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Bridging Nutritional and Environmental Assessment Tools: A One Health Integration Using Zinc Supplementation in Weaned Pigs

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Abstract

Zinc is an essential trace mineral for livestock, but excessive use can contribute to ecotoxicity and antimicrobial resistance. The objective of this study was to assess the impact of different zinc oxide (ZnO) levels in diets for weaned pigs on growth performance, mortality, dietary zinc flow, and environmental impacts. A 6-week feeding trial with 432 weaned pigs assessed three dietary treatments: high ZnO (pharmaceutical levels), intermediate ZnO, and low ZnO (EU recommendation). Growth performance for the growing–finishing period was modeled using the NRC (2012), and dietary Zn intake and fecal Zn excretion were estimated. Environmental impacts were analyzed via life cycle assessment (LCA) using SimaPro LCA software. High ZnO improved growth performance and reduced mortality ($p < 0.05$), but increased nursery fecal zinc excretion, resulting in a total fecal Zn excretion per pig of 54,125 mg, 59,485 mg, and 106,043 mg for low-, intermediate-, and high-ZnO treatments, respectively. In the nursery phase, high-ZnO treatment had the greatest impact on environmental footprint, increasing freshwater ecotoxicity and marine ecotoxicity indicators by 59.6% and 57.9%, respectively. However, high-ZnO-fed pigs had a greater body weight at the end of the nursery phase and were predicted to achieve a higher growth rate per 130 kg market pig, with fewer days to market and by sparing feed. Therefore, high-ZnO-fed pigs had reduced environmental burdens, including global warming potential, ozone depletion, land use, and mineral resource depletion. These findings demonstrate how livestock nutritionists can apply integrated modeling approaches to link animal performance with environmental outcomes within a One Health framework.

Keywords: animal health; environmental health; life cycle assessment; one health; sustainability; swine

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1. Introduction

The One Health approach highlights the interconnectedness of animals, the environment, and human health, offering a foundation for integrated decision-making to optimize resource use and minimize the environmental pollution and public health impacts of livestock production [1]. The One Health framework provides a conceptual and operational platform to bridge these silos by emphasizing the interconnections between animals, humans, and environmental health. However, current approaches to evaluating nutrient use in livestock systems remain fragmented across disciplines. Nutrient requirement models

focus primarily on determining the adequate dietary supply to support animal growth and health [2], while the life cycle assessment (LCA) tool can estimate environmental burdens independently of biological responses [3]. The lack of integration between biological responses to nutrient and environmental models limits the ability to holistically assess how dietary inputs influence both animal health and downstream environmental and public health outcomes. To align with the principles of One Health, there is a critical need for methods that bridge these disciplinary silos by linking what we feed to livestock with its cascading effects on environmental emissions, ecotoxicity, and human health risks. Developing integrated assessment tools will help to determine both the trade-offs and potential co-benefits of nutritional strategies in relation to environmental outcomes, thereby supporting more sustainable and resilient livestock production systems.

Zinc is an indispensable trace mineral in swine nutrition, serving as a structural and catalytic cofactor for over 300 metalloenzymes and playing pivotal roles in nucleic acid metabolism, protein synthesis, epithelial integrity, and immune competence [2,4]. Beyond its biological functions in animals, zinc is also essential for microorganisms inhabiting the gastrointestinal tract of animals and for diverse microbial communities in soil ecosystems [5]. In plants, zinc contributes to enzymatic activity, chlorophyll synthesis, and reproductive development, making it vital for crop productivity and soil–plant–microbe interactions [6]. These multifaceted roles underscore zinc's integrative function across biological systems, linking animal health, plant health, and soil ecology. As such, zinc serves as a compelling example of a nutrient that connects agricultural–livestock systems with environmental sustainability under the One Health framework. In swine production systems, ensuring adequate zinc intake for pigs must be balanced against the risk of excess zinc accumulation in the environment, which can affect soil health, microbial diversity, and the prevalence of antimicrobial-resistant bacteria. This trade-off illustrates the need for a systems-level approach to zinc management that aligns with One Health principles.

