A cooperative study assessing reproductive performance in sows fed diets supplemented with organic or inorganic sources of trace minerals

Tsung Tsai,[†] Gary A. Apgar,[‡] Mark J. Estienne,[‖] Mark Wilson,[$] and Charles V. Maxwell[†,1]

[†]Department of Animal Science, University of Arkansas, Fayetteville, AR 72701; [‡]Department of Animal Science, Southern Illinois University, Carbondale, IL 62901; [‖]Tidewater Agricultural Research and Extension Center, Virginia Tech, Suffolk, VA 23437, and [$]Zinpro Inc., Eden Prairie, MN 55344

ABSTRACT: Sows from three university research facilities (n = 245) were stratified by parity and initial body weight (BW), and within outcome groups, randomly assigned to fortified corn- and soybean meal-based control or organic trace mineral-supplemented, gestation (3,339 kcal/kg ME; 0.62% standradized ileal digestible [SID] lysine), and lactation (3,374 kcal/kg ME; 0.97% SID lysine) diets. Control gestation and lactation diets were supplemented with inorganic trace minerals (120 ppm Zn from ZnO, 30 ppm Cu from $CuSO_4$, and 50 ppm Mn from $MnSO_4$), and the experimental diets contained the same total level of minerals but complexed organic trace minerals replaced 50% of the inorganic trace minerals. Sows were fed to condition during gestation and on an ad libitum basis during lactation. Sow BW (breeding, d 110 of gestation, 48 h post-farrowing, and weaning) and feed consumed were recorded. During gestation, control sows tended to gain less weight (60.4 vs. 64.6 kg, $P = 0.06$) and consumed less feed (263.5 vs. 264.8 kg, $P = 0.05$), and had poorer Gain:Feed (G:F) (0.27 vs. 0.29, $P = 0.04$) than sows fed the organic trace minerals. Sow average daily feed intake (ADFI) during lactation was similar ($P = 0.28$) between groups (4.93 vs. 4.74 kg for control and treated sows, respectively). Number of pigs born alive (11.4 vs. 10.9, $P = 0.24$) and weaned (10.2 vs. 9.8, $P = 0.18$), and pig pre-weaning average daily gain (ADG) (0.27 vs. 0.27 kg/d, $P = 0.77$) and mortality (13.1 vs. 12.9%, $P = 0.92$) were similar for control and treated sows, respectively. Results of the current study demonstrate that sows fed diets supplemented with organic trace minerals displayed similar reproductive performance, but improved weight gain and G:F during gestation compared with sows fed inorganic trace minerals.

Key words: inorganic minerals, organic minerals, reproductive performance, sows

Transl. Anim. Sci. 2020.4:59–66
doi: 10.1093/tas/txz178

INTRODUCTION

Sows, particularly those with modern genotypes, produce large litters of fast-growing pigs, resulting in a decrease in mineral reserves over time (Mahan and Newton, 1995). After several parities, the decline may result in marginal mineral deficiencies that negatively affect growth, reproduction, and health. In intensive pork production systems, sows receive a premix containing trace minerals that supplement levels contributed by plant and/or animal feedstuffs. Trace minerals in premixes, however, vary greatly in bioavailability. One premise for replacing traditional inorganic sources of trace minerals with organically bound trace minerals (termed metal chelates, complexes,

[1]Corresponding author: cmaxwell@uark.edu
Received July 29, 2019.
Accepted December 2, 2019.

or proteinates) is that bioavailability of the latter is greater because they remain stable in the digestive tract longer and do not form insoluble chelates with other dietary components such as phytate. That organic trace minerals have greater bio-availabilities is illustrated by a study in which gilts fed Zn, Cu, and Mn proteinates had greater concentrations of these minerals in conceptus products at d 12 post-coitum and greater Cu at d 30 of gestation (Hostetler et al., 2000). It is hypothesized reproductive performance might be improved in sows fed trace minerals from sources that have greater bioavailability. Thus, the objective of the study reported herein was to determine the effect of organic trace minerals on reproductive performance in sows.

MATERIALS AND METHODS

Research at the universities participating in this study (University of Arkansas, Southern Illinois University, and Virginia Tech—Tidewater Agricultural Research and Extension Center) followed guidelines contained in the "Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching" (FASS, 2010) and protocols approved by the respective Institutional Animal Care and Use Committees.

