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Nutritional Interventions with Zinc Source and Copper Level in Low Acid-Binding Capacity-4 Diets for Nursery Pigs as Alternatives to Pharmacological Levels of Zinc Oxide

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Summary

Pharmacological levels of zinc (Zn) prevent diarrhea and improve the growth performance of nursery pigs, but pose environmental challenges. A total of 360 pigs (241 × 600 DNA; initially 12.5 ± 0.04 lb) were used to investigate effects of Zn source and Cu level in low acid-binding capacity (ABC)-4 diets for nursery pigs as an alternative to pharmacological levels of zinc oxide (ZnO) on growth performance, fecal dry matter (DM), plasma mineral concentrations, apparent total tract digestibility (ATTD) of nitrogen (N) and minerals, and N and minerals balance. At weaning, pigs were randomly assigned within three BW blocks to one of six dietary treatments in a generalized randomized block design. There were five pigs per pen and 12 pens per treatment. Experimental diets were fed in three periods: phase 1 (d 0 to 10), phase 2 (d 10 to 24), and phase 3 (d 24 to 46). Diets were arranged in a 3 × 2 factorial consisting of three Zn treatments and two Cu levels. Zinc treatments involved low (150 mg/kg) or high (800 mg/kg) levels of Zn from potentiated ZnO (pZnO, HiZox, Animine Prevision Minerals, Annecy, France) in both phases 1 and 2, or pharmacological levels of Zn from standard ZnO (Maximo720, Zinc Nacional, Monterrey, Mexico) at 3,000 mg/kg in phase 1 and 2,000 mg/kg in phase 2. Copper was provided as monovalent copper oxide (Cu2O; CoRouge, Animine) at low (18 mg/kg) or high (150 mg/kg) levels. In phase 3, diets were formulated with either low or high levels of Cu2O, each containing 150 mg/kg of Zn from pZnO. Basal diets for phases 1 and 2 were low ABC-4 diets with crystalline lactose, fumaric and formic acids, and their ABC-4 levels were 199 and 248 meq/kg, respectively. In phase 3, a conventional diet (437 meq/kg) was used without consideration of ABC-4 levels. In all periods, there were no significant Zn × Cu interactions or Zn effect on growth performance criteria. In the overall period (d 0 to 46),

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pigs fed high levels of Cu2O had increased ADG compared with low levels of Cu2O (P = 0.049). There was a tendency for a Zn effect on fecal DM on d 10 (P = 0.059) with pigs fed low levels of pZnO having higher fecal DM than pigs fed pharmacological levels of ZnO. The d 24 ATTD of Cu was affected by Zn (P < 0.001), with pigs fed pharmacological levels of ZnO showing the lowest ATTD of Cu. In addition, pigs fed high levels of Cu2O tended to have reduced ATTD of Cu on d 24 (P = 0.067) compared with pigs fed low levels of Cu2O. In conclusion, in low ABC-4 diets, high levels of Zn, regardless of source, did not benefit growth performance, whereas the high levels of Cu_2O improved growth performance. Also, pharmacological levels of Zn from ZnO decreased the ATTD of Cu in pigs fed low ABC-4 diets.

Introduction

Pharmacological levels of zinc oxide (ZnO) in nursery pig diets have been commonly used to reduce the incidence of diarrhea and improve growth performance through beneficial effects on gut health, immune function, and antioxidant capacity[4]. However, its use leads to the accumulation of zinc (Zn) in the environment through fecal excretion. For this reason, the use of pharmacological levels of ZnO in pig diets has been restricted in several countries. The regulations have encouraged the development of alternatives to pharmacological levels of ZnO. Our companion study found that low levels of Zn from potentiated ZnO (pZnO) in low acid-binding capacity (ABC)-4 diets show similar growth performance to pharmacological levels of ZnO in nursery pigs[5]. Nevertheless, further reduction in Zn inclusion is necessary to ensure more sustainable pig production. Considering a study by De Mille et al.[6] reporting that pigs fed diets supplemented with pharmacological levels of both ZnO and copper sulfate (CuSO4) show better growth performance than those fed diets containing pharmacological levels of ZnO alone, the use of pZnO in combination with copper (Cu) in low ABC-4 diets may allow a further reduction in Zn usage. Copper has antimicrobial and antioxidant effects similar to those of Zn, and it also plays a direct role in energy metabolism. Pigs fed Cu from monovalent copper oxide (Cu2O) showed a tendency for increased BW and ADG compared with pigs fed Cu from CuSO4. There is no available research testing combinations of Zn source and level in diets with different Cu2O levels formulated with a low ABC-4 strategy. Therefore, the objective of this study was to evaluate the effects of Zn source and Cu2O level in low ABC-4 diets as an alternative to pharmacological levels of ZnO on growth performance, fecal dry matter (DM), plasma mineral concentrations, apparent total tract digestibility (ATTD) of N and minerals, and Zn and Cu excretion. We hypothesized that low ABC-4 diets with high levels of pZnO and Cu2O would replace pharmacological levels of ZnO, while pZnO without high levels of Cu2O would not have comparable effects.

