The effects of copper source and concentration on growth performance, carcass characteristics, and pen cleanliness in finishing pigs[1,2]

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ABSTRACT A total of 1,143 pigs (PIC 337 × 1050, initially 25.1 ± 0.03 kg BW) were used in a 111-d study to determine the effects of copper sulfate ($CuSO_4$; Prince Agri-Products, Quincy, IL) or tribasic copper chloride (TBCC; IntelliBond C; Micronutrients, Indianapolis, IN) on growth performance, carcass characteristics, and pen cleanliness. Pens of pigs were allotted to 1 of 6 dietary treatments, balanced on average pen weight in a randomized complete block design with 25 to 28 pigs per pen and 7 replications per treatment. Treatments included a corn–soybean meal–based diet (corn-soy), a high-by-product diet with 30% distillers dried grains with solubles and 15% bakery meal (by-product diet), and the by-product diet with 75 or 150 mg/kg added Cu from $CuSO_4$ or TBCC. All diets contained 20 mg/kg Cu from $CuSO_4$ in the trace mineral premix. At the conclusion of the trial, a digital photo of each pen was taken to allow 3 independent observers to score manure texture and buildup and to assess pen cleanliness prior to power washing. Furthermore, the time required to power wash each pen was also measured. Overall, pigs fed the by-product diet tended to have increased ADFI ($P = 0.083$) and had decreased G:F ($P = 0.005$) compared to those fed the corn-soy diet. No Cu source × level interactions or Cu source differences were observed ($P > 0.05$). From d 0 to 71, pigs fed increasing Cu had increased (quadratic, $P < 0.05$) ADG, d 71 BW, and ADFI. From d 71 to 111, pigs fed increasing Cu tended to have increased ADFI (linear, $P = 0.068$) and decreased G:F (quadratic, $P = 0.056$). Overall (d 0 to 111), increasing Cu increased (linear, $P < 0.01$) ADG, final BW, and ADFI (quadratic, $P = 0.026$). Hot carcass weight increased (linear, $P = 0.023$) by 2.4 kg with increasing Cu. Increasing Cu also increased loin depth (linear, $P = 0.019$) and percentage lean (quadratic, $P = 0.024$). Manure buildup and wash time (s/pen) increased ($P < 0.05$) for by-product diet pens compared to corn-soy pens; however, neither wash time nor pen cleanliness were influenced by added Cu. In summary, increasing dietary Cu in high-by-product diets improved growth and feed intake, resulting in increased final BW and HCW for pigs fed both Cu sources, without influencing pen wash time.

Key words: copper sulfate, finishing pig, tribasic copper chloride, wash time

J. Anim. Sci. 2017.95:4052–4059
doi:10.2527/jas2017.1624

INTRODUCTION

In the nursery phase, typical improvements in ADG of 12% and ADFI of 8.4% can be observed when adding pharmacological levels (≤250 mg/kg) of Cu to the diet (Cromwell, 1997). It is hypothesized that pharmacological concentrations of added Cu might influence the microbial population in the gut, leading to increased ADG (Cromwell, 2001). Various inorganic and organic forms of Cu can be used in swine di-

[1]Contribution number 16-232-J from the Kansas Agricultural Experiment Station, Manhattan 66506–0210.

[2]The authors express their appreciation to Micronutrients (Indianapolis, IN) for partial financial support for this project and to New Horizons Farms (Pipestone, MN) for providing the pigs and facilities used in the experiment.

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Received April 11, 2017.

Accepted July 6, 2017.

ets. Copper sulfate has been historically the most commonly utilized inorganic source in swine diets: tribasic copper chloride (**TBCC**; IntelliBond C, Micronutrients, Inc., Indianapolis) is another alternative.

Cromwell et al. (1998) and Hastad (2002) demonstrated that feeding 200 mg/kg Cu from TBCC provided improvements in growth performance similar to those of feeding $CuSO_4$ for nursery pigs and finishing pigs, respectively. However, Kampf and Paboeuf (2014) recently reported that Cu added in the form of TBCC increased ADG and ADFI more than $CuSO_4$ in nursery pigs. One consistent response when feeding pharmacological levels of Cu is an increase in ADFI and ADG typically observed only during the early finishing period (NCR-42 Committee on Swine Nutrition, 1974; Hastad, 2002). The specific reasons for the differing responses over different BW ranges are not fully understood.