Animals and Housing

A multistate study conducted at three research facilities involving 253 sows (of which data from 245 sows were used) evaluated the effects of inorganic or organic trace minerals on reproductive performance. Table 1 contains the number and genetics of sows and characteristics of the facilities participating in the study. Animals were subjected to deworming and vaccination schedules particular to each facility. Technicians processed newborn pigs, and bred females using AI, according to standard operating procedures in place at each university.

Experimental Treatments

At each facility, bred gilts and sows were stratified by parity and BW and within outcome groups, randomly assigned to one of two dietary regimens, formulated to be isocaloric and isolysinic and contain equal total levels of the trace minerals, and to meet NRC (1998) recommendations for the various nutrients (Table 2). Control corn- and soybean meal-based gestation and lactation diets contained 120 ppm Zn (from ZnO), 30 ppm Cu (from $CuSO_4$), and 50 ppm Mn (from $MnSO_4$). The experimental diets contained the same total level of minerals but complexed organic trace minerals (Availa-Zn 100, Availa-Cu 100, and Availa-Mn 80; Zinpro, Inc., Eden Prairie, MN) replaced 60, 15, and 25 ppm (i.e., 50%) of the inorganic Zn, Cu, and Mn, respectively. Control and treatment diets both also provided 120 ppm Ca, 165 ppm Fe, 0.3 ppm I, and 0.3 ppm Se, all from inorganic sources.

The gestation diets (3,339 kcal ME/kg and 0.62% SID lysine; Table 2) were fed at a level of approximately 2.2 kg/d but according to standard practices at each facility with consideration of environmental temperature and sow body condition. Feeding of the gestation diets commenced at breeding (or weaning in sows) and continued through d 110 of gestation.

Beginning at d 110 of gestation and after relocation to the farrowing house, sows were fed lactation diets containing 3,374 kcal/kg ME and 0.97% SID lysine (Table 2). After farrowing, sows were offered the control or experimental lactation diets two to three times/d and were fed on an ad libitum basis.

Measurements

Daily feed consumption of sows was recorded. Gilts and sows were weighed at breeding, d 110 of gestation, 48 h after farrowing, and at weaning. The number and litter weight of pigs at birth (total and live), after cross-fostering, and at weaning were recorded. Pigs were cross-fostered from sows to like-treatment sows only.

Statistical Analyses

Data were analyzed using the mixed model procedure of SAS (SAS Institute Inc., Cary, NC) for

Table 1. Characteristics of participating research facilities

Facility[1]	Sows used, *n*	Mean parity	Sow genetics	Weaning age, d	Gestation accommodation
UA	134	3.69	PIC 29	21	Stalls
SIU	30	2.57	Yorkshire, Duroc	21	Stalls
VT	81	1.88	Yorkshire × Landrace	21	Stalls

[1]UA, University of Arkansas, Fayetteville; SIU, Southern Illinois University, Carbondale; VT, Virginia Tech—Tidewater Agricultural Research and Extension Center, Suffolk.

Table 2. Composition of gestation and lactation diets

	Gestation, %[1]		Lactation, %[1]	
Ingredient	Control	Treated	Control	Treated
Corn, yellow dent	77.38	77.33	64.25	64.20
Soybean meal, 48% high protein, dehulled, solvent extracted	16.50	16.50	28.50	28.50
Fat, (darling, yellow grease)	2.00	2.00	3.00	3.00
Dicalcium phosphate	2.00	2.00	2.05	2.05
Limestone	0.93	0.93	0.93	0.93
Sodium chloride	0.45	0.45	0.45	0.45
L-lysine	0.05	0.05	0.13	0.13
L-threonine	0.04	0.04	0.04	0.04
Sow add pack (NB-6473)[2]	0.25	0.25	0.25	0.25
Vitamin premix (NB-6508)[2]	0.25	0.25	0.25	0.25
Control trace mineral premix (NB-9872)[2]	0.15	–	0.15	–
Organic trace mineral premix (NB-9871)[2]	–	0.20	–	0.20
Total	100.00	100.00	100.00	100.00
Calculated analysis (as fed basis)				
Metabolizable energy, kcal/kg	3339	3337	3374	3372
Crude protein, %	14.34	14.34	19.08	19.08
Standard ileal digestible lysine, %	0.62	0.62	0.97	0.97
Calcium, %	0.99	0.98	1.04	1.03
Available phosphorous, %	0.38	0.38	0.41	0.41
Zinc, ppm	140.8	140.8	144.5	144.5
Manganese, ppm	62.1	62.2	65.9	65.9
Copper, ppm	35.1	35.1	36.5	36.5

[1]Percent as fed.

