# PERFORMANCE CHARACTERISTICS OF WEANED PIGS ON ZINC SUPPLEMENTATION: A META-ANALYSIS

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**Abstract.** The profitability of a swine enterprise depends heavily on high productivity, which to some extent can be achieved using trace elements. However, there are discordant results on the impact of zinc (Zn) supplementation, one of such trace elements on performance indices of weaned pigs. This study aimed to use the meta-analytic method to assess the impact of Zn supplementation on growth performance [i.e., average daily feed intake (ADFI), feed to gain ratio (F/G), average daily gain (ADG) and blood Zn levels] of weaned pigs. 1200 studies on the impact of Zn supplementation on growth performance were identified in a systematic search performed in Google Scholar, PubMed and Scopus databases and screened based on set inclusion criteria. Thirty studies met the inclusion criteria. Pooled results showed that Zn supplementation had a small effect on ADFI [standardised mean difference (SMD = 0.33; 95% confidence interval (CI): 0.23 to 0.44) and F/G (SMD = 0.18; 95% CI: 0.05 to 0.30)], but had a moderate effect on ADG (SMD = 0.63; 95% CI: 0.49 to 0.77) in weaned pigs. Additionally, Zn supplementation had a large effect on blood Zn (SMD = 2.83; 95% CI: 2.13 to 3.52). Subgroup analyses revealed that moderator variables [duration of supplementation (DOS), supplementation level (SL), Zn form and number of pigs included in each group] influenced the results of the meta-analysis, taking cognizance of heterogeneity. Meta-regression analyses found that moderators accounted for most of the sources of heterogeneity. It is concluded that Zn supplementation increased ADG and blood Zn in weaned pigs.

**Keywords:** *weaned pigs, zinc, growth performance, blood zinc, meta-analysis*

## Introduction

Zn is one of the trace elements that influences growth and productivity of weaned pigs (Zhang et al., 2018a). It is an activator or a component of several enzymes involved in reproduction, immune function, antioxidant defense and cell proliferation. Some studies have shown that Zn improves gut health and intestinal barrier functions by increasing the expression of the tight-junction genes as well as small intestinal insulin-like growth factor -1 (IGF-1) and IGF-1 receptor genes (Li et al., 2006). Haung et al. (2009) found that natural feedstuffs are low in Zn, but do contain several factors limiting Zn absorption in the small intestine which call for adequate Zn supplementation in the diets of weaned pigs. NRC (1998) has set the Zn requirements for weaned pigs at 100 mg/kg feed. Several studies have evaluated the effect of Zn dose levels below or above the NRC (1998) recommended level on performance of weaned pigs (Hill et al., 2000; Fernandez et al., 2014; Cemin et al., 2019; Diao et al., 2021). Some investigators found no difference in the effect of Zn supplementation on the performance of weaned pigs (Carlson et al., 2004; Cho et al., 2015), while others found differences (Schell and Kornegay, 1996; Martínez

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et al., 2005; Cemin et al., 2019). These variable reports may be ascribed to differences in breeds, sex, and rearing conditions (Pierozan et al., 2016; Ogbuewu et al., 2022).

The use of meta-analytic method to increase statistical power, identify research gaps and resolve conflicting findings among investigations that addressed the same research question has been highlighted (Hedges and Pigott, 2004; Koricheva et al., 2013). Meta-analysis is an advanced statistical method that aggregates the effect of intervention across studies that addressed the same research objective to provide a more robust estimate of the effects by increasing statistical power (Lean et al., 2014). Presently, no meta-analysis has been performed to evaluate the effect of Zn supplementation in weaned pig performance. Therefore, the objective this study was to assess the effect of dietary Zn supplementation on growth performance and blood Zn levels of weaned pigs using meta-analysis.

## Materials and methods

### *Article selection guidelines*

Google Scholar, PubMed and Scopus databases were searched for studies that evaluated the impact of Zn supplementation on the performance of weaned pigs using the following keywords: zinc, weaned pigs, ADFI, ADG, F/G and blood Zn. References of identified articles were manually reviewed for other relevant publications. Eligibility criteria for the meta-analysis were based on PICO method. PICO stands for Population (i.e., weaned pigs), Intervention (i.e., Zn supplementation), Comparison [i.e., diets with Zn (treatment group) and diets without Zn (control group)] and Outcomes (i.e., ADFI, F/G, ADG and blood Zn). Studies included in the meta-analysis were selected based on following inclusion criteria: (i) Controlled studies that examined the effect of diets with Zn (treatment group) and without Zn (control group) supplementation on the performance of clinically healthy weaned pigs. (ii) Studies were selected if they reported ADFI, ADG, F/G or blood Zn and their measure of variance [i.e., standard error (SE), standard deviation (SD), or 95% CI] for effect size computation. Studies that used animals other than weaned pigs were excluded. Studies that examined the effect of Zn in combination with other feed additives were also excluded. Also excluded were reviews and studies performed in diseased pigs. Identified studies were evaluated for eligibility, and disagreements were resolved through consensus. 1200 studies were identified and 30 studies were considered suitable for inclusion in the meta-analysis following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (*Figure 1*).

### *Data extraction and analysis*

Data on the surname of the first author, year of publication, study location, study design and modifier variables (i.e., number of pigs in each treatment group, duration of supplementation, supplementation level and Zn form) were extracted in each of the article that met the inclusion criteria (*Tables 1a and b*). Data generated from the 30 studies that met eligibility were analysed in OpenMEE software by Brown University (Wallace et al., 2016). Results were presented as SMD at 95% CI using random-effects model. SMD was considered significant when the lower and upper CIs did not include zero (Koricheva et al., 2013). SMD was designated as small (0.2), moderate (0.5) and large effect (≥ 0.8) using the method of Cohen (1992). To explore sources of heterogeneity, data were partitioned using the following modifiers: number of pigs in each treatment group

(< 40 vs > 40), duration of supplementation (≤ 21 d vs > 21 d), supplementation level (1 - 100, 101 - 250, 251 - 500, 501 - 1000, 1001 - 1500, 1501 - 2000, 2001 - 2500, 2501 - 3000 and > 3000 mg/kg) and Zn form (inorganic, organic and nano). Heterogeneity was calculated using Q-statistic and $I^2$ - index (Higgins and Thompson, 2002), and considered significant at $p < 0.05$. Results of subgroup and meta-regression analyses were also considered significant at $p < 0.05$. Sensitivity analysis was performed using the method of Lean et al. (2009) to determine the robustness of the results of the meta-analysis. Publication bias was examined through funnel plot asymmetry and fail-safe number, Nfs (Sterne and Harbord, 2004). According to Jennions et al. (2013), the results of the meta-analysis can be considered robust, despite the presence of publication bias when the Nfs is higher than 5*[(n = number of comparison) + 10].