Research involving Cu supplementation has historically been based on corn–soybean meal–based diets. However, most pig diets in the United States currently contain by-product ingredients. Furthermore, an observational consequence of feeding diets high in by-product ingredients, as well as supplemental Cu, is an increase in manure buildup and pen wash time; however, no published data are available to support these claims. Therefore, the objective of this experiment was to evaluate the effects of $CuSO_4$ and TBCC on growth performance, carcass characteristics, and pen cleanliness of finishing pigs fed diets containing by-product ingredients.

MATERIALS AND METHODS

General

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee. The experiment was conducted in a commercial research facility in southwestern Minnesota. Pigs were housed in a facility that was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 × 5.49 m), of which 42 were used in the study. Each pen was equipped with a 5-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. The facility was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions and diets as specified. This system is capable of feeding each individual pen any of the individual diets. Each diet was manufactured at the New Horizons Feed Mill (Pipestone, MN) and delivered to individual bulk bins at the research site.

Animals and Diets

A total of 1,143 pigs (PIC 337 × 1050; PIC, Hendersonville, TN; initially 25.1 ± 0.03 kg) were used in a 111-d experiment. Pigs were derived from a porcine reproductive and respiratory syndrome virus-positive but stable farm and were relatively healthy throughout the study. Pigs were moved to the facility at an average BW of 20 kg and sorted into pens (25 to 28 pigs per pen), with an equal number or ratio of barrows and gilts per each weight block. Before the start of the experiment, all pigs were fed a common diet containing 186 mg/kg Cu from TBCC. On d 0, pens of pigs were weighed, ranked by average pen BW, and randomly allotted to 1 of the 6 dietary treatments in a 2 × 2 plus 2 factorial arrangement with average pen weight balanced across each treatment. There were 7 replications per treatment. Treatments included a corn–soybean meal–based diet (corn-soy), a diet containing 30% distillers dried grains with solubles (**DDGS**) and 15% bakery meal (by-product), and the by-product diet with either 75 or 150 mg/kg added Cu from either copper sulfate ($CuSO_4$; Prince Agri-Products, Quincy, IL) or TBCC (Tables 1 and 2). All diets contained 20 mg/kg Cu from $CuSO_4$ provided in the trace mineral premix.

Treatment diets were fed in 5 dietary phases in meal form and in the last phase contained 5 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN). Phase 1 diets were fed from d 0 to 27, phase 2 diets were fed from d 27 to 49, phase 3 diets were fed from d 49 to 71, phase 4 diets were fed from d 71 to 92, and phase 5 diets (with ractopamine HCl) were fed from d 92 to 111. All diets were formulated on a standardized ileal digestible (**SID**) Lys basis 0.05% below the estimated requirement for pigs raised in this facility during each phase, determined by previous research (Main et al., 2008). However, the SID Lys and all other nutrient requirements met the NRC (2012) requirements. Nutrient values for ingredients used in the formulation were from NRC (2012). Treatment diet samples were collected for each treatment during each phase from multiple feeders 2 d after the beginning of a phase and 2 d before the end of a phase. The 2 samples were combined to form a composite sample for each treatment within each phase and analyzed, in duplicate, for total Cu (method 985.01; AOAC International, 2000).

Pens of pigs were weighed, and feed disappearance was recorded approximately every 3 wk to determine ADG, ADFI, G:F, and caloric efficiency on an ME and NE basis. Caloric efficiencies were calculated by dividing the sum of total feed intake and diet calorie content by total gain. On d 92, all pens of pigs and feed disappearance were recorded, and then the 3 heaviest pigs in the pen were sold according to standard farm procedures. These pigs were used in the

Table 1. Composition of diets for phases 1, 2, and 3 (as-fed basis)[1]