[2]NB-6473, NB-6508, NB-9872, and NB-9871 are premix products manufactured by Nutra Blend, LLC (Neosho, MO). Minerals complexed with amino acids (Availa-Zn 100, Availa-Cu 100, and Availa-Mn 80; Zinpro, Inc., Eden Prairie, MN) replaced 60, 15, and 25 ppm (i.e., 50%) of the inorganic Zn, Cu, and Mn, respectively.

a randomized complete block design. Sows were placed into one of three parity groups: Parity 1 sows in Group A; Parity 2 and 3 sows in Group B; and Parity ≥ 4 sows in Group C. The model included treatment (organic vs. inorganic minerals), sow parity group, and treatment × sow parity group as possible sources of variation. Facility was considered a random effect. Individual sow was the experimental unit for ANOVA. Least square means for treatment, sow parity group, and treatment × sow parity group were compared using the PDIFF option of PROC MIXED.

RESULTS AND DISCUSSION

The large variation that exists among sows for the economically important reproductive traits hinders research focused on nutrition in the breeding herd (Aaron and Hays, 2001). For example, with normal variation, the number of replications typically needed to detect a 10% difference in litter size at birth with an 80% chance of detecting that difference and a 10% probability level, is 112 sows per treatment. Results contained herein are illustrative of the value of cooperative, multi-state research projects focusing on sow reproduction. Although none of the three participating universities possessed the animals and resources necessary to conduct the current experiment alone, combined data from over 120 farrowing events per treatment were adequate to detect significant differences for several response measures. Members of the multistate research committee of which the authors are members, have successfully used this strategy before (Lindemann et al., 2004, 2008; Carter et al., 2018). Animal and facility characteristics, and performance measures for the research sites employed in this study appear in Tables 1 and 3. In general, overall sow performance approximated that in the commercial swine industry. For example, the overall average total litter size and the number of pigs born alive were approximately 12.4 and 11.6, respectively. Knauer and Hostetler (2013) conducted an analysis of production data generated by approximately 1.8 million commercial sows in the United States between 2005 and 2010, and reported an average total litter size of 12.5 and the average number of pigs born alive of 11.3. As expected, there were numerous differences in sow and litter performance among research facilities (Table 3).

Table 3. Least squares means of facility effects on sow and litter performance

	Facility[1]				
	UA	SIU	VT	SEM	P
Number of sows	134	30	81		
Parity	3.69[b]	2.57[a]	1.83[a]	0.24	<0.01
Sow BW, kg					
Initial	211.7[b]	–	155.6[a]	3.0	<0.01
d 110 of gestation	283.3[c]	252.2[b]	210.4[a]	3.7	<0.01
Gestation change	71.7[b]	–	55.8[a]	1.6	<0.01
Farrowing[2]	267.2[c]	235.4[b]	195.9[a]	4.2	<0.01
Weaning	250.9[c]	227.0[b]	182.4[a]	4.4	<0.01
Farrowing change[3]	−16.19	−18.94	−15.06	1.61	0.36
Lactation change[4]	−16.22[b]	−8.35[a]	−13.48[ab]	1.66	0.01
Lactation feed intake					
Total, kg	96.7[a]	107.5[a]	129.8[b]	4.2	<0.01
ADFI, kg	4.98[b]	3.14[a]	5.58[c]	0.18	<0.01
Sow reproductive performance					
Total number born	13.58[b]	10.76[a]	11.20[a]	0.44	<0.01
Total born litter weight, kg	18.35	–	17.64	0.43	0.25
Number born alive	12.46[b]	9.76[a]	10.83[a]	0.41	<0.01
Born alive litter weight, kg	17.27	15.44	17.14	0.54	0.10
Average born alive BW, kg	1.42[a]	1.70[b]	1.63[b]	0.04	<0.01
Litter performance					
Pigs weaned	10.26[b]	8.38[a]	10.03[b]	0.32	<0.01
Weaning litter weight, kg	62.82[b]	54.99[a]	73.43[c]	2.18	<0.01
Litter weight gain, kg	48.11[b]	39.54[a]	56.29[c]	1.79	<0.01
Average weaning weight, kg	6.23[a]	6.62[a]	7.46[b]	0.15	<0.01
Piglet ADG, kg/d	0.24[b]	0.19[a]	0.32[c]	0.01	<0.01
Pre-weaning mortality, n	2.30[b]	1.61[a,b]	0.80[a]	0.25	<0.01
Pre-weaning mortality, %	16.10[b]	13.39[a,b]	6.91[a]	1.59	<0.01