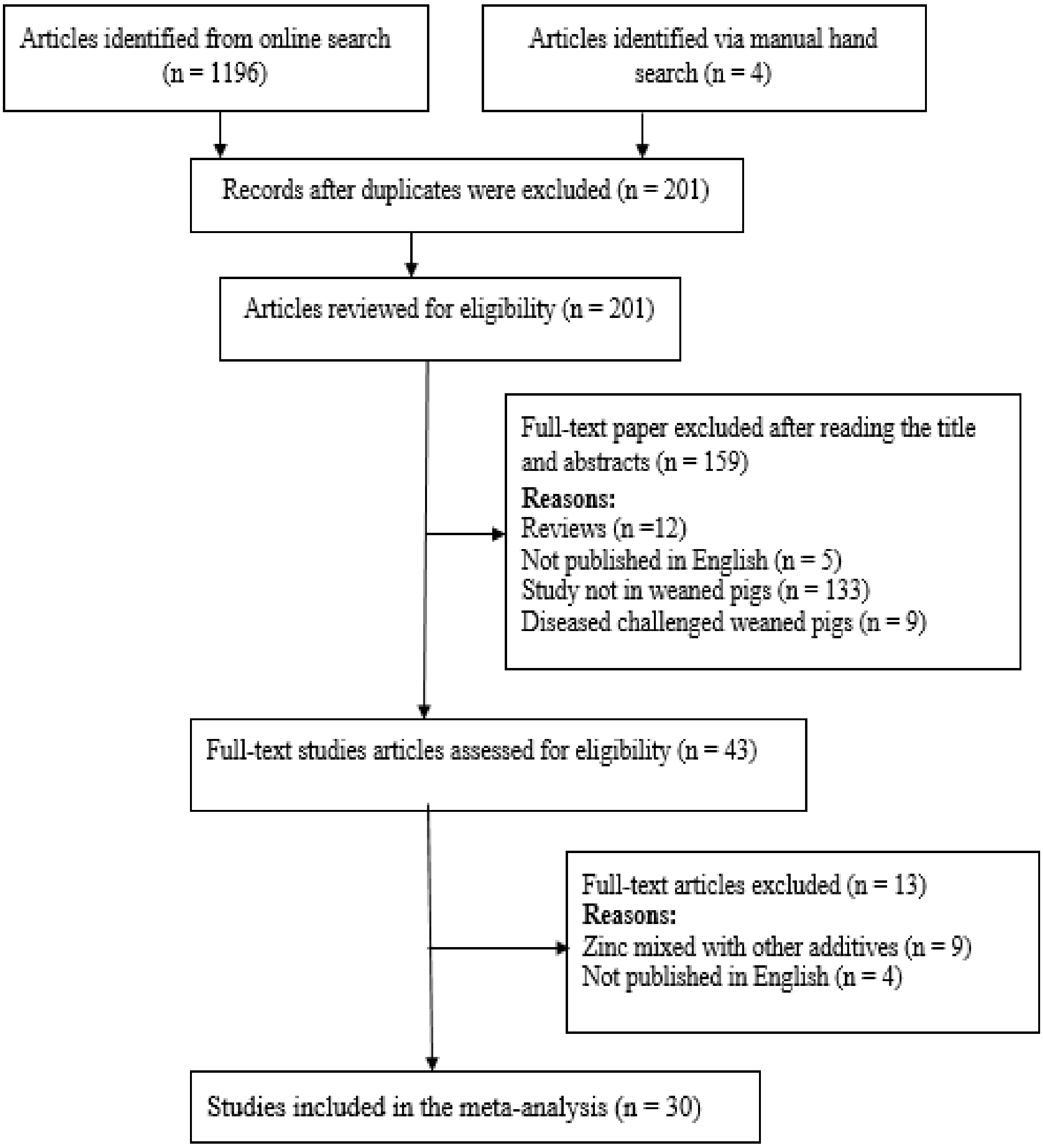

***Figure 1.*** *Flow chart of the articles selection process for the meta-analysis*

***Table 1a.*** *Characteristics of studies included in the meta-analysis*

| **References** | **Country** | **Continent** | **Studied moderators** | | | | **Outcomes** |
|---|---|---|---|---|---|---|---|
| | | | Zn form | SL (mg/kg) | NPT | DOS (d) | |
| Diao et al. (2021) | China | Asia | OZn/IZn | 100 | 24 | 1-28 | FI, FCE, BWG |
| Hill et al. (2014) | USA | North America | OZn/IZn | 0 -100 | 50 | 1-38 | FI, FCE, BWG |
| Schell and Kornegay (1996) | USA | North America | OZn/IZn | 0 - 3000 | 20 | 1-14 | FI, FCE, BWG |
| van Heugten et al. (2013) | USA | North America | OZn/IZn | 0 -160 | 16 | 1-35 | FI, FCE, BWG |
| Zhang et al. (2020) | China | Asia | IZn | 0-3000 | 36 | 1-28 | FI, FCE, BWG |
| Broom et al. (2006) | UK | Europe | IZn | 0-3100 | 52 | 1-20 | FI, FCE, BWG |
| Buff et al. (2005) | USA | North America | OZn/IZn | 0-2000 | 10 | 1-35 | FI, FCE, BWG |
| Hollis et al. (2005) | USA | North America | OZn/IZn | 0-2500 | 123 | 1-28 | FI, FCE, BWG |
| Hu et al. (2012) | China | Asia | IZn | 0-2000 | 36 | 1-14 | FI, FCE, BWG |
| Hu et al. (2013) | China | Asia | IZn | 0- 2250 | 42 | 1-14 | FI, FCE, BWG |
| Li et al. (2016) | Taiwan | Asia | OZn/IZn/NZn | 0- 120 | 24 | 1-45 | FI, FCE, BWG |
| Pei et al. (2019) | China | Asia | NZn | 0-3000 | 30 | 1-21 | FI, FCE, BWG, Blood Zn |
| Pérez et al. (2011) | USA | North America | IZn | 0-3000 | 20/44 | 1-28/1-42 | FI, FCE, BWG |
| Zhang et al. (2018b) | China | Asia | OZn/IZn | 0-800 | 36 | 1-28/1-42 | FI, FCE, BWG |
| Wang et al. (2010) | China | Asia | OZn | 0-3000 | 30 | 1-35 | FI, FCE, BWG, Blood Zn |
| Carlson et al. (2004) | USA | North America | OZn/IZn | 0-2000 | 51 | 1-42 | FI, FCE, BWG, Blood Zn |
| Cho et al. (2015) | Korea | Asia | IZn/NZn | 0-3000 | 35 | 1-42 | FI, FCE, BWG, Blood Zn |
| Hahn and Baker (1993) | USA | North America | OZn/IZn | 0-5000 | 30 | 1-21 | FI, FCE, BWG, Blood Zn |
| Han and Thacker (2010) | Korea | Asia | IZn | 0-2500 | 30 | 1-14/1-28 | FI, FCE, BWG, Blood Zn |
| Lei and Kim (2018) | South Korea | Asia | IZn | 0-2500 | 32 | 1-42 | FI, FCE, BWG, Blood Zn |
| Mavromichalis et al. (2001) | USA | North America | IZn | 0-3000 | 30 | 1-21 | FI, FCE, BWG |
| Milani et al. (2017) | Brazil | South America | IZn/NZn | 0-3000 | 32 | 1-35 | FI, FCE, BWG, Blood Zn |
| Molist et al. (2011) | Spain | Europe | IZn | 0-3000 | 16 | 1-12 | FI, BWG |
| Namkung et al. (2006) | Canada | North America | IZn | 0-3000 | 36 | 1-14 | FI, FCE, BWG |
| Poulsen (1995) | Denmark | Europe | IZn | 0-4000 | 36 | 1-42 | FI, FCE, BWG |
| Walk et al. (2015) | UK | Europe | IZn | 0-3500 | 80 | 1-20 | FI, FCE, BWG, Blood Zn |
| Walk et al. (2013) | UK | Europe | IZn | 0-3500 | 48 | 1-21/1-42 | FI, FCE, BWG, Blood Zn |
| Wang et al. (2011) | China | Asia | OZn | 0-1200 | 48 | 1-28 | FI, FCE, BWG |
| Williams et al. (2005) | USA | North America | IZn | 0-2000 | 35 | 1-19 | FI, FCE, BWG, Blood Zn |
| Wedekind et al. (1994) | USA | North America | IZn | 0-80 | 32 | 1-42 | FI, FCE, BWG, Blood Zn |