Newly weaned piglets experience significant physiological and environmental stressors, including abrupt dietary changes, maternal separation, and exposure to novel pathogens, all of which compromise gastrointestinal integrity and function [7]. During this critical transition, piglets exhibit low feed intake, immature digestive and absorptive capacity, and increased intestinal permeability, leading to suboptimal zinc absorption and retention [8–10]. Moreover, the concurrent establishment of the gut microbiota imposes additional zinc demands to support microbial growth and enzymatic activities within the gut ecosystem [5,10]. This combination of factors creates heightened physiological zinc requirements at the levels of enterocytes, immune cells, and the microbial community during the immediate post-weaning period [11,12]. Consequently, pharmacological levels of zinc, commonly provided as zinc oxide (ZnO) from 2000 to 3000 mg Zn/kg of feed, have been extensively implemented to reduce post-weaning diarrhea (PWD) and enhance growth performance in weaned pigs [9,13]. The beneficial effects of high ZnO inclusion are consistently documented across studies and attributed to zinc's role in maintaining intestinal barrier function, reducing inflammatory responses, and modulating the gut microbiota composition [7,10,11,14].

However, the high inclusion of ZnO results in the majority of dietary zinc being excreted in feces [15,16]. The continuous land application of manure containing elevated zinc concentrations contributes to progressive zinc accumulation in soils, raising concerns about soil phytotoxicity, zinc leaching into groundwater, and runoff into aquatic ecosystems [6]. Moreover, excess zinc in the environment may exert co-selective pressure on antimicrobial resistance genes in microbial communities, compounding public health risks [5,17,18]. In recognition of these environmental and One Health concerns, the European Union imple-

mented a regulatory limit in 2017, reducing allowable ZnO supplementation in weaned pig diets to 150 mg Zn/kg, with the goal of minimizing environmental zinc loading [19].

Despite these regulatory actions, balancing the need for adequate zinc supplementation to support pig health with the imperative to reduce environmental zinc emissions remains a critical challenge. Current decision-making frameworks for zinc use in swine production are fragmented across disciplines. Nutrient requirement models, such as those published by the NRC [2], aim to establish dietary zinc concentrations that meet the physiological needs of the average animal under controlled conditions. In parallel, environmental assessment tools such as LCA quantify resource use and environmental impacts, including heavy metal flows, associated with swine production systems [3]. However, these nutritional and environmental models operate independently, lacking theintegration of biological responses and environmental consequences within a unified evaluative framework. Consequently, nutritional recommendations optimized for animal-level performance may overlook system-level environmental trade-offs, while LCA models may underestimate the downstream effects of dietary interventions on herd health, productivity, and disease-related mortality.

This disciplinary disjunction poses a critical barrier to sustainable nutrient management in livestock systems, where decisions must reconcile the intertwined objectives of maintaining animal health, safeguarding environmental quality, and protecting public health. Applying a One Health lens to nutrient management necessitates integrated approaches that consider how dietary interventions affect not only livestock performance and health outcomes, but also nutrient excretion patterns, environmental emissions, and ecosystem-level impacts.

Therefore, the objective of this study was to evaluate zinc flow, animal health performance, and environmental impacts associated with varying ZnO supplementation levels in nursery pig diets. By integrating growth performance modeling with life cycle assessment, this study seeks to generate system-level insights that inform sustainable zinc management strategies aligning animal productivity, environmental stewardship, and public health protection under a One Health paradigm.

2. Materials and Methods

This study examines the use of zinc in swine production systems using a combination of nursery production system animal trials, modeled growing and finishing systems, and life cycle assessment.

2.1. Animals and Housing

The experimental protocol used in the animal study was approved by the University of Minnesota Institutional Animal Care and use Committee (Protocol ID: 2304-41013A). A total of 432 pigs (Topigs Norsvin TN70 × Compart Duroc), weaned at 18d old, were housed in a wean-to-finish facility at the Southern Research and Outreach Center in Waseca, MN, USA. The pigs [5.88 ± 0.97 kg initial body weight (BW)] were assigned to 36 pens to provide 12 pigs per pen, balanced by initial BW and sex. In each room (block of 12 pens), pens were randomly distributed to one of three dietary treatments (total 12 pens/each treatment). Pens were equipped with a waterer cup, a five-spaced dry feeder, and full slatted flooring. All pigs had ad libitum access to feed and water throughout the trial. Room temperature and ventilation were controlled via an Expert Series II computerized controller (Automated Products, Marshfield, WI, USA).