[1]UA, University of Arkansas, Fayetteville; SIU, Southern Illinois University, Carbondale; VT, Virginia Tech—Tidewater Agricultural Research and Extension Center, Suffolk.

[2]Farrowing BW was collected within 48 h after farrowing.

[3]Farrowing change was equal to d 110 BW—Farrowing BW.

[4]Lactation change was equal to farrowing BW—Wean BW.

For the performance measures listed, however, there were no effects ($P \geq 0.26$) of facility × treatment, so data were pooled across facilities.

For statistical analysis of the data, sows were placed into one of three parity groups: Parity 1 sows in Group A; Parity 2 and 3 sows in Group B; and Parity ≥ 4 sows in Group C. There were no effects of parity group × treatment ($P \geq 0.13$) on sow and litter performance measures. There existed, however, many main effects of parity on sow growth characteristics, and in general, these were normal changes associated with advancing age (Table 4). Koketsu et al. (2017) reviewed the scientific literature and reported that total litter size and the number of pigs born alive increases from parity one to parity three. However, some researchers have reported that pigs born alive decreases from parity one to parity two, apparently a consequence of low feed intake by sows during the first lactation (Hoving et al., 2011). This could at least partially explain our finding that the number of pigs born alive was numerically less in Parity Group B sows (which included Parity 2 and 3 sows) than in Parity Group A sows (which included Parity 1 sows only). However, the average birth weight of pigs born alive was greatest and the percentage of pigs born alive that weighed less than 0.91 kg, the least in Parity Group B sows. These animals also nursed pigs with the greatest ADG and weaning weights.

Table 5 provides a summary of BW, and gestation and lactation feed intake, for sows, fed diets supplemented with either organic or inorganic trace minerals. There were no effects ($P > 0.27$) of parity group × treatment. Control sows and sows fed organic trace minerals had similar ($P = 0.97$) BW at the beginning of the experiment. Organic trace mineral-fed sows, however, consumed more feed ($P = 0.05$), tended to gain more BW ($P = 0.06$), and

Table 4. Least squares means of parity group effect on sow and litter performance