DOS - Duration of supplementation; d - day; NZn - Nano zinc; ADFI - Average daily feed intake; F/G feed – to - gain ratio,; ADG – Average daily gain

***Table 1b.*** *Breed and experimental design of studies in the thirty articles included in the meta-analysis*

| **Reference** | **Breed** | **APBE** | **IBW (kg)** | **Number of treatment** | **Replication** | **Pigs/ replicate** | **Number of pigs** | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Expt groups | Ctl group |
| Diao et al. (2021) | Duroc x landrace x Yorkshire | - | 8.81 | 4 | 6 | 4 | 72 | 24 |
| Hill et al. (2014) | [Yorkshire × Landrace] × PIC | 18 | - | 10 | 10 | 5 | 450 | 50 |
| Schell and Kornegay (1996) | Yorkshire, Duroc × Hampshire | 26 | 6.63 | 4 | 4 | 5 | 60 | 20 |
| van Heugten et al. (2013) | [Landrace × Yorkshire] × [Hampshire × Duroc]) | 21 | 6.45 | 6 | 4 | 4 | 80 | 16 |
| Zhang et al. (2020) | Duroc × Landrace × Yorkshire | 28 | 8.92 | 5 | 6 | 6 | 144 | 36 |
| Broom et al. (2006) | Duroc × Landrace × Large White | 23 | 6.80 | 4 | 8 | 7 or 8 | 156 | 52 |
| Buff et al. (2005) | - | 21 | 6.20 | 5 | 10 | 1 | 40 | 10 |
| Hollis et al. (2005) | - | 20.6 | 6.30 | 8 | 26 | 4 or 5 | 492 | 123 |
| Hu et al. (2012) | Duroc × Landrace × Yorkshire | 27 | 7.20 | 5 | 6 | 6 | 144 | 36 |
| Hu et al. (2013) | Duroc × Landrace × Yorkshire | 21 | 6.12 | 5 | 6 | 7 | 168 | 42 |
| Li et al. (2016) | Duroc × Landrace × Yorkshire | 28 | 8.04 | 4 | 4 | 6 | 72 | 24 |
| Pei et al. (2019) | Duroc × Landrace × Large White | - | 9.37 | 5 | 3 | 10 | 120 | 30 |
| Pérez et al. (2011) | Duroc × Landrace × Yorkshire | 19 | 5.80 | 4 | 7 | 6 or 7 | 132 | 44 |
| Zhang et al. (2018b) | Duroc × Landrace × Large White | - | 8.47 | 6 | 6 | 6 | 180 | 36 |
| Wang et al. (2010) | Duroc × Landrace × Yorkshire | - | 7.68 | 4 | 3 | 10 | 90 | 30 |
| Carlson et al. (2004) | PIC: C22 × TF4 | 17 | 5.14 | 6 | 17 | 3 | 255 | 51 |
| Cho et al. (2015) | Duroc × Landrace × Yorkshire | 21 | 6.50 | 4 | 7 | 5 | 105 | 35 |
| Hahn and Baker (1993) | Yorkshire, Duroc × Hampshire | 28 | 6.20 | 5 | 3 | 6 | 72 | 18 |
| Han and Thacker (2010) | Duroc × Landrace × Yorkshire | 24 | 6.28 | 5 | 3 | 10 | 120 | 30 |
| Lei and Kim (2018) | Duroc × Landrace × Yorkshire | 28 | 7.42 | 6 | 8 | 4 | 160 | 32 |
| Mavromichalis et al. (2001) | - | 15 | 5.20 | 5 | 5 | 6 | 120 | 30 |
| Milani et al. (2017) | - | 21 | 5.89 | 5 | 8 | 4 | 128 | 32 |
| Molist et al. (2011) | (Large White × Landrace) × Pietrain | 21 | 6·70 | 4 | 8 | 2 | 48 | 16 |
| Namkung et al. (2006) | Yorkshire | 16-19 | 5.90 | 3 | 6 | 10 | 120 | 60 |
| Poulsen (1995) | | 28 | - | 6 | 6 | 6 | 180 | 36 |
| Walk et al. (2015) | PIC337 | 28 | 9.50 | 9 | 4 | 20 | 640 | 80 |
| Walk et al. (2013) | Duroc × Landrace × Large White | 21 | 7.10 | 6 | 8 | 6 | 240 | 48 |
| Wang et al. (2011) | Rongchang | 28 | 8.40 | 4 | 6 | 8 | 144 | 48 |
| Williams et al. (2005) | Yorkshire, Duroc × Landrace × Yorkshire | 18 | 5.70 | 6 | 5 | 7 | 175 | 35 |
| Wedekind et al. (1994) | Yorkshire x Landrace x Hampshire x Duroc | 28 | - | 6 | 4 | 8 | 160 | 32 |

IBW - Initial body weight; APBE - Age of pigs at the beginning of the experiment; PIC - Pig Improvement Company

## Results

### *Characteristics of included studies*

1200 studies that evaluated the impacts of Zn supplementation on performance of weaned pigs were identified, of which 30 articles were considered suitable for the meta-analysis (*Tables 1a and b and Fig. 1*). The articles utilised for the analysis span for 28 years (1993-2021). 43% of the articles published between 1993 and 2010 and 57% were published after 2010 (*Table 2*). The most commonly used Zn additives were ZnO, $ZnSO_4$, Zn-met, ZnONP, and the least used Zn additives were ZnOMMT, ZnAAch, and ZnLact. Majority of the studies utilised for the analysis were performed in China, USA, Korea, and UK. Inorganic Zn source (64.29%) was the most used, followed with organic Zn sources (28.57%), and the least used was ZnONP (7.14%). Most of the studies included in the meta-analysis fed Zn for more than 21 days.

### *Growth performance and blood Zn concentrations*

*Tables 3 and 4* show that Zn had a small effect on ADFI (SMD = 0.33; 0.23 to 0.44) and F/G (SMD = 0.18; 0.05 to 0.30) in weaned pigs. Dietary Zn supplementation for ≤ 21 days had a moderate effect on ADFI, while Zn supplementation for > 21 days had a small effect on ADFI. Zn form and NPT had small impacts on ADFI in weaned pigs. SL at 1001 – 1500 and 2501 – 3000 mg/kg feed had moderate effects on ADFI while SL at 2001 – 2500 mg/kg feed had a large effect on ADFI. However, SL between 1 and 1000 mg/kg feed had small effects on ADFI in weaned pigs. DOS, NPT and SL had small effects on F/G. The magnitude of effect sizes for F/G was large in pigs fed nano Zn (SMD = 0.62; 0.17 to 1.06) and small in those fed organic Zn (SMD = 0.14; -0.11 to 0.39) and inorganic Zn (SMD = 0.15; 0.01 to 0.29). Pooled results as presented in *Table 5* show that Zn supplementation had a moderate magnitude of effect on ADG (SMD = 0.63; 0.49 to 0.77). In terms of ADG, studies that used > 40 pigs in each treatment group and fed Zn for ≤ 21 days had large effect estimates, while those studies that used < 40 pigs in each treatment group and fed Zn for >21 days had moderate effect estimates. The magnitude of effect sizes was large in pigs fed nano Zn (SMD = 1.04; 0.17 to 1.92) and inorganic Zn (SMD = 0.84; 0.66 to 1.02), and small in pigs offered organic Zn (SMD = 0.21; -0.03 to 0.44). SL at levels > 1000 mg/kg feed had a large effect on ADG. However, SL at ≤ 1000 mg/kg feed had small effects on ADG, except for SL at 251-500 mg/kg feed that had a moderate effect on ADG. *Table 6* shows that Zn had a large effect on blood Zn levels (SMD = 2.83; 2.13 to 3.52). DOS, NPT, SL and Zn form had large effects on blood Zn.