[4] Bonetti, A., B. Tugnoli, A. Piva, and E. Grilli. 2021. Towards zero zinc oxide: Feeding strategies to manage post weaning diarrhea in piglets. Animals 11:642. doi:10.3390/ani11030642.

[5] Riedmüller, J., J. E. Faccin, A. R. Monteiro, J. Zentek, J. M. DeRouchey, J. T. Gebhardt, R. D. Goodband, J. C. Woodworth, and M. D. Tokach. 2023. Effects of zinc source and level in low ABC-4 diets on nursery pig growth performance and fecal characteristics. Kansas Agricultural Experiment Station Research Reports, 9(7):7. doi:10.4148/2378-5977.8508.

[6] De Mille, C. M., E. R. Burrough, B. J. Kerr, W. P. Schweer and N. K. Gabler., 2022. Dietary pharmacological zinc and copper enhances voluntary feed intake of nursery pigs. Front. Anim. Sci. 3:874284. doi:10.3389/fanim.2022.874284.

Procedures

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was performed at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Each pen (5 × 5 ft) was equipped with a 4-hole, dry self-feeder and nipple waterer to provide ad libitum access to feed and water.

Animals and diets

A total of 360 pigs (241 × 600 DNA; initially 12.5 ± 0.04 lb) were used in a 46-d nursery trial. The experiment was divided into three feeding phases: phase 1 (d 0 to 10), phase 2 (d 10 to 24), and phase 3 (d 24 to 46). The pigs were weaned at 18 ± 1 d old into pens of five pigs each based on initial weight (light, medium, or heavy) and sex. The pens were randomly assigned to one of six dietary treatments in a design consisting of three Zn treatments combined with two Cu levels. The first factor, Zn, included low (150 mg/kg) or high (800 mg/kg) levels of Zn from pZnO for both phase 1 and 2, or pharmacological levels of Zn from standard ZnO (Maximo720, Zinc Nacional, Monterrey, Mexico) at 3,000 and 2,000 mg/kg for phases 1 and 2, respectively. The second factor, Cu, consisted of low (18 mg/kg) or high (150 mg/kg) levels of monovalent copper oxide (Cu2O, CoRouge, Animine). In phase 3, dietary Cu2O concentrations were maintained at the same levels as in phases 1 and 2, and Zn supplementation was standardized to 150 mg/kg of pZnO. Basal diets for phases 1 and 2 were low ABC-4 diets with crystalline lactose, fumaric and formic acids and were formulated to 199 and 248 meq/kg, respectively. For phase 3, the basal diet was a conventional formulation in which the ABC-4 level was not considered (437 meq/kg). The ABC-4 level of each dietary treatment varied with the inclusion of Zn and Cu. All dietary treatments were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center in Manhattan, KS. The phase 1 diets were in pelleted form, and the phase 2 and 3 diets were in meal form.

Pig weights and feed disappearance were measured on d 0, 10, 24, and 46 to calculate ADG, ADFI, and F/G. Fecal samples were collected via rectal palpation from four pigs per pen, excluding the lightest pig, on d 10, 17, 24, and 46 to determine fecal DM percentage. The fecal samples were dried in a forced-air oven for 48 h at 131°F (55°C).

Plasma and fecal Zn, Cu, P, Ca, and Fe concentrations and fecal excretions

Blood samples were taken from 10% of the pigs at placement, and from pigs with a middle BW at placement on d 24 and 46. The blood samples were centrifuged for 30 min at 1,800 RPM and plasma samples were obtained and stored at −112°F (−80°C) until mineral analysis.

Phase 1 and 2 diets included an indigestible marker, 0.5% titanium dioxide (TiO2). After fecal DM analysis, dried fecal samples were ground and pooled (equal proportion from each pig) on a pen basis.

The mineral concentrations in plasma and dried fecal samples were analyzed through an atomic absorption spectrometer. For the analysis, dried fecal samples were digested in 4 M nitric acid at 90°C for 4 h. Plasma samples were diluted in 0.4 M nitric acid at a 1:5 ratio.

The following equation was used to calculate the total feces production:

The daily excretions of minerals were calculated by multiplying the daily feces production by the fecal mineral concentrations. Mineral retentions were calculated as intake minus excretion.

Apparent total tract digestibility of Zn, Cu, P, Ca, Fe, and N calculations

For N analysis, both feed and fecal samples were analyzed in duplicate (University of Missouri Agricultural Experiment Station Laboratory). The ATTD of N was determined using the index marker method.