	Parity group[1]				
	A	B	C	SEM	*P*
Number of sows	85	90	70	–	–
Sow BW[2], kg					
Initial	158.5[a]	183.8[b]	221.8[c]	17.5	<0.01
110 d	226.1[a]	251.2[b]	277.9[c]	16.8	<0.01
Gestation change	66.1[a]	67.5[a]	53.9[b]	11.3	<0.01
Farrowing[3]	205.3[a]	235.9[b]	268.6[c]	15.3	<0.01
Weaning	190.5[a]	223.2[b]	257.8[c]	14.5	<0.01
Farrowing change[4]	−20.83[a]	−16.69[b]	−10.13[c]	2.19	<0.01
Lactation change[5]	−15.61	−12.79	−11.12	2.46	0.11
Feed intake					
Gestation					
Total intake, kg	263.7	264.7	264.1	0.7	0.56
G:F	0.31[a]	0.29[b]	0.24[c]	0.01	<0.01
Lactation					
Total intake, kg	99.0[a]	124.7[b]	126.2[b]	9.0	<0.01
ADFI, kg	3.91[a]	5.22[b]	5.37[b]	0.79	<0.01
Sow reproductive performance					
Total number born	12.36	11.69	12.14	0.86	0.46
Total born litter weight[2], kg	17.41	18.86	17.59	0.72	0.11
Number born alive, *n*	11.56	11.01	10.93	0.80	0.41
Born alive litter weight, kg	16.71	17.60	16.34	0.60	0.19
Average born alive BW, kg	1.50[a]	1.67[b]	1.52[a]	0.07	<0.01
Born alive BW < 0.91 kg, *n*	1.21	0.97	1.70	0.31	0.25
Born alive BW < 0.91 kg, %	7.40[a]	6.64[a]	14.00[b]	2.15	0.05
Post-cross foster[2]					
Litter size, *n*	11.59	10.89	11.05	0.76	0.30
Litter weight, kg	16.74	17.39	16.54	0.55	0.43
Average piglets BW, kg	1.50[a]	1.66[b]	1.52[a]	0.08	<0.01
Litter performance					
Pigs weaned, *n*	10.40	9.81	9.73	0.29	0.20
Weaning litter weight, kg	64.28	66.29	59.88	5.49	0.12
Litter weight gain, kg	48.44	49.64	44.80	5.16	0.16
Average weaning BW, kg	6.42[a]	7.08[b]	6.31[a]	0.38	<0.01
Piglet ADG, kg/d	0.26[a]	0.29[b]	0.26[a]	0.03	<0.01
Pre-weaning mortality, *n*	1.54	1.50	1.83	0.46	0.55
Pre-weaning mortality, %	12.00	11.92	15.07	3.17	0.31

[1]Group A, Parity 1 sows; Group B, Parity 2 and 3 sows; Group C, Parity ≥ 4 sows.

[2]With the exception of Initial BW, gestation change, total born litter weight, and post-cross foster litter weight (data from University of Arkansas and Virginia Tech only), data for all response measures represents all three facilities.

[3]Farrowing BW was collected 48 h after farrowing.

[4]Farrowing change was equal to d 110 BW—Farrowing BW.

[5]Lactation change was equal to farrowing BW—Wean BW.

[a,b,c]Within a row, means with different superscripts differ ($P < 0.05$).

had a greater G:F ($P = 0.04$) during gestation compared with controls. Similarly, the sows fed organic trace minerals tended to weigh more ($P = 0.10$) at farrowing; however, lactation feed intake ($P = 0.13$) and BW change ($P = 0.67$) were not different between groups.

Peters and Mahan (2008) reported results of a six-parity study in which sows consumed diets with either organic or inorganic sources of trace minerals, at levels either recommended by NRC (1998) or typically used by commercial swine operations. In contrast to our findings, sow BW changes during gestation and lactation were not affected by dietary treatment. In concert with our results, the source of trace minerals (organic vs. inorganic) did not affect lactation feed intake. The biological significance of our finding that BW gain and G:F were greater in the sows fed organic trace minerals

Table 5. Least squares means of treatment effects on BW and feed intake during gestation and lactation in sows[1,2]

	Treatment			
	Control	Organic	SEM	*P*
Number of sows	123	122		
Sow BW, kg				
Initial	188.1	188.0	17.4	0.97
d 110 of gestation	250.0	253.4	16.7	0.22
Gestation change	60.4	64.6	11.2	0.06[6]
Farrowing[3]	234.2	239.0	15.2	0.10
Weaning	221.4	226.3	14.4	0.12
Farrowing change[4]	−16.34	−15.42	2.00	0.56
Lactation change[5]	−12.81	−13.53	2.27	0.67
Feed Intake				
Gestation				
Total intake, kg	263.51	264.80	0.46	0.05
G:F	0.27	0.29	0.01	0.04[6]
Lactation				
Total intake, kg	119.64	113.63	8.70	0.13
ADFI, kg/d	4.93	4.74	0.79	0.28

[1]Sows were grouped by parity (parity 1 sows, parity group A; parities 2 and 3 sows, parity group B; and parity ≥ 4 sows, parity group C) and body weight and within outcome groups randomly allotted to control (100% inorganic) or organic (50% inorganic and 50% organic) trace mineral diets. There were no effects ($P > 0.27$) of parity group × treatment on any of the performance measures.