### *Heterogeneity and publication bias*

*Tables 2 to 5* show evidence of significant heterogeneity ($I^2$) among the articles included in the meta-analysis, and $I^2$ ranged from 85 to 98%. Subgroup analysis results as shown in *Tables 2-5* could not resolve the problem of significant heterogeneity. *Table 7* found significant linear relationships between studied moderators (DOS, LS, and Zn form) and ADFI in pigs. There is significant treatment-predictor interaction effect between DOS and Zn form ($Q = 16.91$, $P < 0.001$; $R^2 = 27\%$) and SL and Zn form ($Q = 25.62$, $P < 0.001$; $R^2 = 23\%$) for ADFI. There was no significant linear relationship between NPT and ADFI. NPT and its interactions with SL, DOS, and Zn form were predictors of Zn effect on F/G in weaned pigs. There were also significant linear relationships existed between ADG and moderators (DOS and Zn form). Significant

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treatment-predictors interaction effect was found between BWG and modifiers (DOS*Zn form, SL*NPT, and SL*Zn form). Our results suggest that modifiers and their interactions were significant predictors of the effect of Zn on blood Zn levels in weaned pigs. Publication bias was evaluated and presented as funnel graphs (*Fig. 2a-d*). The funnel plots were asymmetry, indicating the presence of publication bias among the selected articles. The Rosenberg’s Nfs for the database were 456 (ADFI), 5194 (F/G), 39680 (ADG), and 14579 (blood Zn), and were higher than the calculated values of 685, 655, 705 and 275, respectively.

***Table 2.*** *Definition of variables and their % distribution in the matrix*

| Variables | levels | Definition | % distribution in the matrix |
|---|---|---|---|
| **Study country** | China | | 26.67 |
| | USA | United State of America | 36.67 |
| | UK | United Kingdom | 10 |
| | Taiwan | | 3.33 |
| | Korea | | 10 |
| | Brazil | | 3.33 |
| | Spain | | 3.33 |
| | Canada | | 3.33 |
| | Denmark | | 3.33 |
| **Continent** | Asia | | 40.00 |
| | North America | | 40.00 |
| | Europe | | 16.67 |
| | South America | | 3.33 |
| **Zinc sources** | ZnSO4 | Zinc sulphate | 13.57 |
| | ZnO | Zinc oxide | 38.08 |
| | mZnO | Modified zinc oxide | |
| | ZnONP | Zinc oxide nanoparticle | 8.49 |
| | ZnOMMT | Montmorillonite zinc oxide | 1.99 |
| | Zn-Prot | Zinc protein | 5.08 |
| | ZnAAco | Zinc amino acid complex | 3.39 |
| | ZnAAch | Zinc amino acid chelate | 1.99 |
| | ZnLact | Zinc lactate | 1.99 |
| | ZnGly | Zinc glycine | 3.39 |
| | ZnMet | Zinc methionine | 10.17 |
| | ZnLys | Zinc lysine | 3.39 |
| | TBZC | Tetrabasic zinc chloride | 3.39 |
| | ZnPS | Zinc polysaccharide | 5.08 |
| **Zn form** | IZn | Inorganic zinc | 64.29 |
| | OZn | Organic zinc | 28.57 |
| | NZn | Nano zinc | 7.14 |
| **DOS (day)** | ≤ 21 | | 40 |
| | >21 | | 60 |
| **SL (mg/kg)** | 1 - 100 | | 13.24 |
| | 101 - 250 | | 11.76 |
| | 251 - 500 | | 10.29 |
| | 501 - 1000 | | 13.24 |
| | 1001 - 1500 | | 5.88 |
| | 1501 - 2000 | | 16.18 |
| | 2001 - 2500 | | 8.82 |
| | 2501 - 3000 | | 16.18 |
| | >3000 | | 4.41 |
| **Publication year** | ≤ 2010 (1993-2010) | | 43.33 |
| | >2010 (2011-2021) | | 56.67 |

***Table 3.*** *Average daily feed intake of weaned pigs on dietary Zn supplementation*

| **Pooled/ Sub analysis** | **SMD** | **95% CI** | **SE** | **p-Val** | **Heterogeneity (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Q | df | p-Val | $I^2$ |
| Pooled | 0.33 | 0.23, 0.44 | 0.05 | < 0.001 | 915.15 | 134 | < 0.001 | 85 |
| DOS (days) | | | | | | | | |
| ≤ 21 | 0.62 | 0.37, 0.86 | 0.13 | < 0.001 | | | | |
| > 21 | 0.20 | 0.10, 0.30 | 0.05 | < 0.001 | | | | |
| SL (mg/kg) | | | | | | | | |
| 1 - 100 | 0.12 | -0.07, 0.30 | 0.09 | 0.224 | | | | |
| 101 - 250 | 0.10 | -0.24, 0.43 | 0.17 | 0.568 | | | | |
| 251 - 500 | 0.24 | 0.03, 0.44 | 0.10 | 0.023 | | | | |
| 501 - 1000 | 0.17 | -0.24, 0.57 | 0.21 | 0.424 | | | | |
| 1001 - 1500 | 0.58 | 0.38, 0.78 | 0.10 | < 0.001 | | | | |
| 1501 - 2000 | 0.42 | 0.06, 0.78 | 0.19 | 0.024 | | | | |
| 2001 - 2500 | 0.93 | 0.54, 1.32 | 0.20 | < 0.001 | | | | |
| 2501 - 3000 | 0.64 | 0.29, 0.99 | 0.18 | < 0.001 | | | | |
| > 3000 | 0.40 | -0.13, 0.93 | 0.27 | 0.137 | | | | |
| Zn form | | | | | | | | |
| Inorganic | 0.49 | 0.36, 0.62 | 0.07 | < 0.001 | | | | |
| Organic | 0.06 | -0.09, 0.20 | 0.08 | 0.466 | | | | |
| Nano | 0.34 | -0.37, 1.05 | 0.36 | 0.352 | | | | |
| NPT | | | | | | | | |
| < 40 | 0.30 | 0.15, 0.45 | 0.08 | < 0.001 | | | | |
| > 40 | 0.38 | 0.24, 0.52 | 0.07 | < 0.001 | | | | |

SL - Supplementation level; DOS - Duration of supplementation; NPT - Number of pigs in each treatment group; SMD - Standardised mean difference; SE - Standard error; Q - Cochran statistic; I - Confidence interval; DF - Degree of freedom; $I^2$ - Inconsistency index