2.2. Experimental Design and Procedure in Weaning Phase

Experimental diets were (1) high ZnO: a corn–soybean meal (SBM)-based basal diet with ZnO supplementation at the pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), (2) intermediate ZnO: a corn–SBM-based basal diet with ZnO supplementation at the intermediate level between the pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and (3) a corn–SBM-based basal diet with ZnO supplementation at the EU recommendation level (150 ppm) throughout the entire period (Table 1). Pigs were fed one of three dietary treatments over a 42-day nursery period in three feeding phases: Phase 1 (0 to 2 weeks), Phase 2 (2 to 4 weeks), and Phase 3 (4 to 6 weeks). All diets, delivered in mash form, were formulated to meet or exceed the nutrient recommendations for nursery pigs [2] (Table 2).

Table 1. Zinc oxide (ZnO) concentration in diets for nursery pigs.

Scenario	Zinc Source [1]	Phase 1 [2], ppm	Phase 2, ppm	Phase 3, ppm
Low-ZnO treatment	ZnO	150	150	150
Intermediate-ZnO treatment	ZnO	1200	600	150
High-ZnO treatment	ZnO	3000	3000	1200

[1] Zinc content in zinc oxide is 72.0%; [2] Phase 1: 0 to 2 weeks, Phase 2: 2 to 4 weeks, and Phase 3: 4 to 6 weeks.

Table 2. Ingredient and chemical composition of experimental diets (as-fed basis).

Item	Phase 1	Phase 2	Phase 3
Ingredient, %			
Corn	43.00	54.10	66.03
Soybean meal	10.00	21.17	30.21
Enzyme-treated soybean meal	14.29	7.00	0.00
Whey permeate	10.00	5.00	0.00
Dried skim milk	10.00	5.00	0.00
Lactose	7.00	3.00	0.00
Soybean oil	2.00	1.00	0.00
L-lysine HCl	0.54	0.40	0.39
DL-methionine	0.24	0.14	0.11
L-threonine	0.19	0.11	0.10
L-tryptophan	0.01	0.00	0.00
Monocalcium phosphate 21%	0.97	1.15	1.18
Limestone	0.85	0.87	0.94
Salt	0.40	0.55	0.55
Vitamin premix [1]	0.25	0.25	0.25
Trace mineral premix [2]	0.25	0.25	0.25
Total	100.00	100.00	100.00
Nutrient composition			
NE, kcal/kg	2553	2450	2374
Crude protein, %	21.00	20.94	20.34
SID Lys, %	1.49	1.35	1.26
SID Met, %	0.56	0.44	0.39
SID Thr, %	0.87	0.79	0.75
SID Trp, %	0.24	0.23	0.21
Total calcium, %	0.80	0.75	0.68
Digestible P, %	0.43	0.39	0.32

[1] Vitamin premix supplied the following nutrients per kilogram of premix: 2,200,000 IU of vitamin A; 550,000 IU of vitamin D3; 17,600 IU of vitamin E; 880 mg of vitamin K; 1980 mg of riboflavin; 11,000 mg of niacin; 6600 mg of pantothenic acid; 99,000 mg of choline; 11 mg of vitamin B12; 440 mg of pyridoxine; 330 mg of folic acid; 220 mg of thiamine; and 66 mg of biotin. [2] Trace mineral premix supplied the following nutrients per kilogram of premix: 440 mg of EDDI iodine; 59 mg of organic selenium; 40 mg of chromium; 18,000 mg of SQM zinc (QualiTech, Chaska, MN, USA); 11,000 mg of SQM iron; 1500 mg of SQM copper; and 3500 mg of SQM manganese.

Individual pig body weights were recorded at the start of the experiment and at the end of each feeding phase to calculate the average daily gain (ADG). Feed disappearance per pen was recorded throughout the study to calculate the average daily feed intake (ADFI) and gain to feed ratio (G:F ratio). Pig mortality and lameness were assessed and recorded daily throughout the trial.