	Phase 1[2]		Phase 2		Phase 3	
Item	Corn-soy	By-product	Corn-soy	By-product	Corn-soy	By-product
Ingredient, %						
Corn	73.07	36.05	77.96	41.07	81.76	44.69
Soybean meal, 46.5% CP	23.98	16.51	19.47	11.80	15.80	8.24
Distillers dried grains with solubles	—	30.00	—	30.00	—	30.00
Bakery meal	—	15.00	—	15.00	—	15.00
Monocalcium P, 21%	0.75	0.18	0.55	—	0.52	—
Limestone	1.18	1.25	1.11	1.17	1.08	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[3]	0.10	0.10	0.10	0.10	0.10	0.10
Lysine sulfate[4]	0.460	0.565	0.400	0.515	0.360	0.470
L-Thr	0.060	—	0.040	—	0.030	—
MHA[5]	0.055	—	0.015	—	—	—
Phytase[6]	0.005	0.005	0.005	0.005	0.005	0.005
Copper source[7]		+/−		+/−		+/−
Total	100	100	100	100	100	100
Calculated analysis						
Standard ileal digestible (SID) AA, %						
Lys	1.00	1.00	0.86	0.86	0.75	0.75
Ile:Lys	63	71	64	74	65	77
Met:Lys	30	32	29	35	29	38
Met + Cys:Lys	55	59	56	64	58	69
Thr:Lys	60	60	60	62	61	64
Trp:Lys	18	18	18	18	18	18
Val:Lys	70	82	72	87	75	92
Total Lys, %	1.13	1.20	0.97	1.04	0.85	0.93
SID Lys:ME, g/Mcal	3.04	2.95	2.60	2.53	2.26	2.20
ME, kcal/kg	3,294	3,388	3,307	3,402	3,311	3,406
NE, kcal/kg	2,471	2,476	2,504	2,508	2,526	2,531
CP, %	17.9	21.3	16.1	19.5	14.6	18.0
Ca, %	0.65	0.58	0.57	0.51	0.54	0.49
P, %	0.52	0.47	0.46	0.41	0.44	0.39
Available P, %	0.28	0.28	0.24	0.24	0.22	0.23
Crude fiber, %	2.4	4.0	2.3	3.9	2.2	3.9
NDF, %	8.6	14.1	8.7	14.1	8.7	14.2

[1]Phase 1 diets were fed from d 0 to 27, phase 2 diets were fed from d 27 to 49, and phase 3 diets were fed from d 49 to 71.

[2]Each diet was fed in meal form.

[3]Provided per kilogram of premix: 4,509,410 IU vitamin A, 701,464 IU vitamin D_3, 24,050 IU vitamin E, 1,402 mg vitamin K, 3,006 mg riboflavin, 12,025 mg pantothenic acid, 18,038 mg niacin, 15.0 mg vitamin B_{12}, 40 g Mn from manganese oxide, 90 g Fe from ferrous sulfate, 100 g Zn from zinc oxide, 10 g Cu from copper sulfate, 500 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4]Lysine source (Evonik Inc., Kennesaw, GA).

[5]Methionine hydroxyl analog (88% methionine; Novus International, St. Charles, MO).

[6]Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 phytase units (FTU)/kg, with a release of 0.07% available P.

[7]Supplemental copper provided in the form of $CuSO_4$ or tribasic copper chloride (IntelliBond C; Micronutrients, Indianapolis, IN) at either 75 or 150 mg/kg at the expense of corn in the by-product diet.

calculation of pen growth performance but not carcass characteristics. Prior to marketing the remaining pigs in the barn, all pigs were individually tattooed with a pen identification number to allow for carcass measurements to be recorded on an individual basis. On d 111, final pen weights were taken, and pigs were transported to a commercial packing plant (JBS Swift and Co., Worthington, MN) for processing and carcass data collection. Hot carcass weights were measured immediately after evisceration, and each carcass was evaluated for carcass yield, back fat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe (Fat-O-Meater; SFK Technology A/S, Denmark) inserted between the third and fourth last ribs (counting from the

Table 2. Composition of diets for phases 4 and 5 (as-fed basis)[1]