***Table 4.*** *Feed to gain ratio of weaned pigs on dietary Zn supplementations*

| **Pooled/ Subanalysis** | **SMD** | **95% CI** | **SE** | **p-Val** | **Heterogeneity (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Q | df | p-Val | $I^2$ |
| Pooled | 0.18 | 0.05, 0.30 | 0.06 | 0.005 | 1140.44 | 128 | < 0.001 | 89 |
| DOS (day) | | | | | | | | |
| ≤ 21 | 0.21 | -0.01, 0.43 | 0.11 | 0.060 | | | | |
| > 21 | 0.16 | 0.01, 0.30 | 0.07 | 0.032 | | | | |
| SL (mg/kg) | | | | | | | | |
| 1 - 100 | 0.40 | 0.02, 0.78 | 0.19 | 0.041 | | | | |
| 101 - 250 | 0.03 | -0.13, 0.20 | 0.08 | 0.698 | | | | |
| 501 - 1000 | 0.05 | -0.23, 0.33 | 0.14 | 0.733 | | | | |
| 1001 - 1500 | 0.08 | -0.18, 0.35 | 0.13 | 0.542 | | | | |
| 1501 - 2000 | 0.20 | -0.18, 0.58 | 0.19 | 0.309 | | | | |
| 2001 - 2500 | 0.15 | -0.07, 0.37 | 0.11 | 0.188 | | | | |
| 2501 - 3000 | 0.01 | -0.24, 0.27 | 0.13 | 0.919 | | | | |
| > 3000 | -0.07 | -0.56, 0.41 | 0.25 | 0.762 | | | | |
| Zn form | | | | | | | | |
| Inorganic | 0.15 | 0.01, 0.29 | 0.07 | 0.043 | | | | |
| Organic | 0.14 | -0.11, 0.39 | 0.13 | 0.273 | | | | |
| Nano | 0.62 | 0.17, 1.06 | 0.23 | 0.006 | | | | |
| NPT | | | | | | | | |
| < 40 | 0.08 | -0.04, 0.19 | 0.06 | 0.191 | | | | |
| > 40 | 0.38 | 0.14, 0.62 | 0.062 | 0.005 | | | | |

SL - Supplementation level; DOS - Duration of supplementation; NPT - Number of pigs in each treatment group; SMD - Standardised mean difference; SE - Standard error; Q - Cochran statistic; CI - Confidence interval; DF - Degree of freedom; $I^2$ - Inconsistency index

***Table 5.*** *Average daily gain of weaned pigs on dietary Zn supplementations*

| **Pooled/ Subanalysis** | **SMD** | **95% CI** | **SE** | **p-Val** | **Heterogeneity (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Q | df | p-Val | $I^2$ |
| Pooled | 0.63 | 0.49, 0.77 | 0.07 | < 0.001 | 1737.87 | 138 | < 0.001 | 92 |
| DOS (days) | | | | | | | | |
| ≤ 21 | 0.92 | 0.57, 1.26 | 0.18 | < 0.001 | | | | |
| > 21 | 0.52 | 0.36, 0.67 | 0.08 | < 0.001 | | | | |
| SL (mg/kg) | | | | | | | | |
| 1 - 100 | 0.48 | 0.14, 0.81 | 0.17 | 0.006 | | | | |
| 101 - 250 | 0.26 | -0.10, 0.61 | 0.18 | 0.161 | | | | |
| 251 - 500 | 0.51 | 0.26, 0.76 | 0.13 | < 0.001 | | | | |
| 501 - 1000 | 0.20 | -0.29, 0.68 | 0.25 | 0.424 | | | | |
| 1001 - 1500 | 0.91 | 0.62, 1.19 | 0.15 | < 0.001 | | | | |
| 1501 - 2000 | 0.84 | 0.29, 1.38 | 0.28 | 0.003 | | | | |
| 2001 - 2500 | 1.11 | 0.85, 1.36 | 0.13 | < 0.001 | | | | |
| 2501 - 3000 | 0.98 | 0.53, 1.43 | 0.23 | < 0.001 | | | | |
| > 3000 | 0.82 | -0.05, 1.70 | 0.45 | 0.066 | | | | |
| Zn form | | | | | | | | |
| Inorganic | 0.84 | 0.66, 1.02 | 0.09 | < 0.001 | | | | |
| Organic | 0.21 | -0.03, 0.44 | 0.12 | 0.081 | | | | |
| Nano | 1.04 | 0.17, 1.92 | 0.45 | 0.019 | | | | |
| NPT | | | | | | | | |
| < 40 | 0.53 | 0.34, 0.72 | 0.10 | < 0.001 | | | | |
| > 40 | 0.86 | 0.63, 1.10 | 0.12 | < 0.001 | | | | |

SL - Supplementation level; DOS - Duration of supplementation; NPT - Number of pigs in each treatment group; SMD - Standardised mean difference; SE - Standard error; Q - Cochran statistic; CI - Confidence interval; DF - Degree of freedom; $I^2$ - Inconsistency index

***Table 6.*** *Blood Zn concentrations of weaned pigs on dietary Zn supplementations*

| **Pooled/ Subanalysis** | **SMD** | **95% CI** | **SE** | **p-Val** | **Heterogeneity (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Q | df | p-Val | $I^2$ |
| Pooled | 2.83 | 2.13, 3.52 | 0.35 | < 0.001 | 2609.80 | 52 | < 0.001 | 98 |
| DOS (days) | | | | | | | | |
| ≤ 21 | 6.64 | 5.15, 8.12 | 0.76 | < 0.001 | | | | |
| > 21 | 0.96 | 0.31 , 1.60 | 0.33 | 0.004 | | | | |
| SL (mg/kg) | | | | | | | | |
| 1 - 100 | -0.91 | -2.59, 0.78 | 0.86 | 0.291 | | | | |
| 251 - 500 | 1.73 | 0.85, 2.61 | 0.45 | < 0.001 | | | | |
| 501 - 1000 | 1.20 | 0.28, 3.71 | 0.877 | 0.023 | | | | |
| 1501 - 2000 | 3.75 | 1.88, 5.63 | 10.96 | < 0.001 | | | | |
| 2501 - 3000 | 3.76 | 1.88, 5.64 | 0.96 | < 0.001 | | | | |
| > 3000 | 8.03 | 2.71, 13.34 | 2.71 | 0.003 | | | | |
| Zn form | | | | | | | | |
| Inorganic | 3.57 | 2.52, 4.62 | 0.54 | < 0.001 | | | | |
| Organic | 1.36 | 0.86, 1.87 | 0.26 | < 0.001 | | | | |
| NPT | | | | | | | | |
| < 40 | 2.44 | 1.62, 3.26 | 0.42 | < 0.001 | | | | |
| > 40 | 4.27 | 2.87, 5.66 | 0.71 | < 0.001 | | | | |

SL - Supplementation level; DOS - Duration of supplementation; NPT - Number of pigs in each treatment group; SMD - Standardised mean difference; SE - Standard error; Q - Cochran statistic; CI - Confidence interval; DF - Degree of freedom; $I^2$ - Inconsistency index