[2]Except for initial BW, gestation BW change, and gestation FE (data from UA andVT only), data of variables were derived from all stations (UA, VT, and Southern Illinois University). There were no effects ($P > 0.26$) of facility × treatment on any of the performance measures.

[3]Farrowing BW was collected 48 h postpartum.

[4]Farrowing weight change was equal to 110 d BW—Farrowing BW.

[5]Lactation weight change was obtained by farrowing BW—Wean BW.

[6]Tendency for statistical significance despite relatively large SE is a consequence of data for these items being collected at only two of the three stations and station remaining as a random effect in the mixed model ANOVA (Contact the corresponding author for supplemental information).

remains to be determined. However, Thomas et al. (2018) reported weak but statistically significant positive correlations between gestation BW gain and total born in Parity 1, 2, and 3 sows. Moreover, the efficiency with which nutrients are partitioned among various tissue pools in the pregnant sow and the roles parity and stage of gestation play is an emerging area of study (Thomas et al., 2018). Finally, the authors acknowledge that in the current experiment, weight gain and feed conversion efficiency could have been impacted by body condition with leaner, more efficient sows receiving more feed than fatter sows during gestation.

In the current study, there were no effects ($P > 0.13$) of parity group × dietary treatment on measures of reproductive performance in sows. The main effects of diet on characteristics of reproduction in sows are summarized in Table 6. There were no effects of dietary treatment on total number of pigs born ($P = 0.55$), the numbers of pigs born alive ($P = 0.24$) or weaned ($P = 0.18$), or pre-weaning mortality ($P = 0.92$). Similarly, average BW for pigs born alive ($P = 0.76$), or the number ($P = 0.80$) or proportion ($P = 0.80$) of pigs born alive that weighed less than 0.91 kg, were similar between treatments. There were tendencies for weaning litter weight ($P = 0.09$) and litter weight gain ($P = 0.10$) to be greater for sows fed the inorganic control diet compared with sows fed organic trace minerals. This probably reflects the numerical, but not statistically significant, greater number of pigs nursed and weaned in the sows fed the inorganic minerals.

Only a few studies have been conducted during which reproduction was compared with sows provided inorganic or organic sources of trace minerals and results have been equivocal. In some experiments, no significant effects of organic trace minerals on reproductive performance were detected (Mahan and Peters, 2004; Payne et al., 2006). Consistent with our study, there was no effect of feeding organic Se on total or live pigs born; however, compared with controls, the number of pigs born was increased in sows fed diets supplemented with 0.15 ppm Se from either inorganic or organic sources (Mahan and Peters, 2004). Payne et al. (2006) supplemented a control diet containing 100 ppm inorganic Zn with an additional 100 ppm from either $ZnSO_4$ or from an organic Zn

Table 6. Least squares means of treatment effects on sow and litter performance

Items[1]	Control	Organic	SEM	*P*
Number of sows or litters	123	122	–	–
Sow reproductive performance				
Total born/litter	12.20	11.93	0.82	0.54
Total born litter weight, kg	18.15	17.76	0.64	0.51
Born alive	11.41	10.92	0.76	0.24
Born alive litter weight, kg	17.12	16.64	0.52	0.38
Born alive average BW, kg	1.56	1.57	0.07	0.80
Born alive BW < 0.91 kg, *n*	1.33	1.25	0.22	0.80
Born alive BW < 0.91, %	9.61	9.08	1.51	0.80
Post-cross foster				
Litter size, *n*	11.43	10.92	0.73	0.20
Litter weight, kg	17.14	16.64	0.47	0.36
Average pig BW, kg	1.55	1.57	0.07	0.73
Litter performance				
Pigs weaned, *n*	10.20	9.76	0.23	0.18
Weaning Litter weight, kg	65.38	61.58	5.34	0.09
Litter weight gain, kg	49.15	46.10	5.05	0.10
Average weaning weight, kg	6.66	6.55	0.37	0.46
Pig ADG, kg/d	0.27	0.27	0.03	0.77
Pre-weaning mortality, *n*	1.65	1.60	0.44	0.84
Pre-weaning mortality, %	13.08	12.92	3.03	0.92

