 3.4%. This suggests the predicted ADG outcome was underestimated by Gonyou et al. (2006). In our study, the reduction in ADG for the period of growth where performance was not expected to be impacted was like what Flohr et al. (2016) had observed in their study, but to a greater magnitude with as high as a 5.0% reduction in ADG for pigs stocked at 0.61 m² throughout the study. Thomas et al. (2015) evaluated the effects of floor space allowance on finishing pigs in a study where they controlled feeder space by adjusting gates and reported similar findings. Based on the present data, as well as studies by Thomas et al. (2015) and Flohr et al. (2016), it appears growth restriction can occur prior to when the equations from Gonyou et al. (2006) predict.

In conclusion, pigs provided 0.91 m² grew faster and consumed more feed than pigs provided 0.63 m². It also appeared either removing the heaviest pig(s) or adjusting the gating as pigs reached the critical k value affected pig performance similarly. We speculate that along with pig performance, pen social dynamics of the remaining pigs could have been affected by removing the heaviest pigs; however, our study indicates the performance benefit from removing the heaviest pig(s) from the pen is primarily from the increased space allowance alone. As pigs grew to the minimum predicted space requirement and were subsequently provided more space, performance was not like unrestricted pigs. Increasing the space allowance by removing pig(s) or

gate adjustment increased ADG compared to pigs provided 0.63 m² for the entire experiment; however, neither increased space allowance treatment allowed pigs to maintain ADG like space-unrestricted pigs provided 0.91 m² throughout the study. This indicates the industry accepted minimum space prediction equation [(m²) = 0.0336 × BW (kg)^{0.67}] may not fully explain impacts on pig performance across multiple body weight ranges.

Literature Cited

- DeDecker, J. M., M. Ellis, B. F. Wolter, B. P. Corrigan, S. E. Curtis, E. N. Parr, and D. M. Webel. 2005. Effects of proportion of pigs removed from a group and subsequent floor space on growth performance of finishing pigs. *J. Anim. Sci.* 83:449–454. doi:10.2527/2005.832449x
- Flohr, J.R., M. D. Tokach, J. M. DeRouchey, J.C. Woodworth, R. D. Goodband, and S.S. Dritz. 2016. Evaluating the removal of pigs from a group and subsequent floor space allowance on the growth performance of heavy-weight finishing pigs. *J. Anim. Sci.* 94:4388-4400. doi:10.2527/jas2016-0407
- Gonyou, H. W., M. C. Brumm, E. Bush, J. Deen, S. A. Edwards, R. Fangman, J. J. McGlone, M. Meunier-Salaun, R. B. Morrison, H. Spolder, P. L. Sundberg, and A. K. Johnson. 2006. Application of broken-line analysis to assess floor space requirements of nursery and grower-finisher pigs expressed on an allometric basis. *J. Anim. Sci.* 84:229–235. doi:10.2527/2006.841229x
- Jacela, J. Y., S. S. Dritz, M. D. Tokach, J. M. DeRouchey, R. D Goodband, and J. L. Nelssen. 2009. Economic impact of removing pigs before marketing on the remaining pig's growth performance. *Kansas Swine Ind. Day Rep. Prog. No. 1020*. Kansas State University Agricultural Experiment Station, Manhattan, KS. p. 262–269.
- NRC. 2012. *Nutrient requirements of swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC.
- Thomas, L. L., R. D. Goodband, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, and S. S. Dritz. 2015. The effects of increasing stocking density on finishing pig growth performance and carcass characteristics. *Kans. Agric. Exp. Stn. Res. Rep.* 1(7):37.
- Woodworth, J. C., S. S. Dritz, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2000. Examination of the interactive effects of stocking density and marketing strategies in a commercial production environment. *J. Anim. Sci.* 78(Suppl. 2):56. (Abstr.)

Table 4-1 Space allowance and *k*-value through the experiment¹

Item	0.91 m ²	0.63 m ²	Gate adjustment ²	Pig removal ³
d 0				
<i>k</i> -value ⁴	0.0614	0.0425	0.0425	0.0425
m ² per pig	0.91	0.63	0.63	0.63
d 28				
<i>k</i> -value				
Before adj.	0.0471	0.0326	0.0326	0.0326
After adj.	---	---	0.0373	0.0373
m ² per pig	0.91	0.63	0.72	0.72
d 45				
<i>k</i> -value				
Before adj.	0.0420	0.0291	0.0333	0.0333
After adj.	---	---	0.0374	0.0388
m ² per pig	0.91	0.63	0.81	0.84
d 62				
<i>k</i> -value				
Before adj.	0.0377	0.0261	0.0335	0.0348
After adj.	---	---	0.0377	0.0348
m ² per pig	0.91	0.63	0.91	0.84
d 71				
<i>k</i> -value	0.0360	0.0249	0.0360	0.0332
m ² per pig	0.91	0.63	0.91	0.84

¹A total of 256 pigs (PIC 327 × 1050; Hendersonville, TN; initially 55.9±0.43 kg) were used in a 71-d growth trial. Average BW's on d 0, 28, 45, 62 and 71 were 55.9, 82.9, 98.4, 115.9, and 124.1 kg, respectively.

²Increased space by gate adjustment

³Increased space by pig removal

⁴*k*-value [(m²)=k×BW (kg)^{0.67}] calculated before and after a pig was removed or gates were adjusted.