Apparent total tract digestibility of minerals was calculated with the following equation:100

Statistical analysis

Data were analyzed as a generalized randomized block design using the RStudio environment (Version 1.3.1093; RStudio, Inc., Boston, MA) with R programming language (Version 4.5.2, R Core Team, Vienna, Austria] with pen as the experimental unit. The effects of Zn source and Cu level and their interaction were analyzed. For data on growth performance, ATTD and balance of minerals and N, the model used treatment and BW block as fixed effects. Fecal DM data were analyzed using a repeated-measures model with the fixed effects of day, treatment, and their interactions. For fecal DM data analysis, pen was used as a random effect because fecal samples were collected from four pigs per pen. Plasma mineral concentrations were analyzed using a repeated-measures model including the fixed effects of day, treatment, and their interaction, without incorporating any random effects since plasma samples were collected from one pig per pen. For the repeated-measures model, a compound symmetry covariance matrix was applied to fecal DM and plasma Fe data, whereas an unstructured covariance matrix was used for plasma Zn, Cu, and P. A covariance matrix of autoregressive order 1 was used for plasma Ca data. The lmer function from the lme4 package was used to analyze fecal DM data, and the lm function was used to analyze the rest of the data. Results were considered significant at P 0.05 and were considered marginally significant at 0.05 P 0.10.

Results and Discussion

Growth performance

In all periods, no significant Zn × Cu interaction or Zn effect was observed (Table 3).

In phases 1 (d 0 to 10) and 2 (d 10 to 24), no main effects of Cu were observed in any performance variables. In phase 3 (d 24 to 46), pigs fed diets with a high level of Cu2O had increased ADG compared with pigs fed diets with a low level of Cu2O (P = 0.021; Table 3), while no response to Cu2O level was observed for ADFI and F/G. For the overall period (d 0 to 46), pigs fed diets with a high level of Cu2O had increased ADG and final BW (P ≤ 0.049); however, ADFI and F/G were not influenced by Cu2O level.

Fecal dry matter

A tendency for a Zn × Cu × day interaction (P = 0.093; Table 3) was observed. On d 10, there was a tendency for Zn effects (P = 0.059) where pigs fed diets with low levels of pZnO had the highest fecal DM. No treatment effects were observed for fecal DM on d 17 or 46, but on d 24, there was a tendency for a Zn × Cu interaction (P = 0.068) with the numerically highest fecal DM of pigs fed a low level of pZnO and a high level of Cu2O.

Plasma mineral concentrations

For plasma Zn concentrations, there was a tendency for Zn × Cu × day interaction ($P = 0.092$; Table 4) and a significant Zn × day interaction ($P < 0.001$). Plasma Zn concentrations increased with higher dietary Zn levels on d 10 ($P < 0.001$). On d 24, there was also a Zn × Cu interaction ($P = 0.027$) with plasma Zn increasing to a greater extent for pigs fed pharmacological levels of Zn when Cu was also included at pharmacological levels. Plasma Zn was similar between all treatments on d 46. For plasma Cu concentrations, there were tendencies for Zn × Cu × day and Zn × day interactions ($P \leq 0.086$). On d 24, pigs fed the high Cu2O diet exhibited higher plasma Cu concentrations than those fed the low Cu diet ($P = 0.002$), with no differences on d 10 or 46. Plasma Ca concentrations were higher on d 10 in pigs fed pharmacological levels of ZnO than in those fed a low level of pZnO ($P = 0.025$); however, there were no differences on d 24 or 46. No treatment differences were observed in plasma P and Fe concentrations.

Zn, Cu, Ca, P, and N balance and ATTD

On d 10, Zn × Cu interactions ($P \leq 0.032$; Table 5) were observed for Zn intake and absorption, where intake and absorption increased as Zn levels increased in the diet with a greater increase across Zn levels when diets contained low levels of Cu2O. There were Zn effects ($P \leq 0.03$) in fecal Zn excretion and ATTD of Zn where pigs fed pharmacological levels of Zn had the highest fecal Zn excretion. Conversely, ATTD of Zn was greater in pigs fed low levels of pZnO than in pigs fed pharmacological levels of Zn. On d 24, there were tendencies for Zn × Cu interactions in Zn intake and fecal excretion ($P \leq 0.072$). Within the low pZnO treatments, pigs fed a high Cu2O level showed numerically greater Zn intake, which was accompanied by higher fecal Zn excretion, compared with pigs fed a low Cu2O level. For d 24 Zn absorption, pigs fed pharmacological levels of Zn had the greatest ($P < 0.001$) Zn absorption. There was a tendency for d 24 ATTD of Zn ($P = 0.10$), where pigs fed low levels of pZnO had the greatest ATTD of Zn.