Item	Phase 4[2]		Phase 5	
	Corn-soy	By-product	Corn-soy	By-product
Ingredient, %				
Corn	84.42	47.29	76.66	39.65
Soybean meal, 46.5% CP	13.25	5.69	20.79	13.13
Distillers dried grains with solubles	—	30.00	—	30.00
Bakery meal	—	15.00	—	15.00
Monocalcium P, 21%	0.48	—	0.44	—
Limestone	1.05	1.13	1.08	1.18
Salt	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[3]	0.10	0.10	0.10	0.10
Lysine sulfate[4]	0.325	0.435	0.415	0.530
L-Thr	0.025	—	0.090	0.035
MHA[5]	—	—	0.050	—
Phytase[6]	0.005	0.005	0.005	0.005
Ractopamine HCl[7]	—	—	0.025	0.025
Copper source[8]		+/−		+/−
Total	100	100	100	100
Calculated analysis				
Standard ileal digestible (SID) AA, %				
Lys	0.67	0.67	0.90	0.90
Ile:Lys	67	79	64	73
Met:Lys	31	40	31	34
Met + Cys:Lys	61	74	58	63
Thr:Lys	62	67	65	65
Trp:Lys	18	18	18	18
Val:Lys	78	97	72	85
Total Lys, %	0.77	0.84	1.02	1.09
SID Lys:ME, g/Mcal	2.02	1.97	2.72	2.65
ME, kcal/kg	3,318	3,408	3,311	3,399
NE, kcal/kg	2,544	2,546	2,500	2,500
CP, %	13.5	17.0	16.6	20.0
Ca, %	0.52	0.48	0.55	0.52
P, %	0.42	0.38	0.44	0.41
Available P, %	0.21	0.23	0.21	0.24
Crude fiber, %	2.2	3.8	2.3	4.0
NDF, %	8.8	14.2	8.7	14.1

[1]Phase 4 diets were fed from d 71 to 92, and phase 5 diets were fed from d 92 to 111.

[2]Each diet was fed in meal form.

[3]Provided per kilogram of premix: 4,509,410 IU vitamin A, 701,464 IU vitamin D_3, 24,050 IU vitamin E, 1,402 mg vitamin K, 3,006 mg riboflavin, 12,025 mg pantothenic acid, 18,038 mg niacin, 15.0 mg vitamin B_{12}, 40 g Mn from manganese oxide, 90 g Fe from ferrous sulfate, 100 g Zn from zinc oxide, 10 g Cu from copper sulfate, 500 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4]Lysine source (Evonik Inc., Kennesaw, GA).

[5]Methionine hydroxyl analog (88% methionine; Novus International, St. Charles, MO).

[6]Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 phytase units (FTU)/kg, with a release of 0.07% available P.

[7]Paylean (Elanco Animal Health, Greenfield, IN).

[8]Supplemental copper provided in the form of $CuSO_4$ or tribasic copper chloride (IntelliBond C; Micronutrients, Indianapolis, IN) at either 75 or 150 mg/kg at the expense of corn in the by-product diet.

ham end of the carcass) at a distance approximately 7 cm from the dorsal midline.

At the conclusion of the experiment, a digital photo of each pen was taken to allow 3 independent observers (farm employees, each with over 10 yr of experience in finishing pig management) to score manure texture and buildup to assess pen cleanliness before power washing. A Casio EXILIM EX-ZS5 14.1-megapixel camera with flash was used to take all pictures (Casio Computer Co., Ltd, Shibuya, Tokyo, Japan).

The photographer stood in the same exact location in the center of each pen along the front gate using a ladder to take an aerial picture. One picture from the aisle and 1 standing directly in the middle of the pen close to the slats were taken. The scores were averaged to determine a mean score for each pen, which was used for analysis. Manure textures were categorized as firm, medium, or loose, with scores of 1, 2, and 3, respectively. Manure buildup was categorized as 1 for visual buildup of over 2.5 cm of hard-packed manure and −1 for no visual buildup. Afterward, a professional power-washing crew recorded the wash time for each pen with a stop watch to determine the difference in wash time between treatments. The barn sat empty 1 d before power washing was initiated and was not presoaked. A hot-water power-washing system (82°C) was used, and there were no detergents or other additives used when washing.