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***Table 7.*** *Meta-regression comparing the associations between moderators and measured outcomes*

| Outcomes | Moderators | $Q_M$ | df | $R^2$ (%) | p-Val |
|---|---|---|---|---|---|
| ADFI | DOS | 11.60 | 1 | 11 | 0.0007 |
| | SL | 16.30 | 8 | 7 | 0.0378 |
| | Zn form | 12.50 | 2 | 9 | 0.0020 |
| | NPT | 0.386 | 1 | 0 | 0.535 |
| | DOS * Zn form | 16.91 | 2 | 27 | 0.0002 |
| | SL* Zn form | 25.62 | 8 | 23 | 0.0012 |
| F/G | DOS | 0.15 | 1 | 0 | 0.700 |
| | SL | 8.46 | 8 | 2 | 0.390 |
| | Zn form | 3.76 | 2 | 1 | 0.152 |
| | NPT | 6.32 | 1 | 4 | 0.012 |
| | NPT * SL | 71.65 | 8 | 46 | 2.30E-12 |
| | NPT * DOS | 24.09 | 1 | 22 | 9.21E-07 |
| | NPT * Zn form | 5.99 | 1 | 13 | 0.014 |
| ADG | DOS | 5.11 | 1 | 3 | 0.0238 |
| | SL | 12.50 | 8 | 3 | 0.1320 |
| | Zn form | 16.00 | 2 | 10 | 0.0003 |
| | NPT | 3.46 | 1 | 2 | 0.0628 |
| | DOS * Zn form | 15.63 | 2 | 20 | 0.00040 |
| | SL * NPT | 21.45 | 8 | 19 | 0.00604 |
| | SL * Zn form | 8.95 | 2 | 8 | 0.0114 |
| Blood Zn | DOS | 37.60 | 1 | 42 | 8.81E-10 |
| | SL | 36.30 | 8 | 36 | 1.56E-05 |
| | Zn form | 3.49 | 1 | 6 | 0.062 |
| | NPT | 1.80 | 1 | 2 | 0.179 |
| | DOS * SL | 9.14 | 5 | 56 | 1.04E-01 |
| | DOS * NPT | 0.89 | 1 | 44 | 3.46E-01 |
| | DOS * Zn form | 0.54 | 1 | 42 | 4.63E-01 |
| | SL * NPT | 0.89 | 3 | 31 | 8.29E-01 |
| | SL * Zn form | 1.27 | 4 | 31 | 8.66E-01 |

* - Interaction; ADFI - Average daily feed intake; F/G - Feed to gain ratio; ADG - Average daily gain; DOS - Duration of supplementation; SL - Supplementation level; NPT - Number of pigs per treatment group; P - probability value; $Q_M$ - Coefficient of moderators, DF - Degree of freedom, $R^2$ - Amount of heterogeneity explained by the moderators

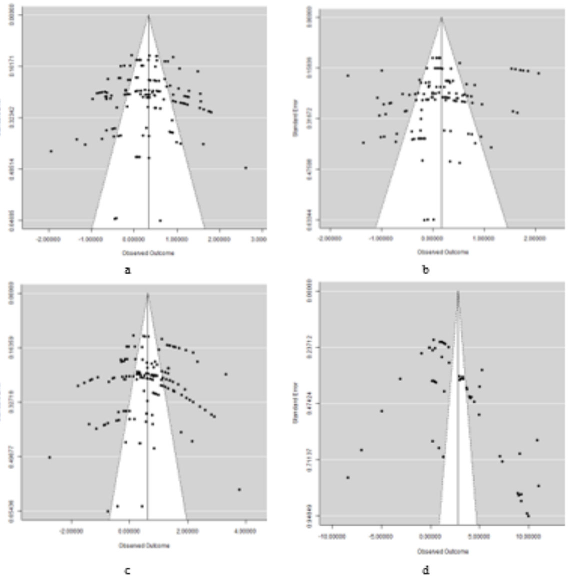

***Figure 2.*** *Funnel graphs of the effect of zinc supplementation on (a) ADFI, (b) F/G, (c) ADG, and (d) blood Zn concentration in weaned pigs*

## Discussion

The increased use of Zn supplementation in the diets of weaned pig could be attributed to the campaign to reduce the use of antibiotics in animal production industry. The fact that more than 60% of the studies included in the meta-analysis are from China and USA is consistent with the recent report that China and USA are the leading countries in global pig production (Hu and Cowling, 2020). Most of the papers included in this study used ZnO followed by $ZnSO_4$ and Zn-met, and this agrees with Abd El-Hack et al. (2017) that ZnO and $ZnSO_4$ were the two inorganic feed-grade Zn source used in the animal production industry. The observed increase in the number of studies that used Zn-met in comparison with other organic sources in the current study support the results of Rahman et al. (2002) that Zn-met was better than inorganic Zn sources (ZnO and $ZnSO_4$) in terms of bioavailability, and has become part of recent feed additives utilised in the pig industry (Jahanian et al., 2008).

The results of this meta-analysis indicate that zinc supplementation had a moderate effect on ADG in weaned pigs. The enhanced ADG in weaned pigs fed Zn-enriched diets could be attributed to the ability of Zn enhance cellular immunity (Liu et al., 2014) as well as promotes muscle cell proliferation and differentiation (Fernandez et al., 2014). This is similar to others (Broom et al., 2006; Diao et al., 2021), who reported 5 - 12% increase in ADG in weaned pigs fed diets supplemented with Zn in comparison with controls. This meta-analysis shows that zinc supplementation has a large effect on blood Zn concentrations in weaned pigs, implying that dietary Zn may have reached a point in the body where excretion cannot keep pace with absorption, resulting in progressive increases in blood Zn (Hill et al., 2000).

The results of this meta-analysis showed moderate to large effect on ADFI in weaned pigs fed high dose of Zn (2001-3000 mg/kg feed) for ≤ 21 days. Furthermore, inclusion of high doses of Zn in the diets of weaned for ≤ 21 days had large impact on ADG. This agrees with Daio et al. (2021), who reported the positive effect of Zn in pigs during weaning when the pigs are vulnerable to nutritional, environmental and psychological stress leading to alterations in intestinal integrity and immune response, causing scouring and poor growth (Campbell et al., 2013). There is evidence that nano and organic Zn sources are more bioavailable than Zn from inorganic sources (Hill et al., 2014; Daio et al., 2021). In this meta-analysis, the impact of Zn on growth traits was evident in weaned pigs fed nanosized ZnO; supporting the concept that nano Zn has higher bioavailability, and can meet the requirements of weaned pigs at lower dietary concentrations.

There is evidence of high heterogeneity and meta-regression analysis found that tested moderators and their interactions accounted most of the sources of heterogeneity. Results showed that Zn form is a predictor of Zn effect on BWG (Pierozan et al., 2016; Cemin et al., 2019; Daio et al., 2021). Our model revealed that NPT and SL were not significant predictors of Zn intervention on ADFI, blood Zn and ADG in weaned pigs. In addition, there were no relationships between F/G and aspects of moderators. The effect of factors such as diet composition, sex, breed, stocking density, and others (Pierozan et al., 2016), not examined in this study could have accounted for the residual heterogeneity not explained by the model. There is evidence of publication bias in this meta-analysis and this is of no consequence as the Nfs number was higher than the thresholds needed to declare the mean effect size significant, despite the presence of publication bias (Jennions et al., 2013).

## Conclusion

Results demonstrated the addition of zinc in weaned pig diets had large effect on blood Zn, moderate effect on average daily gain and small effect on average daily feed intake and feed – to – gain ratio in weaned pigs despite the inconsistent results in the literature. Incorporation of high doses of zinc in weaned pig diets increased ADG and blood Zn. However, the use high doses of zinc in the diets of weaned pigs should be discouraged because of environmental pollution resulting from zinc excretion. The current study demonstrated the presence of significant heterogeneity among studies included in the meta-analysis and meta-regression analysis showed that tested moderator variables accounted for most of the sources of variations. The present study showed that Zn source influenced the outcomes of the meta-analysis.