In Cu balance values, no Zn × Cu interactions were observed on d 10. Day 10 Cu intake, fecal excretion, and absorption, were greater ($P \leq 0.001$; Table 5) in pigs fed high levels of Cu2O than in pigs fed low levels of Cu2O, but d 10 ATTD of Cu was lower ($P = 0.002$) when high Cu2O was fed. There were Zn × Cu interactions ($P \leq 0.003$) in d 24 Cu fecal excretion and absorption. Pigs fed pharmacological levels of ZnO with high levels of Cu2O had the greatest Cu fecal excretion, and pigs fed low or high levels of pZnO with high levels of Cu2O showed the greatest Cu absorption. There was a tendency for a Zn × Cu interaction ($P = 0.075$) in d 24 Cu intake. Day 24 Cu intake was highest when pigs were fed either a high level of pZnO or a pharmacological level of ZnO, with a high level of Cu2O. Zinc effects ($P < 0.001$) in d 24 ATTD of Cu were further found, in which pigs fed pharmacological levels of ZnO showed lower ATTD of Cu than other treatments. Pigs fed high levels of Cu2O also tended to have reduced d 24 ATTD of Cu ($P = 0.067$; Table 5), compared with pigs fed low levels of Cu2O.

For d 10 Ca balance, there were Cu effects ($P \leq 0.036$; Table 6) resulting in lower Ca intake and absorption in pigs fed high levels of Cu2O. There were also Zn × Cu interactions ($P \leq 0.003$; Table 6) for d 10 fecal Ca excretion and ATTD of Ca, in which when pigs were fed a low level of pZnO, a high level of Cu2O increased Ca excretion and decreased ATTD of Ca. On d 24, Zn effects were observed ($P = 0.036$; Table 6)

presenting the lowest Ca intake in pigs fed pharmacological levels of ZnO. There were Zn × Cu interactions (P ≤ 0.003; Table 6) in d 24 Ca fecal excretion and absorption, and ATTD of Ca. In contrast to low Cu2O treatments, pigs fed a low level of pZnO with high levels of Cu2O showed increased Ca fecal excretion and both reduced Ca absorption and ATTD of Ca.

There were Zn × Cu interactions in d 10 P fecal excretion and ATTD of P (P < 0.001; Table 6), showing that high levels of Cu2O increased P fecal excretion and decreased ATTD of P in pigs fed low levels of pZnO. In addition, d 10 P absorption tended to be lower (P = 0.059; Table 6) in pigs fed high Cu2O. For d 24 P balance, there were Zn effects (P = 0.007; Table 6) on P intake, with pigs fed low levels of pZnO showing the greatest P intake. High levels of Cu2O also tended to increase P intake (P = 0.067; Table 6). There were Zn × Cu interactions (P ≤ 0.001; Table 6) wherein high levels of Cu2O increased P fecal excretion, and reduced P absorption and ATTD of P in pigs fed a low level of pZnO, compared with pigs fed a low level of Cu2O. Moreover, in low Cu2O treatments, pigs fed a low level of pZnO had the greatest ATTD of P, whereas in the high Cu2O treatments, pigs fed a low level of pZnO showed the lowest ATTD of P.

For d 10 N balance, Zn × Cu interactions (P ≤ 0.001; Table 6) in fecal N excretion and ATTD of N were observed. In high Cu2O treatments, fecal N excretion numerically decreased with increasing dietary Zn levels, whereas in low Cu2O treatments, pigs fed a low level of pZnO showed the lowest fecal N excretion. The ATTD of N decreased as dietary Zn levels increased in low Cu2O treatments; however, in high Cu2O treatments, pigs fed low levels of pZnO showed the lowest ATTD of N. Nitrogen absorption tended to be higher (P = 0.057; Table 6) in pigs fed low levels of Cu2O, compared with pigs fed high levels of Cu2O. On d 24, there were Zn × Cu interactions (P ≤ 0.002; Table 6) in fecal N excretion, N absorption, and ATTD of N. In contrast to low Cu2O treatments, pigs fed low levels of pZnO had the highest fecal N excretion in high Cu2O treatments. In low Cu2O treatments, N absorption in pigs fed low levels of pZnO was comparable to that of pigs fed high levels of pZnO. However, in high Cu2O treatments, N absorption in pigs fed low levels of pZnO was lower than in pigs fed high levels of pZnO. The ATTD of N was greatest in pigs fed a low level of pZnO in low Cu2O treatments, whereas in high Cu2O treatments, pigs fed low levels of pZnO showed the lowest ATTD of N.

In conclusion, in the low ABC-4 diets, high levels of dietary Zn sources did not improve growth performance, and pharmacological levels of ZnO tended to reduce fecal dry matter on d 10. In contrast, inclusion of high levels of Cu2O showed positive effects on overall growth performance. On d 24, low ABC-4 diets with high levels of Cu2O increased plasma Cu concentrations in pigs. Pharmacological levels of ZnO decreased d 24 ATTD of Cu in pigs fed low ABC-4 diets. It also reduced d 24 ATTD of P in pigs fed low ABC-4 diets with a low level of Cu2O. However, when pigs were fed low ABC-4 diets with high levels of Cu, a low level of pZnO reduced d 24 ATTD of P and N.