Statistical Analysis

Experimental data were analyzed using the PROC MIXED procedure in SAS (SAS Inst. Inc., Cary, NC) as a 2 × 2 plus 2 factorial arrangement in a randomized complete-block design. Pen was the experimental unit, and initial BW was used as a blocking factor. Residual assumptions were checked using standard diagnostics on Studentized residuals. Evidence for a normal distribution and homogeneous variance was reasonably met. The main effect of Cu source, linear and quadratic effects of added Cu level, and their interactions were tested. Additionally, the contrast between the corn–soybean meal–based diet and by-product diet was also evaluated. Back fat depth, loin depth, and lean percentage were adjusted to a common HCW for analysis. Results from the experiment were considered significant at $P \leq 0.05$, and a tendency was considered between $P > 0.05$ and $P \leq 0.10$.

RESULTS

Diets had analyzed Cu concentrations generally similar to calculated values and within an acceptable range based on analytical variation (Table 3). Permitted analytical variation for Cu analysis is 25% (procedure 968.08; Association of American Feed Control Officials, 2014). The analyzed values for the corn-soy diet and by-product diet that had Cu added to the diet only via the trace mineral premix were from 21 to 42 mg/kg. For treatment diets with 75 mg/kg added Cu, analyzed Cu concentrations ranged from 116 to 137 mg/kg when in the form of $CuSO_4$ and 83 to 134 mg/kg when in the form of TBCC. For treatment diets with 150 mg/kg added Cu, analyzed Cu concentrations ranged from 192 to 267 mg/kg when in the form of $CuSO_4$ and 157 to 189 mg/kg when in the form of TBCC.

Pigs fed the corn–soybean meal–based diet or the high-by-product diet had similar ADG from d 0 to 71, 71 to 111, and overall (d 0 to 111; Table 4). Pigs fed the by-product diet tended to have increased ADFI ($P < 0.083$) from d 0 to 71 and d 0 to 111 compared to those fed the corn-soy diet. As a result, G:F decreased ($P = 0.031$) for pigs fed the by-product compared to the corn-soy diet from d 71 to 111 and overall. Caloric efficiency on both an ME and NE basis was reduced ($P < 0.05$) in pigs fed the by-product diet compared to the corn-soy diet.

No significant Cu level × source interactions or differences between Cu sources ($P > 0.05$) were observed for any of the response criteria. From d 0 to 71, pigs fed increasing Cu had increased ADG (quadratic, $P = 0.002$) and ADFI (linear, $P = 0.007$), whereas G:F tended to decrease ($P = 0.052$). As a result, BW on d 71 increased (quadratic, $P = 0.004$) with increasing added Cu. From d 71 to 111, ADFI tended to increase (linear, $P = 0.068$), whereas G:F tended (quadratic, $P = 0.056$) to decrease for pigs fed 75 mg/kg added Cu but increased for those fed 150 mg/kg added Cu. Overall, from d 0 to 111, increasing Cu increased ADG (linear, $P < 0.001$) and ADFI (quadratic, $P < 0.026$), which led to an increase in final BW (linear, $P = 0.003$).

For carcass characteristics, pigs fed the corn-soy diet tended to have increased loin depth ($P = 0.079$) compared to those fed the by-product diet (Table 5). Pigs fed increasing Cu had increased HCW (linear, $P = 0.023$), loin depth (linear, $P = 0.019$), and percentage lean (quadratic, $P = 0.024$).

For pen cleanliness, pigs fed the by-product diet with DDGS and bakery meal had increased ($P < 0.05$) manure buildup and pen wash time compared to the pigs fed the corn-soy diet. No differences in pen cleanliness characteristics were observed between Cu sources or level.

DISCUSSION

Copper sulfate is manufactured from Cu metal and sulfuric acid, whereas TBCC is a by-product of the circuit board manufacturing process where acidic cupric chloride and alkaline cupramine chloride solution are neutralized to form a green purified source of Cu. Copper sulfate has been shown to be highly soluble, whereas TBCC is less than 1% soluble in water (Miles et al., 1998). The concentration of Cu is also twice as high (58%) in TBCC compared to $CuSO_4$ (25.4%). Furthermore, less oxidative instability during storage has been shown with TBCC compared to $CuSO_4$, which may offer benefits when including in a vitamin–trace mineral premix (Luo et al., 2005).