[1]For each item data was available from three facilities (University of Arkansas, Southern Illinois University, and Virginia Tech—Tidewater Agricultural Research and Extension Center) except total born litter weight (University of Arkansas and Virginia Tech—Tidewater Agricultural Research and Extension Center only). There were no effects of parity group (parity 1 sows, parity group A; parities 2 and 3 sows, parity group B, and parity ≥ 4 sows, parity group C) × treatment ($P > 0.27$) or facility × treatment ($P > 0.26$) on any of the performance measures.

complex and fed sows from d 15 of gestation and through lactation. The number of sows involved in the study was limited (7 to 9 per treatment group), and there were no effects of dietary treatment on litter size. Litter birth weight, however, tended to be greater in sows fed organic zinc compared with sows fed the control or $ZnSO_4$ diets. Sows fed organic zinc tended to nurse more pigs than sows fed the $ZnSO_4$ diet and weaned more pigs than sows fed the control diet.

Conversely, there have been some reports of positive effects of organic minerals on litter size in swine. Over six parities, females ($n = 216$) were fed organic or inorganic sources of trace minerals at NRC (1998) levels (Cu, 5 ppm; Fe, 80 ppm; Mn, 20 ppm; Se, 0.15 ppm; Zinc, 50 ppm) or greater levels used by industry (Cu, 15 ppm; Fe, 120 ppm; Mn, 40 ppm; Se, 0.30 ppm; Zinc, 120 ppm) (Peters and Mahan, 2008). Females fed the organic minerals farrowed more total and live born pigs. Litter birth weights, but not individual pig weight, were greater in organic mineral-fed sows than for sows fed inorganic trace minerals; the pre-weaning ADG of pigs nursing sows fed organic minerals tended to be greater as well. Mirando et al. (1993) fed poorly producing sows (litters of ≤10 pigs) a control diet ($n = 10$) or a diet in which 25% of the inorganic sources of Zn, Cu, and Mn were replaced with mineral proteinates ($n = 12$) during lactation and until 30 d post-mating when the sows were slaughtered. The organic trace minerals had no effects on lactation performance, but compared with controls, the number of viable embryos tended to be greater at d 30 of gestation. In a subsequent experiment, diets similar to those employed by Mirando et al. (1993) were fed to gilts beginning at 105 d of age and continued until d 15 of pregnancy (Hostetler and Mirando, 1998). Gilts fed the organic minerals reached puberty 13 d earlier than gilts fed inorganic minerals, but pregnancy and ovulation rates were not affected by treatment.

Finally, Flowers et al. (2001) reported that gilts ($n = 216$) fed inorganic Cu, Fe, Mn, and Zn at 25% of the inorganic control diet (15, 100, 100, and 40 ppm, respectively) had more pigs born alive and weaned through three parities compared with controls or gilts fed reduced minerals with 50% of the inorganic minerals being replaced with metal proteinates. There was no difference in reproductive performance between the control gilts and gilts fed the organic minerals; despite weaning fewer pigs than the reduced inorganic treatment, sows fed the reduced organic treatment had heavier litter weaning weights.

In summary, results of the current study demonstrate that sows fed diets supplemented with organic trace minerals displayed similar reproductive performance but improved weight gain and G:F during gestation compared with sows fed inorganic trace minerals.

ACKNOWLEDGMENTS

This work was supported by the USDA National Institute of Food and Agriculture, Multi-State Project S-1061 entitled, “Nutritional Systems for Swine to Increase Reproductive Efficiency” (accession number: 1003592). The authors acknowledge the expert technical assistance provided by technicians at the University of Arkansas, Southern Illinois University, and Virginia Tech, and thank Dr Jeffrey J. Chewning and Dr Edward E. Gbur for guidance in conducting the statistical analyses.

Conflict of interest statement: The authors confirm that there is no conflict of interest in the present article.

LITERATURE CITED

Aaron, D.K., and V.W. Hays. 2001. Statistical techniques for the design and analysis of swine nutrition experiments. In: Lewis, A.J., and L.L. Southern, editors, Swine nutrition. 2nd ed. Washington (DC): CRC Press; p. 605–622.