Table 1. Basal diet composition for phase 1, 2, and 3[1]

Item	Phase 1	Phase 2	Phase 3
Ingredients, %			
Corn	49.71	57.30	64.74
Soybean meal, 47.7% CP	15.43	21.73	31.30
Specialty soy product[2]	10.00	7.50	-
Spray-dried bovine plasma	2.50	-	-
Crystalline lactose	15.00	7.50	-
Soybean oil	2.00	1.00	-
Calcium carbonate	0.50	0.50	0.90
Monocalcium P, 21% P	1.25	1.00	0.90
Salt	0.80	0.80	0.60
L-Lys-HCl	0.45	0.52	0.52
DL-Met	0.21	0.23	0.22
L-Thr	0.21	0.24	0.25
L-Trp	0.04	0.06	0.06
L-Val	0.08	0.12	0.14
Vitamin premix	0.25	0.25	0.25
Trace mineral premix[3]	0.06	0.06	0.06
Phytase[4]	0.06	0.06	0.06
Titanium dioxide	0.50	0.50	-
Fumaric acid	0.50	0.35	-
Formic acid	0.45	0.30	-
Zinc source[5]	±	±	±
Copper source[6]	±	±	±
Total	100	100	100
Calculated analysis			
SID amino acids, %			
Lys	1.36	1.35	1.35
Ile:Lys	58	58	55
Leu:Lys	115	114	114
Met:Lys	35	37	37
Met & Cys:Lys	58	58	58
Thr:Lys	65	65	65
Trp:Lys	20.6	20.8	20.6
Val:Lys	70	70	70
His:Lys	36	36	36
Total Lys, %	1.52	1.50	1.49
NE, kcal/lb	1,160	1,128	1,100
SID Lys:NE, g/Mcal	5.32	5.44	5.57
CP, %	21.3	21.3	21.2
Ca, %	0.55	0.52	0.67

P, %	0.58	0.55	0.58
STTD P, %	0.52	0.46	0.46
Ca:P	0.94	0.94	1.15

[1] Phases 1, 2, and 3 were fed d 0 to 10, 10 to 24, and 24 to 46, respectively.

[2] HP 300; Hamlet Protein, Findlay, OH

[3] Provided per pound of premix: 243 mg/kg of Fe, 82 mg/kg of Mn, 0.71 mg/kg of I, 0.66 mg/kg of Se.

[4] Ronozyme HiPhos 2700 (DSM-Firmenich; Parsippany, NJ) provided 681 FYT/lb of phytase with assumed release of 0.14% STTD P.

[5] Zinc treatments consisted of 150 mg/kg and 800 mg/kg of Zn from pZnO for both phase 1 and 2, and pharmacological levels of Zn from standard ZnO at 3,000 and 2,000 mg/kg for phases 1 and 2, respectively. For phase3, Zn supplementation was standardized to 150 ppm of pZnO.

[6] For phase 1, 2, and 3, Cu treatments consisted of 18 mg/kg and 150 mg/kg of Cu from Cu2O.

Table 2. Chemical analysis of experimental diets[1]

	Phase 1						Phase 2						Phase 3	
Cu_2O, mg/kg:	18			150			18			150			18	150
Zn source:	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO	pZnO	pZnO
mg/kg:	150	800	3,000	150	800	3,000	150	800	2,000	150	800	2,000	150	150
Zn, mg/kg	172	663	2,323	246	756	2,403	176	795	1,957	191	831	2,077	191	193
Cu, mg/kg	22	24	24	116	150	151	22	28	32	135	183	169	24	175
Calculated ABC-4, meq/kg	204	225	291	207	228	293	253	274	309	256	277	312	442	445
Analyzed ABC-4, meq/kg	176	193	259	188	195	263	220	244	271	220	253	271	406	418

[1] Phases 1, 2, and 3 were fed d 0 to 10, 10 to 24, and 24 to 46, respectively.

Table 3. Effects of zinc source and copper level in low acid-binding capacity-4 diets as an alternative to pharmacological levels of zinc oxide on growth performance and fecal dry matter[1]