The diets used in formulation were formulated 0.05% below the estimated SID Lys requirement on the basis of the procedures of Rochell et al. (2015). Rochell et al. (2015) fed broilers 2 levels of digestible Lys (1.00% or 1.20%) and 2 levels of added Cu (0 or 200 mg/kg) from TBCC. They reported that broilers fed low amounts of digestible Lys and 200 mg/kg of added Cu from TBCC had greater improvements in ADFI than broilers fed the high level of digestible Lys. This response, however, has yet to be investigated in finishing pigs. Although we did not compare SID Lys levels, results from Rochell et al. (2015) suggested the potential for a more definitive response to Cu if SID Lys were reduced. The estimated SID Lys requirements for each phase were determined by previous research conducted in this facility with the same sire and dam lines (Main et al., 2008).

The NRC (2012) suggests that the dietary requirement for Cu is 3 to 6 mg/kg for pigs from 5 to 135 kg of BW, respectively. The corn-soy diet and by-product diet that contained no added Cu had analyzed values that ranged from 21 to 42 mg/kg, exceeding the pig's nutrient requirement estimated for Cu. These analyzed values are similar to what would be expected as a result of the 20 mg/kg of Cu provided to the diet in the trace mineral premix and Cu originating from the ingredients used in formulation. Similarly, the analyzed total Cu had values across phases within treatments

Table 3. Analyzed copper concentrations of complete diets[1]

Phase	Corn-soy	By-product	$CuSO_4$,[2] mg/kg 75	$CuSO_4$,[2] mg/kg 150	TBCC,[3] mg/kg 75	TBCC,[3] mg/kg 150
1	27	21	137	208	83	180
2	24	38	129	192	77	157
3	28	38	116	200	134	172
4	27	37	136	267	104	187
5	42	32	135	257	129	189

[1]Values represent means from 1 composite sample, analyzed in duplicate. Permitted analytical variation for Cu analysis is 25% (procedure 968.08; Association of American Feed Control Officials, 2014).

[2]Copper sulfate (Prince Agri-Products, Quincy, IL).

[3]Tribasic copper chloride (IntelliBond C; Micronutrients, Indianapolis, IN).

Table 4. Effects of $CuSO_4$ or TBCC on growth performance of finishing pigs[1]

			$CuSO_4$,[4] mg/kg		TBCC,[5] mg/kg			Probability $P <$ [6]			
										Cu level	
Item	Corn-soy[2]	By-product[3]	75	150	75	150	SEM	Corn-soy vs. by-product	Cu source	Linear	Quadratic
BW, kg											
d 0	25.1	25.1	25.1	25.1	25.1	25.1	0.93	0.971	0.990	0.991	0.972
d 71	84.6	86.3	89.3	88.3	90.6	89.0	1.77	0.187	0.248	0.034	0.004
d 111	124.5	124.2	127.6	127.5	128.4	130.0	2.04	0.875	0.145	0.003	0.157
d 0 to 71											
ADG, kg	0.84	0.86	0.90	0.89	0.92	0.89	0.015	0.162	0.332	0.035	0.002
ADFI, kg	1.95	2.03	2.14	2.15	2.18	2.13	0.046	0.056	0.643	0.007	0.012
G:F	0.429	0.424	0.424	0.413	0.421	0.420	0.004	0.175	0.425	0.052	0.464
d 71 to 111											
ADG, kg	1.03	1.00	1.00	1.02	0.99	1.06	0.020	0.286	0.533	0.142	0.248
ADFI, kg	2.90	2.95	3.02	3.00	2.99	3.07	0.051	0.453	0.561	0.068	0.658
G:F	0.356	0.340	0.333	0.341	0.331	0.344	0.006	0.031	0.817	0.742	0.056
d 0 to 111											
ADG, kg	0.90	0.91	0.94	0.93	0.94	0.95	0.011	0.757	0.231	0.007	0.064
ADFI, kg	2.27	2.34	2.44	2.44	2.46	2.45	0.043	0.083	0.565	0.004	0.026
G:F	0.397	0.388	0.385	0.383	0.383	0.388	0.004	0.005	0.369	0.335	0.244
Caloric efficiency,[7] Mcal/kg											
ME	8.33	8.78	8.84	8.89	8.88	8.77	0.080	0.001	0.404	0.369	0.249
NE	6.33	6.49	6.54	6.58	6.56	6.49	0.060	0.005	0.400	0.372	0.247

[1]A total of 1,143 pigs (PIC 337 × 1050, PIC, Hendersonville, TN; initial BW = 25.1 ± 0.03 kg) were used in this 111-d study, with 7 pens per treatment and 25 to 28 pigs per pen.