Carter, S.D., M.D. Lindemann, L.I. Chiba, M.J. Estienne, and G.J.M.M. Lima. 2018. Effects of inclusion of spray-dried porcine plasma in lactation diets on sow and litter performance. Livest. Sci. 216:32–35.

Federation of Animal Science Societies (FASS). 2010. Guide for the care and use of agricultural animals in research and teaching. 3rd rev. ed. Champaign (IL): Federation of Animal Science Societies.

Flowers, W.L., J.W. Spears, and G.M. Hill. 2001. Effect of reduced Cu, Zn, Fe, and Mn on reproductive performance of sows. J. Anim. Sci. 79(Suppl. 2):140 (Abstr.).

Hostetler, C.E., J.D. Cronath, W.C. Becker, and M.A. Mirando. 2000. Dietary supplementation of proteinated trace minerals (OPTiMIN) in sow and replacement gilts increases mineral concentrations in reproductive tissues. 14th International Congress on Animal Reproduction, Stockholm, Sweden. Amsterdam (Netherlands): Elsevier; 1:272.

Hostetler, C.E., and M.A. Mirando. 1998. Dietary supplementation of proteinated trace minerals influences reproductive and growth performance of gilts. J. Anim. Sci. 76(Suppl. 1):274 (Abstr.).

Hoving, L.L., N.M. Soede, E.A.M. Gratt, H. Feitsma, and B. Kemp. 2011. Reproductive performance of second parity sows: relations with subsequent reproduction. Livest. Sci. 139:252–257

Knauer, M.T., and C.E. Hostetler. 2013. US swine industry productivity analysis, 2005 to 2010. J. Swine Health Prod. 21:248–252.

Koketsu, Y., S. Tani, and R. Iida. 2017. Factors for improving reproductive performance of sows and herd productivity in commercial breeding herds. Porcine Health Manag. 3:1. doi:10.1186/s40813-016-0049-7.

Lindemann, M.D., J.H. Brendemuhl, L.I. Chiba, C.S. Darroch, C.R. Dove, M.J. Estienne, and A.F. Harper. 2008. A regional evaluation of injections of high levels of vitamin A on reproductive performance of sows. J. Anim. Sci. 86:333–338. doi:10.2527/jas.2007-0153.

Lindemann, M.D., S.D. Carter, L.I. Chiba, C.R. Dove, F.M. LeMieux, and L.L. Southern. 2004. A regional evaluation of chromium tripicolinate supplementation of diets fed to reproducing sows. J. Anim. Sci. 82:2972–2977. doi:10.2527/2004.82102972x.

Mahan, D.C., and E.A. Newton. 1995. Effects of initial breeding weight on macro- and micromineral composition over a three-parity period using a high-producing sow genotype. J. Anim. Sci. 73:151–158.

Mahan, D.C., and J.C. Peters. 2004. Long-term effects of dietary organic and inorganic selenium sources and levels on reproducing sows and their progeny. J. Anim. Sci. 82:1343–1358. doi:10.2527/2004.8251343x.

Mirando, M.A., D.N. Peters, C.E. Hostetler, W.C. Becker, S.S. Whiteaker, and R.E. Rompala. 1993. Dietary supplementation of proteinated trace minerals influences reproductive performance of sows. J. Anim Sci. 74(Suppl. 1).180 (Abstr.).

National Research Council (NRC). 1998. Nutrient requirements of swine. 10th rev. ed. Washington (DC): National Academic Press.

Payne, R.L., T.D. Bidner, T.M. Fakler, and L.L. Southern. 2006. Growth and intestinal morphology of pigs from sows fed two zinc sources during gestation and lactation. J. Anim. Sci. 84:2141–2149. doi:10.2527/jas.2005-627.

Peters, J.C., and D.C. Mahan. 2008. Effects of dietary organic and inorganic trace mineral levels on sow reproductive performances and daily mineral intakes over six parities. J. Anim. Sci. 86:2247–2260. doi:10.2527/jas.2007-0431.

Thomas, L.L., R.D. Goodband, M.D. Tokach, S.S. Dritz, J.C. Woodworth, and J.M. DeRouchey. 2018. Partitioning components of maternal growth to determine efficiency of feed use in gestating sows. J. Anim. Sci. 96:4313–4326. doi:10.1093/jas/sky219.