Cu_2O, mg/kg:	18			150						
Zinc source:	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO		*P* =		
Phase 1, mg/kg:	150	800	3,000	150	800	3,000				
Phase 2, mg/kg:	150	800	2,000	150	800	2,000				
Phase 3, mg/kg:	150 of pZnO			150 of pZnO			SEM	Zn × Cu	Zn	Cu
BW, lb										
d 0	12.5	12.5	12.5	12.5	12.5	12.5	0.04	0.999	0.999	0.938
d 10	14.1	14.7	14.6	14.7	14.6	14.8	0.22	0.440	0.286	0.184
d 24	26.4	27.2	27.3	27.0	27.3	28.0	0.51	0.822	0.190	0.250
d 46	61.5	61.4	62.6	62.7	64.5	63.4	1.04	0.482	0.623	0.048
Phase 1(d 0 to 10)										
ADG, lb	0.16	0.22	0.21	0.22	0.21	0.23	0.021	0.421	0.276	0.180
ADFI, lb	0.26	0.28	0.28	0.28	0.29	0.29	0.016	0.885	0.499	0.317
F/G	1.74	1.43	0.60	1.36	1.38	1.26	0.324	0.265	0.144	0.774
Phase 2 (d 10 to 24)										
ADG, lb	0.87	0.90	0.90	0.87	0.90	0.94	0.028	0.674	0.214	0.576
ADFI, lb	1.14	1.19	1.19	1.16	1.20	1.23	0.038	0.938	0.289	0.470
F/G	1.32	1.32	1.33	1.34	1.34	1.31	0.024	0.644	0.765	0.724
Phase 3 (d 24 to 46)										
ADG, lb	1.60	1.55	1.59	1.62	1.69	1.61	0.032	0.127	0.779	0.021
ADFI, lb	2.43	2.32	2.40	2.43	2.51	2.38	0.045	0.053	0.681	0.153
F/G	1.53	1.49	1.51	1.50	1.48	1.48	0.020	0.867	0.456	0.121
Overall (d 0 to 46)										
ADG, lb	1.06	1.06	1.07	1.07	1.12	1.11	0.023	0.608	0.493	0.049
ADFI, lb	1.56	1.53	1.55	1.56	1.62	1.58	0.033	0.362	0.855	0.191
F/G	1.48	1.44	1.45	1.45	1.44	1.42	0.015	0.592	0.228	0.113
Fecal dry matter, %[2]										
d 10	27.3	26.0	24.4	26.7	26.3	25.0	0.98	0.823	0.059	0.904
d 17	25.1	23.9	22.8	23.3	22.9	23.2	0.74	0.325	0.263	0.189
d 24	23.8[a]	24.6[a]	25.4[a]	25.8[a]	23.5[a]	23.6[a]	0.90	0.068	0.713	0.678
d 46	22.8	23.3	24.9	23.8	22.0	23.5	0.83	0.263	0.171	0.401

[1] A total of 360 weaned pigs (initially 12.5 ± 0.04 lb) were used in a 46-d nursery trial. A total of six dietary treatments were arranged in a 2×3 factorial design consisting of three zinc treatments (low and high pZnO, and pharmacological levels of ZnO) and low or high levels of Cu2O. There were 5 pigs per pen and 12 replications per treatment.

[2] Zn × Cu × day interaction, P = 0.093; All other interactions (P > 0.10).

Table 4. Effects of zinc source and copper level in low acid-binding capacity-4 diets as alternatives to pharmacological levels of zinc oxide on plasma mineral concentrations[1]

Cu_2O, mg/kg:	18			150						
Zinc source:	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO				
Phase 1, mg/kg:	150	800	3,000	150	800	3,000				
Phase 2, mg/kg:	150	800	2,000	150	800	2,000				
Phase 3, mg/kg:	150 of pZnO			of pZnO			SEM	*P* =		
								Zn × Cu	Zn	Cu
Zn, mg/L[2]										
d 0	0.95 0.12						-	-	-	-
d 10	0.60	0.94	1.10	0.61	0.94	1.28	0.060	0.279	< 0.001	0.224
d 24	0.86^{cd}	1.21^{bc}	1.47^{ab}	0.71^{d}	1.26^{bc}	1.85^{a}	0.098	0.027	< 0.001	0.250
d 46	0.94	0.96	0.94	0.94	1.03	0.90	0.057	0.649	0.360	0.824
Cu, mg/L[3]										
d 0	1.76 0.35						-	-	-	-
d 10	1.78	1.65	1.90	1.80	1.87	1.84	0.098	0.358	0.488	0.465
d 24	1.75	1.71	1.66	1.89	1.77	1.99	0.070	0.135	0.368	0.002
d 46	1.67	1.70	1.70	1.62	1.74	1.74	0.066	0.714	0.426	0.856
P, mg/L										
d 0	124.17 14.8						-	-	-	-
d 10	99.5	97.1	98.0	103.3	102.2	103.2	4.01	0.982	0.908	0.152
d 24	121.6	122.6	129.6	124.0	118.1	122.7	5.08	0.630	0.525	0.471
d 46	113.1	114.4	114.0	110.3	115.8	111.7	3.29	0.782	0.578	0.642
Ca, mg/L										
d 0	94.89 9.22						-	-	-	-
d 10	100.3	98.9	107.4	98.8	103.1	104.3	2.40	0.278	0.025	0.959
d 24	113.7	111.7	116.4	112.2	114.6	116.9	2.40	0.658	0.226	0.741
d 46	105.3	104.4	103.3	103.0	108.0	104.7	2.40	0.459	0.591	0.657
Fe, mg/L										
d 0	1.07 0.87						-	-	-	-
d 10	2.00	1.80	1.40	1.63	1.22	1.56	0.222	0.233	0.256	0.146
d 24	1.91	2.61	2.10	2.09	2.20	1.91	0.262	0.523	0.215	0.512
d 46	1.52	1.62	1.50	1.69	1.54	1.28	0.194	0.618	0.480	0.782