[2]Corn–soybean meal–based diet without by-products with 20 mg/kg added Cu from $CuSO_4$ provided in the trace mineral premix.

[3]Corn–soybean meal–based diet with 30% distillers dried grains with solubles and 15% bakery meal with 20 mg/kg added Cu from $CuSO_4$ provided in the trace mineral premix. Added Cu, regardless of source or level, was added to the by-product diet in addition to that provided in the trace mineral premix.

[4]Copper sulfate (Prince Agri-Products, Quincy, IL).

[5]Tribasic copper chloride (IntelliBond C; Micronutrients, Indianapolis, IN).

[6]Linear and quadratic effects of Cu include the by-product diet and the means of pigs fed 75 and 150 mg/kg added Cu. No copper level × source interactions were found ($P > 0.05$).

[7]Caloric efficiencies were calculated by dividing the sum of total feed intake and diet calorie content by total gain.

similar to those expected, given the control diet levels and that the analytical variation that can be observed in lab analysis of Cu in complete feeds is 25% (Association of American Feed Control Officials, 2014).

Much of the published literature investigating added Cu suggests that Cu improves growth performance during the early finishing period, with little to no response during the late finishing period. The NCR-42 Committee on Swine Nutrition (1974) concluded that Cu improved growth performance during the first 8 wk from 22 to 61 kg BW but not the last 8 wk of the finishing period from 61 to 91 kg. Hastad (2002) also suggested that Cu in the form of either $CuSO_4$ or TBCC provided growth benefits only until approximately 61 kg. In contrast, Davis et al. (2002) reported that pigs fed 125 mg/kg from $CuSO_4$ had increased ADG and G:F in both the early grower period from 32 to 68 kg and the finishing period from 68 to 106 kg.

The 3% increase in overall ADG with added Cu is similar to other responses in corn–soybean meal–based diets (NCR-42 Committee on Swine Nutrition, 1974; Davis et al., 2002; Hastad, 2002). However, the 4% increase in ADFI in the current experiment is 2 percentage units higher than previously reported. Although diet type could have possibly influenced this result, exact reasons are unknown. However, pigs in the current experiment were fed to a heavier final weight than in most previous experiments.

Previous research has ruled out the possibility for Cu to increase ADFI though improvements in palatability. Coble et al. (2014) determined that when pigs are given a choice, pigs prefer diets without added Cu, regardless of whether the Cu is in the form of $CuSO_4$ or TBCC. However, they also reported that when pigs were given a choice between $CuSO_4$ or TBCC, pigs preferred TBCC. It is unclear if the results of a preference study where pigs are given a choice between 2 or more feeds will correlate to what is observed when pigs have access to only 1 feed at a time.

An increase in the concentration of added Cu offers a possible explanation for the observed increase in feed intake. Yang et al. (2011) reported an increase

Table 5. Effects of $CuSO_4$ or TBCC on carcass characteristics and pen cleanliness of finishing pigs[1]

								Probability $P <$ [6]			
			$CuSO_4$,[4] mg/kg		TBCC,[5] mg/kg					Cu level	
Item	Corn-soy[2]	By-product[3]	75	150	75	150	SEM	Corn-soy vs. by-product	Cu source	Linear	Quadratic
Carcass characteristics											
HCW, kg	92.5	91.8	93.3	93.1	93.6	95.3	1.19	0.589	0.111	0.023	0.587
Yield, %	73.3	72.8	72.4	72.5	72.5	72.9	0.40	0.350	0.555	0.857	0.467
Back fat depth,[7] mm	17.4	17.0	15.8	16.7	16.6	16.8	0.44	0.464	0.306	0.635	0.702
Loin depth,[7] mm	64.2	62.4	63.4	65.1	66.0	64.2	0.72	0.079	0.225	0.019	0.055
Lean,[7] %	55.9	56.0	56.8	56.5	56.7	56.3	2.90	0.777	0.443	0.172	0.024
Pen cleanliness											
Texture[8]	2.00	2.09	1.86	1.81	1.80	2.19	0.214	0.767	0.445	0.733	0.268
Buildup[9]	−1.00	0.62	0.90	0.62	−0.05	1.00	0.206	0.001	0.141	0.416	0.116
Wash time, s	268	417	413	383	373	389	21.5	0.001	0.432	0.242	0.673