## REFERENCES

[1] Abd El-Hack, M. E., Alagawany, M., Arif, M., Chaudhry, M. T., Emam, M., Patra, A. (2017): Organic or inorganic zinc in poultry nutrition: a review. – World's Poult Science Journal 73: 904-915.

[2] Broom, L. J., Miller, H. M., Kerr, K. G., Knapp, J. S. (2006): Effects of zinc oxide and *Enterococcus faecium* SF68 dietary supplementation on the performance, intestinal microbiota and immune status of weaned piglets. – Res Vet Sci 80: 45-54.

[3] Buff, C. E., Bollinger, D. W., Ellersieck, M. R., Brommelsiek, W. A., Veum, T. L. (2005): Comparison of growth performance and zinc absorption, retention, and excretion in weanling pigs fed diets supplemented with zinc-polysaccharide or zinc oxide. – Journal of Animal Science 83: 2380-2386.

[4] Campbell, J. M., Crenshaw, J. D., Polo, J. (2013): The biological stress of early weaned piglets. – Journal of Animal Science and Biotechnology 4: 45-48.

[5] Carlson, M. S., Boren, C. A., Wu, C., Huntington, C. E., Bollinger, D. W., Veum, T. L. (2004): Evaluation of various inclusion rates of organic zinc either as polysaccharide or proteinate complex on the growth performance, plasma, and excretion of nursery pigs. – Journal of Animal Science 82: 1359-1366.

[6] Cemin, H. S., Carpenter, C. B., Woodworth, J. C., Tokach, M. D., Dritz, S. S., DeRouchey, J. M., Goodband, R. D., Usry, J. L. (2019): Effects of zinc source and level on growth performance and carcass characteristics of finishing pigs. – Translational Animal Science 3: 742-748.

[7] Cho, J. H., Upadhaya, S. D., Kim, I. H. (2015): Effects of dietary supplementation of modified zinc oxide on growth performance, nutrient digestibility, blood profiles, fecal microbial shedding and fecal score in weanling pigs. – Animal Science Journal 86: 617-623.

[8] Cohen, J. (1992): Statistical Power Analysis. – Current Direction Psychological Science 3: 98-101.

[9] Diao, H., Yan, J., Li, S., Kuang, S., Wei, X., Zhou, M., Zhang, J., Huang, C., He, P., Tang, W. (2021): Effects of dietary zinc sources on growth performance and gut health of weaned piglets. – Frontiers in Microbiology 12: 771617.

[10] Fernandez, M. V. S., Pearce, S. C., Gabler, N. K., Patience, J. F., Baumgard, L. H. (2014): Effects of supplemental zinc amino acid complex on gut integrity in heat-stressed growing pigs. – Animal 8: 43-50.

[11] Hahn, J. D., Baker, D. H. (1993): Growth and plasma zinc responses of young pigs fed pharmacologic levels of zinc. – Journal of Animal Science 71: 3020-3024.

[12] Han, Y., Thacker, P. A. (2010): Effects of antibiotics, zinc oxide or a rare earth mineral-yeast product on performance, nutrient digestibility and serum parameters in weanling pigs. – Asian-Australasian Journal of Animal Science 23: 1057-1065.

[13] Hedges, L. V., Pigott, T. D. (2004): The power of statistical tests for moderators in meta-analysis. – Psychological Methods 9: 426-445.

[14] Higgins, J. P. T., Thompson, S. G. (2002): Quantifying heterogeneity in a meta-analysis. – Statistical Medicine 21: 1539-1558.

[15] Hill, G. M., Cromwell, G. L., Crenshaw, T. D., Dove, C. R., Ewan, R. C., Knabe, D. A., Lewis, A. J., Libal, G. W., Mahan, D. C., Shurson, G. C., Southern, L. L., Veum, T. L. (2000): Growth promotion effects and plasma changes from feeding high dietary concentrations of zinc and copper to weanling pigs (regional study). – Journal of Animal Science 78: 1010-1016.

[16] Hill, G. M., Mahan, D. C., Jolliff, J. S. (2014): Comparison of organic and inorganic zinc sources to maximize growth and meet the zinc needs of the nursery pig. – Journal of Animal Science 92: 1582-1594.

[17] Hollis, G. R., Carter, S. D., Cline, T. R., Crenshaw, T. D., Cromwell, G. L., Hill, G. M., Kim, S. W., Lewis, A. J., Mahan, D. C., Miller, P. S., Stein, H. H., Veum, T. L. (2005): Effects of replacing pharmacological levels of dietary zinc oxide with lower dietary levels of various organic zinc sources for weanling pigs. – Journal of Animal Science 83: 2123-2129.

[18] Hu, C. H., Gu, E. Y., Luan, Z. S., Song, J., Zhu, K. (2012): Effects of montmorillonite–zinc oxide hybrid on performance, diarrhea, intestinal permeability and morphology of weanling pigs. – Animal Feed Science and Technology 177: 108-115.

[19] Hu, C. H., Xiao, K., Song, J., Luan, L. S. (2013): Effects of zinc oxide supported on zeolite on growth performance, intestinal microflora and permeability, and cytokines expression of weaned pigs. – Animal Feed Science and Technology 181: 65-71.

[20] Hu, Y. J., Cowling, B. J. (2020): Reducing antibiotic use in livestock, China. – Bulletin World Health Organ 98: 360-361.

[21] Huang, Y. L., Lu, L., Li, S. F., Luo, X. G., Liu, B. (2009): Relative bioavailabilities of organic zinc sources with different chelation strengths for broilers fed a conventional corn soybean meal diet. – Journal of Animal Science 87: 2038-2046.

[22] Jahanian, R., Nassirimoghaddam, H., Rezaei, A., Haghparast, A. R. (2008): The influence of dietary zinc-methionine substitution for zinc sulphate on broiler chick performance. – Journal of Biological Science 8: 321-327.

[23] Jennions, M. D., Lortie, C. J., Rosenberg, M. S., Rothstein, H. R. (2013): Chapter 4: Publication and related bias. – In: Koricheva, J., Gurevitch, J., Mengersen, K. (eds.) Handbook of meta-analysis in Ecology and Evolution. Princeton University Press, Princeton, and London, pp. 207-236.

[24] Koricheva, J., Gurevitch, J., Mengersen, K. (2013): Handbook of meta-analysis in ecology and evolution. – Princeton University Press, Princeton and Oxford, UK.

[25] Lean, I. J., Rabiee, A. R., Duffield, T. F., Dohoo, I. R. (2009): Invited review: use of meta-analysis in animal health and reproduction: methods and applications. – Journal of Dairy Science 92: 3545-3565.

[26] Lean, I. J., Thompson, J. M., Dunshea, F. R. (2014): A meta-analysis of zilpaterol and ractopamine effects on feedlot performance, carcass traits and shear strength of meat in cattle. – PLoS ONE 9: e115904.

[27] Lei, X. J., Kim, I. H. (2018): Low dose of coated zinc oxide is as effective as pharmacological zinc oxide in promoting growth performance, reducing fecal scores, and improving nutrient digestibility and intestinal morphology in weaned pigs. – Animal Feed Science and Technology 245: 117-125.

[28] Li, X., Yin, J., Li, D., Chen, X., Zang, J., Zhou, X. (2006): Dietary supplementation with zinc oxide increases Igf-I and Igf-I receptor gene expression in the small intestine of weanling piglets. – Journal of Nutrition 136: 1786-1791.