[1]A total of 360 weaned pigs (initially 12.5 ± 0.04 lb) were used in a 46-d nursery trial. A total of six dietary treatments were arranged in a 2×3 factorial consisting of three Zn treatments (low and high pZnO, and pharmacological levels of ZnO) and low or high levels of Cu2O. There were 5 pigs per pen and 12 replications per treatment. No Zn × Cu × day, Zn × day, or Cu × day interactions unless otherwise indicated.

[2]Zn × Cu × day, P = 0.092; Zn × day, P < 0.001.

[3]Zn × Cu × day, P = 0.086; Zn × day, P = 0.068.

Table 5. Effects of Zn source and Cu level in low acid-binding capacity-4 diets as alternatives to pharmacological levels of ZnO on Zn and Cu balance and ATTD, dry matter-basis[1]

Cu_2O, mg/kg:	18			150				$P =$		
Zinc source:	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO				
Phase 1, mg/kg:	150	800	3,000	150	800	3,000				
Phase 2, mg/kg:	150	800	2,000	150	800	2,000				
Phase 3, mg/kg:	150 of pZnO			150 of pZnO			SEM	Zn × Cu	Zn	Cu
Zn										
d 10										
Intake, mg/d	30.8^{c}	170.4^{b}	499.7^{a}	76.2^{bc}	145.0^{b}	418.3^{a}	23.60	0.032	< 0.001	0.292
Fecal excretion, mg/d	23.7	134.5	402.2	58.2	111.5	344.0	21.89	0.110	< 0.001	0.388
Absorption, mg/d	7.0^{d}	35.9^{c}	97.5^{a}	17.9^{cd}	33.5^{c}	74.2^{b}	5.59	0.012	< 0.001	0.284
ATTD, %	23.4	20.5	20.7	23.6	23.0	18.1	1.51	0.253	0.030	0.971
d 24										
Intake, mg/d	101.9^{c}	445.3^{b}	1,532.2^{a}	253.1^{c}	518.8^{b}	1,478.2^{a}	42.05	0.055	< 0.001	0.103
Fecal excretion, mg/d	76.8^{d}	341.2^{bc}	1,229.9^{a}	195.0^{cd}	408.9^{b}	1,179.5^{a}	36.95	0.072	< 0.001	0.139
Absorption, mg/d	25.1	104.1	302.4	58.2	109.9	298.7	18.12	0.577	< 0.001	0.433
ATTD, %	25.2	23.2	19.8	23.0	21.0	20.0	1.90	0.775	0.100	0.381
Cu										
d 10										
Intake, mg/d	3.1	4.6	4.2	25.1	27.8	26.3	1.36	0.879	0.302	< 0.001
Fecal excretion, mg/d	1.8	2.8	2.5	16.8	18.5	17.1	0.97	0.825	0.386	< 0.001
Absorption, mg/d	1.3	1.9	1.7	8.3	9.3	9.2	0.78	0.941	0.561	< 0.001
ATTD, %	41.7	41.0	40.4	33.6	33.3	34.5	2.75	0.913	0.983	0.002
d 24										
Intake, mg/d	10.4^{c}	12.1^{c}	12.9^{c}	83.3^{b}	99.6^{a}	92.9^{ab}	3.15	0.075	0.018	< 0.001
Fecal excretion, mg/d	6.3^{c}	7.1^{c}	10.1^{c}	52.0^{b}	66.1^{a}	74.5^{a}	2.46	0.001	< 0.001	< 0.001
Absorption, mg/d	4.1^{c}	5.0^{c}	2.8^{c}	31.3^{a}	33.5^{a}	18.5^{b}	1.98	0.003	< 0.001	< 0.001
ATTD, %	39.1	41.2	21.3	37.5	33.3	19.5	2.49	0.357	< 0.001	0.067

[1] A total of 360 weaned pigs (initially 12.5 ± 0.04 lb) were used in a 46-d nursery trial. A total of six dietary treatments were arranged in a 2×3 factorial design consisting of three Zn treatments (low and high pZnO, and pharmacological levels of ZnO) and low or high levels of Cu2O. There were 5 pigs per pen and 12 replications per treatment.