[1]A total of 1,143 pigs (PIC 337 × 1050, PIC, Hendersonville, TN; initial BW = 25.1 ± 0.03 kg) were used in this 111-d study, with 7 pens per treatment and 25 to 28 pigs per pen.

[2]Corn–soybean meal–based diet without by-products with 20 mg/kg added Cu from $CuSO_4$ provided in the trace mineral premix.

[3]Corn–soybean meal–based diet with 30% distillers dried grains with solubles and 15% bakery meal with 20 mg/kg added Cu from $CuSO_4$ provided in the trace mineral premix. Added Cu, regardless of source or level, was added to the by-product diet in addition to that provided in the trace mineral premix.

[4]Copper sulfate (Prince Agri-Products, Quincy, IL).

[5]Tribasic copper chloride (IntelliBond C; Micronutrients, Indianapolis, IN).

[6]Linear and quadratic effects of Cu include the by-product diet and the means of pigs fed 75 and 150 mg/kg added Cu. No copper level × source interactions were found ($P > 0.05$).

[7]Adjusted by using HCW as a covariate.

[8]Residual manure texture in the pen after pigs were marketed was categorized as firm, medium, or loose with scores of 1, 2, and 3, respectively.

[9]Residual manure buildup in the pen after pigs were marketed was based on a value of 1 for visual buildup and −1 for no visual manure buildup.

in mRNA expression levels for GhRH, which provides positive feedback to the hypothalamus to increased appetite. This increase in appetite comes as a result of increasing neuropeptide Y concentration, a neurotransmitter in the brain that signals increased feed intake and has also been demonstrated to be increased as a result of Cu additions to diets fed to swine (Li et al., 2008). Also, Zhou et al. (1994b) reported that mRNA concentrations for growth hormone in the pituitary gland was numerically higher in pigs fed 215 mg/kg added Cu. Zhou et al. (1994a) also reported that pigs that were injected with a Cu solution to achieve circulating blood levels of those consuming 250 mg/kg of Cu via feed also had improvements in ADG and G:F, suggesting that Cu impacts growth and metabolism in more ways than its antimicrobial-like properties.

The last focus of this experiment was to determine if diet type and supplemental Cu negatively impacted manure buildup and wash time in a commercial finishing barn. Anecdotal reports from swine producers suggest that when by-products or pharmacological levels of Cu are added to the diet, barn wash time increases. This outcome is likely because of the association of pigs fed diets high in by-product having greater manure volume than those fed corn–soybean meal–based diets. Furthermore, pharmacological concentrations of added dietary Cu may turn the pig's feces black and arguably make the pig look "dirtier" than when feeding a diet without pharmacological concentrations of Cu. Indeed, in this experiment, manure buildup and pen wash time were increased in pens where pigs were fed a diet containing by-product ingredients compared to the corn–soybean meal–based diet. On a whole-barn basis, although not significant, wash time was increased just under 2 h when the by-product diet was fed. However, this experiment showed that adding pharmacological Cu has little influence on manure buildup and, in fact, a numerically shorter pen wash time. The change in fecal color associated with feeding Cu (Hill et al., 2000) may simply be creating the illusion of more fecal content in the pen and increased wash time

In conclusion, adding supplemental Cu in the form of either $CuSO_4$ or TBCC improved growth performance, leading to an increase in HCW. The magnitude of response to added Cu may have been greater than in previous research because we fed diets that were formulated to be slightly below the SID Lys requirement; however, further research is needed to determine if the response to feeding Cu is SID Lys dependent. Diets high in by-product ingredients did increase manure buildup in the pen and increased pen wash time; however, added Cu did not negatively affect manure buildup or wash time.

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