Table 4-2 Diet composition (as-fed basis)

Item	Phase ¹		
	1	2	3
Ingredient, %			
Corn	71.48	78.42	82.85
Soybean meal (47.7% CP)	25.71	19.20	14.93
Monocalcium P (21% P)	0.55	0.33	0.30
Limestone	1.13	1.10	1.08
Salt	0.35	0.35	0.35
L-Lys HCl	0.31	0.25	0.22
DL-Met	0.06	0.02	---
L-Thr	0.09	0.05	0.05
Trace mineral premix ²	0.15	0.13	0.10
Vitamin premix ³	0.15	0.13	0.10
Phytase ⁴	0.02	0.02	0.02
Total	100	100	100
Calculated analysis			
Standardized ileal digestible (SID) AA, %			
Lys	1.05	0.85	0.72
Ile:Lys	62	64	66
Met:Lys	30	29	30
Met & Cys:Lys	55	56	59
Thr:Lys	61	61	64
Trp:Lys	18.0	18.0	18.0
Val:Lys	69	73	76
Total Lys, %	1.18	0.96	0.82
NE, kcal/kg	2,462	2,507	2,534
SID Lys:NE, g/Mcal	4.26	3.39	2.84
CP, %	18.5	15.9	14.2
Ca, %	0.62	0.55	0.52
P, %	0.49	0.41	0.39
Available P, %	0.29	0.23	0.22
Chemical Analysis ⁵ , %			
DM	88.32	87.25	87.41
CP	18.5	15.4	14.8

¹Diets were fed in meal form from d 0 to 71 of the experiment. Phase 1, 2 and 3 were fed from approximately 56 to 83, 83 to 98 and 98 to 124 kg, respectively.

²Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

³Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menidione.

⁴HiPhos (DSM Inc, Parsippany, NJ) provided phytase units 3,174,624 (FTU)/kg of product and released 0.10% P available P.

⁵ Six samples of each diet were collected, blended and subsampled, and analyzed (Ward Laboratories, Inc. Kearney, NE). Values are represented on an as-fed basis.

Table 4-3 Effects of increasing space allowance by removing a pig or gate adjustment on finishing pig growth performance

Item	0.91 m ²	0.63 m ²	Gate adjustment ³	Pig removal ⁴	SEM	<i>P</i> <
d 0 to 14						
d 0 BW, kg	55.9	56.0	55.9	55.6	0.15	0.361
ADG, kg	0.94	0.94	0.96	0.96	0.015	0.495
ADFI, kg	2.19	2.15	2.19	2.19	0.044	0.894
G:F	0.429	0.439	0.440	0.442	0.008	0.657
d 14 to 28						
d 14 BW, kg	69.1	69.2	69.4	69.1	0.26	0.835
ADG, kg	1.05 ^a	0.94 ^b	0.95 ^b	0.98 ^b	0.020	0.002
ADFI, kg	2.59 ^a	2.41 ^b	2.50 ^{ab}	2.54 ^a	0.041	0.041
G:F	0.407 ^a	0.388 ^b	0.379 ^b	0.386 ^b	0.0067	0.021
d 28 to 45						
d 28 BW, kg	84.0 ^x	82.3 ^y	82.6 ^y	82.8 ^y	0.47	0.081
ADG, kg	0.98	0.88	0.92	0.93	0.028	0.143
ADFI, kg	2.87 ^a	2.69 ^b	2.79 ^{ab}	2.68 ^b	0.046	0.025
G:F	0.339	0.327	0.330	0.349	0.0086	0.266
d 45 to 62						
d 45 BW, kg	100.6 ^a	97.3 ^b	98.2 ^b	97.4 ^b	0.49	0.001
ADG, kg	1.06	1.01	1.08	1.05	0.022	0.260
ADFI, kg	3.20 ^a	2.90 ^b	3.16 ^a	3.12 ^a	0.046	0.001
G:F	0.331	0.350	0.341	0.337	0.0066	0.259
d 62 to 71						
d 62 BW, kg	118.6 ^a	114.6 ^c	116.5 ^b	114.0 ^c	0.63	0.001
ADG, kg	0.97 ^a	0.80 ^b	0.93 ^a	0.94 ^a	0.035	0.008
ADFI, kg	2.92 ^a	2.67 ^b	2.98 ^a	2.93 ^a	0.046	0.001
G:F	0.331	0.298	0.314	0.320	0.0113	0.233
d 0 to 71						
d 71 BW, kg	127.3 ^a	121.7 ^c	124.9 ^b	122.5 ^c	0.73	0.001
ADG, kg	1.00 ^a	0.93 ^c	0.97 ^b	0.98 ^b	0.009	0.001
ADFI, kg	2.76 ^a	2.58 ^c	2.73 ^{ab}	2.66 ^b	0.029	0.001
G:F	0.363	0.356	0.356	0.361	0.0038	0.476

¹A total of 256 pigs (PIC 327 × 1050; Hendersonville, TN; initially 55.9±0.43 kg BW) were used in a 71-d growth study with 4 barrows and 4 gilts per pen and 8 pens per treatment.

²Means within a row with different superscripts differ: ^{abc} *P* < 0.05 ^{xyz} *P* < 0.10.

³Increased space = increased gate adjustment; initially 0.63 m²/pig with gates adjusted as pigs reached the *k* value to be non-limiting (0.72 m² at 82.9 kg (d 28), 0.81 m² at 98.4 kg (d 45), and 0.91 m² at 115.9 kg (d 62).

⁴Increased space = removal of heaviest pig; initially 0.63 m²/pig with a pig removed as the *k*-value is reached to be non-limiting: 1 pig at 82.9 kg (d 28) and 98.4 kg (d 45).