Table 6. Effects of Zn source and Cu level in low acid-binding capacity-4 diets as alternatives to pharmacological levels of ZnO on Ca, P, and N balance and ATTD, dry matter-basis[1]

Cu_2O, mg/kg:	18			150				$P =$		
Zinc source:	pZnO	pZnO	ZnO	pZnO	pZnO	ZnO				
Phase 1, mg/kg:	150	800	3,000	150	800	3,000				
Phase 2, mg/kg:	150	800	2,000	150	800	2,000				
Phase 3, mg/kg:	150 of pZnO			150 of pZnO			SEM	Zn × Cu	Zn	Cu
Ca										
d 10										
Intake, mg/d	1,282	1,555	1,345	1,102	1,203	1,147	139.5	0.795	0.392	0.036
Fecal excretion, mg/d	229^{b}	363^{ab}	346^{ab}	378^{a}	271^{ab}	376^{a}	33.4	0.003	0.207	0.288
Absorption, mg/d	1053	1193	999	724	932	771	116.5	0.906	0.228	0.006
ATTD, %	82.0^{a}	74.6^{a}	74.3^{a}	65.7^{b}	77.6^{a}	66.4^{b}	1.90	< 0.001	0.013	< 0.001
d 24										
Intake, mg/d	4,398	3,898	3,803	4,071	4,332	3,649	201.0	0.149	0.036	0.923
Fecal excretion, mg/d	479^{c}	451^{c}	840^{ab}	1,022^{a}	505^{c}	671^{bc}	78.0	< 0.001	0.001	0.029
Absorption, mg/d	3,919^{a}	3,447^{ab}	2,963^{b}	3,049^{b}	3,827^{a}	2,978^{b}	178.3	0.003	0.001	0.280
ATTD, %	89.3^{a}	88.2^{ab}	77.4^{c}	75.4^{c}	88.5^{ab}	81.8^{bc}	1.64	< 0.001	< 0.001	0.026
P										
d 10										
Intake, mg/d	1,121	1,359	1,225	1,137	1,074	1,030	123.6	0.461	0.712	0.131
Fecal excretion, mg/d	264^{c}	447^{a}	380^{abc}	432^{ab}	289^{bc}	353^{abc}	37.5	< 0.001	0.840	0.850
Absorption, mg/d	856	912	844	705	785	677	94.5	0.977	0.626	0.059
ATTD, %	76.9^{a}	64.9^{c}	68.7^{bc}	61.7^{c}	72.9^{ab}	65.6^{bc}	1.89	< 0.001	0.486	0.032
d 24										
Intake, mg/d	3,476	3,206	2,873	3,666	3,449	3,192	164.9	0.926	0.007	0.067
Fecal excretion, mg/d	697^{d}	924^{cd}	1,508^{b}	1,816^{a}	961^{c}	1,258^{b}	62.8	< 0.001	< 0.001	< 0.001
Absorption, mg/d	2,779^{a}	2,282^{ab}	1,365^{d}	1,851^{cd}	2,489^{abc}	1,934^{bcd}	146.2	< 0.001	< 0.001	0.671
ATTD, %	79.8^{a}	70.7^{b}	46.3^{d}	49.7^{d}	71.8^{ab}	60.2^{c}	2.17	< 0.001	< 0.001	0.006
N										
d 10										
Intake, g/d	6.5	9.1	7.3	6.8	6.8	6.4	0.78	0.271	0.240	0.134
Fecal excretion, g/d	1.6^{b}	2.4^{a}	2.1^{ab}	2.5^{a}	1.8^{ab}	1.7^{ab}	0.23	< 0.001	0.792	0.842
Absorption, g/d	4.9	6.6	5.2	4.4	5.0	4.7	0.57	0.584	0.104	0.057
ATTD, %	75.9^{a}	72.3^{ab}	71.5^{b}	64.0^{c}	74.3^{ab}	72.5^{ab}	0.92	< 0.001	0.002	< 0.001
d 24										
Intake, g/d	20.7	22.7	21.9	22.3	22.7	22.2	1.07	0.743	0.538	0.463
Fecal excretion, g/d	3.9^{c}	5.2^{c}	8.6^{ab}	10.0^{a}	4.9^{c}	7.3^{b}	0.39	< 0.001	< 0.001	< 0.001
Absorption, g/d	16.8^{ab}	17.5^{a}	13.3^{bc}	12.3^{c}	17.8^{a}	14.9^{abc}	0.87	0.002	< 0.001	0.217
ATTD, %	81.5^{a}	77.0^{a}	60.5^{c}	54.8^{c}	78.0^{a}	67.0^{b}	1.42	< 0.001	< 0.001	< 0.001

[1] A total of 360 weaned pigs (initially 12.5 ± 0.04 lb) were used in a 46-d nursery trial. A total of six dietary treatments were arranged in a 2×3 factorial design consisting of three Zn treatments (low and high pZnO, and pharmacological levels of ZnO) and low or high levels of Cu2O. There were 5 pigs per pen and 12 replications per treatment.