[29] Li, M., Huang, J., Tsai, Y., Mao, S., Fu, C., Lien, T. (2016): Nanosize of zinc oxide and the effects on zinc digestibility, growth performances, immune response and serum parameters of weanling piglets. – Animal Science Journal 87: 1379-1385.

[30] Liu, P., Pieper, R., Tedin, L., Martin, L., Meyer, W., Rieger, J., Plendl, J., Vahjen, W., Zentek, J. (2014): Effect of dietary zinc oxide on jejunal morphological and immunological characteristics in weaned piglets. – Journal of Animal Science 92: 5009-5018.

[31] Martínez, M. M., Link, J. E., Hill, G. M. (2005): Dietary pharmacological or excess zinc and phytase effects on tissue mineral concentrations, metallothionein, and apparent mineral retention in the newly weaned pig. – Biological Trace Element Research 105: 97-115.

[32] Mavromichalis, I., Webel, D. M., Parr, E. N., Baker, D. H. (2001): Growth-promoting efficacy of pharmacological doses of tetrabasic zinc chloride in diets for nursery pigs. – Canadian Journal of Animal Science 81: 387-391.

[33] Milani, N. C., Sbardella, M., Ikeda, N. Y., Arno, A., Mascarenhas, B. C., Miyada, V. S. (2017): Dietary zinc oxide nanoparticles as growth promoter for weanling pigs. – Animal Feed Science and Technology 227: 13-23.

[34] Molist, F., Hermes, R. G., de Segura, A. G., Martín-Orúe, S. M., Gasa, J., Manzanilla, E. G., Pérez, J. F. (2011): Effect and interaction between wheat bran and zinc oxide on productive performance and intestinal health in post-weaning piglets. – British Journal of Nutrition 105: 1592-1600.

[35] Namkung, H., Gong, J., Yu, H., de Lange, C. F. M. (2006): Effect of pharmacological intakes of zinc and copper on growth performance, circulating cytokines and gut microbiota of newly weaned piglets challenged with coliform lipopolysaccharides. – Canadian Journal of Animal Science 86: 511-52.

[36] National Research Council (1998): Nutrient Requirements of Swine. – 10th edition, National Academy Press, Washington, DC.

[37] Ogbuewu, I. P., Modisaojang-Mojanaga, M. M. C., Mokolopi, B. G., Mbajiorgu, C. A. (2022): A meta-analysis of responses of broiler chickens to dietary zinc supplementation: feed intake, feed conversion ratio and average daily gain. – Biological Trace Element Research 10.1007/s12011-022-03320-5.

[38] Pei, X., Xiao, Z., Liu, L., Wang, G., Tao, W., Wang, M., Zou, J., Leng, D. (2019): Effects of dietary zinc oxide nanoparticles supplementation on growth performance, zinc status, intestinal morphology, microflora population, and immune response in weaned pigs. – Journal of Science, Food and Agriculture 99: 1366-1374.

[39] Pérez, V. G., Waguespack, A. M., Bidner, T. D., Southern, L. L., Fakler, T. M., Ward, T. L., Steidinger, M., Pettigrew, J. E. (2011): Additivity of effects from dietary copper and zinc on growth performance and fecal microbiota of pigs after weaning. – Journal of Animal Science 89: 414-425.

[40] Pierozan, C. R., Agostini, P. S., Gasa, J., Novais, A. K., Dias, C. P., Santos, R. S. K., Pereira, M., Nagi, J. G., Alves, J. B., Silva, C. A. (2016): Factors affecting the daily feed intake and feed conversion ratio of pigs in grow-finishing units: the case of a company. – Porcine Health Management 2: 7.

[41] Poulsen, H. D. (1995): Zinc oxide for weanling piglets. – Acta Agriculturae Scandinavica Section A Animal Science 45: 159-167.

[42] Rahman, M. M., Wahed, M. A., Fchs, G. J., Bayui, A. H., Alvarez, J. I. (2002): Synergetic effect of zinc and vitamin A on the biochemical indexes of vitamin A nutrition in children. – American Journal of Clinical Nutrition 1: 92-98.

[43] Schell, T. C., Kornegay, E. T. (1996): Zinc concentration in tissues and performance of weanling pigs fed pharmacological levels of zinc from ZnO, Zn-methionine, Zn-lysine, or $ZnSO_4$. – Journal of Animal Science 74: 1584-1593.

[44] Sterne, J. A. C., Harbord, R. M. (2004): Funnel plots in meta-analysis. – Stata Journal 4: 127-141.

[45] van Heugten, E., Spears, J. W., Kegley, E. B., Ward, J. D., Qureshi, M. A. (2003): Effects of organic forms of zinc on growth performance, tissue zinc distribution, and immune response of weanling pigs. – Journal of Animal Science 81: 2063-2071.

[46] Walk, C. I., Srinongkote, S., Wilcock, P. (2013): Influence of a microbial phytase and zinc oxide on young pig growth performance and serum minerals. – Journal of Animal Science 91: 286-291.

[47] Walk, C. L., Wilcock, P., Magowa, E. (2015): Evaluation of the effects of pharmacological zinc oxide and phosphorus source on weaned piglet growth performance, plasma minerals and mineral digestibility. – Animal 9: 1145-1152.

[48] Wallace, B. C., Lajeunesse, M. J., Dietz, G., Dahabreh, I. J., Trikalinos, T. A., Schmid, C. H., Gurevitch, J. (2016): OpenMEE: intuitive, open-source software for meta-analysis in ecology and evolutionary biology. – Methods Ecology and Evolution 8: 941-947.

[49] Wang, Y., Tang, J. W., Ma, W. Q., Feng, J., Feng, J. (2010): Dietary zinc glycine chelate on growth performance, tissue mineral concentrations, and serum enzyme activity in weanling piglets. – Biological Trace Element Research 133: 325-334.

[50] Wang, J. H., Wu, C. C., Feng, J. (2011): Effect of dietary antibacterial peptide and zinc-methionine on performance and serum biochemical parameters in piglets. – Czech Journal of Animal Science 56: 30-36.

[51] Wedekind, K. J., Lewis, A. J., Giesemann, M. A., Miller, P. J. (1994): Bioavailability of zinc from inorganic and organic sources for pigs fed corn-soybean meal diets. – Journal of Animal Science 72: 2681-2689.

[52] Williams, S. B., Southern, L. L., Bidner, T. D. (2005): Effects of supplemental dietary phytase and pharmacological concentrations of zinc on growth performance and tissue zinc concentrations of weanling pigs. – Journal of Animal Science 83: 386-392.

[53] Zhang, T. Y., Liu, J. L., Zhang, J. L., Zhang, N., Yang, X., Qu, H. X., Xi, L., Han, J. C. (2018a): Effects of dietary zinc levels on the growth performance, organ zinc content, and zinc retention in broiler chickens. – Brazilian Journal of Poultry Science 20: 127-132.

[54] Zhang, Y., Ward, T. L., Ji, F., Peng, C., Zhu, L., Gong, L., Dong, B. (2018b): Effects of zinc sources and levels of zinc amino acid complex on growth performance, haematological and biochemical parameters in weanling pigs. – Asian-Australasian Journal of Animal Science 31: 1267-1274.

[55] Zhang, G., Xia, T., Zhao, J., Liu, L., He, P., Zhang, S., Zhang, L. (2020): Moderate tetrabasic zinc chloride supplementation improves growth performance and reduces diarrhoea incidence in weaned pigs. – Asian-Australasian Journal of Animal Science 33: 264-276.

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