2.3. Estimation of Growth Performance to Reach Market Weight

For the growing–finishing period, the NRC growth model [2] was used to estimate growth performance (ADG and ADFI) and feeding days to market weight (130 kg) based on diet composition in a 5 phase grow–finish feeding program. A total of 5 corn–SBM-based diets were formulated to simulate the three 5-phase feeding programs for growing–finishing pigs from the final BW of each treatment in the feeding trial (6 weeks) to 130 kg BW. Diets (Supplementary Table S1) were formulated to meet the nutrient requirements for the growing–finishing pigs model [2] for each of the five dietary phases (Phase 4: 20–40 kg BW; Phase 5: 40–60 kg BW; Phase 6: 60–80 kg BW; Phase 7: 80–100 kg BW; and Phase 8: 100–130 kg BW). The estimated average daily body weight gain from the NRC [2] was used to determine the projected feeding duration (120 to 127 days). The ADFI for each phase was applied to estimate individual pigs' total feed consumption). The final pen market weight was calculated by multiplying the number of pigs remaining at the end of the Finishing 3 phase by the assumed market weight of 130 kg. It was assumed that the initial number of pigs per pen was 12, with nursery period mortality accounted for and 4.922% of mortality assumed during the growing–finishing period [20]. The pen carcass weight was calculated using the dressing percentage from the corn–SBM-based diet feeding program from the previous study [21].

2.4. Feed Zinc Intake and Fecal Zinc Excretion

The feed zinc intake of a pig for dietary treatments from weaning to market weight were calculated based on the zinc content in the diet formulation and pig feed intake amount. Fecal zinc excretions for dietary treatments from weaning to market weight were calculated using fecal zinc excretion data for post-weaning pig (91.38% of zinc intake at <2000 ppm, 97.4% of pharmaceutical Zn intake at 3000 ppm) and growing–finishing pig (94.72% of zinc intake) periods from Gourlez et al. [16]. Zinc intake was calculated for each feeding phase by multiplying the total feed consumption by the corresponding zinc concentration in the diet for that feeding phase.

2.5. Life Cycle Assessment

A cradle-to-farm gate attributional LCA was conducted to evaluate the environmental impacts of live weight pork production across dietary treatment programs. System boundaries included crop cultivation, feed production, on-farm animal raising, and manure management, as well as the associated impacts of transportation between steps (Figure 1). The swine life cycle inventory and LCA scenario of the swine production system were based on the swine component of the commercial swine production described by Tallaksen et al. [22]. Diet composition, growth performance, pig mortality, and estimated feeding days to market weight based on a nursery feeding trial and NRC growth modeling data were used as inputs in this LCA model. The environmental impact data for producing feed ingredients used in the diet formulations were based on the Global Feed LCA Institute (GFLI; http://globalfeedlca.org/, accessed on 1 February 2025) and established data from the West Central Research and Outreach Center, University of Minnesota (Morris, MN, USA [22]). In manure management, manure volumes and volatile solids were calculated based on manure characteristics and production data from Lorimor et al. [23] and ASABE [24], using the appropriate animal stages and weights as inputs. In addition, fecal Zn excretion into manure was accounted for as zinc emissions into soil (zinc (II) soil–agricultural subcategory, ReCiPe 2016). Downstream emissions of manure applied to fields and credits for the replacement of synthetic fertilizer were not included. Methane emissions were calculated using IPCC Tables for given storage methods (open air tanks or deep pits under slated floors) and temperatures [25]. Modeling work for life cycle impact

assessment (LCIA) was carried out using SimaPro LCA software (version 9.6, PRé, Amersfoort, The Netherlands) with some background items from the DATASMART 2018 [26], ecoinvent [27], and US LCI inventories [28]. The LCIA was performed using the method of ReCiPe 2016 Midpoint (H) V1.09/World (2010)H. The analyzed LCIA included global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human and terrestrial ecosystem), fine particulate matter formation, terrestrial acidification, eutrophication (freshwater and marine), ecotoxicity (terrestrial, freshwater, and marine), human carcinogenic toxicity, human non-carcinogenic toxicity, land use, resource scarcity (mineral and fossil), and water consumption. The functional unit for LCIA outputs was defined as one pig in the nursery pig production scenario and as 1 kg of market pig in the wean-to-market pig production scenario, which was used to estimate the environmental impacts of a 130 kg market pig. A model assumption and background data representing likely ranges for major assumptions important for the study goals were tested in a sensitivity analysis using the commercial average scenarios (pig mortality range for growing–finishing period: 2.28 to 10.84% [20]). Since the mortality values varied greatly, 4.922% of the mortality rate value for the growing–finishing period was used [20]. Sensitivity analysis revealed that increased pig mortality during the growing–finishing period led to higher environmental impacts across all LCIA categories (Supplementary Table S2). However, despite the changes in magnitude, the relative ranking and trend of environmental impacts among the dietary treatments remained consistent.

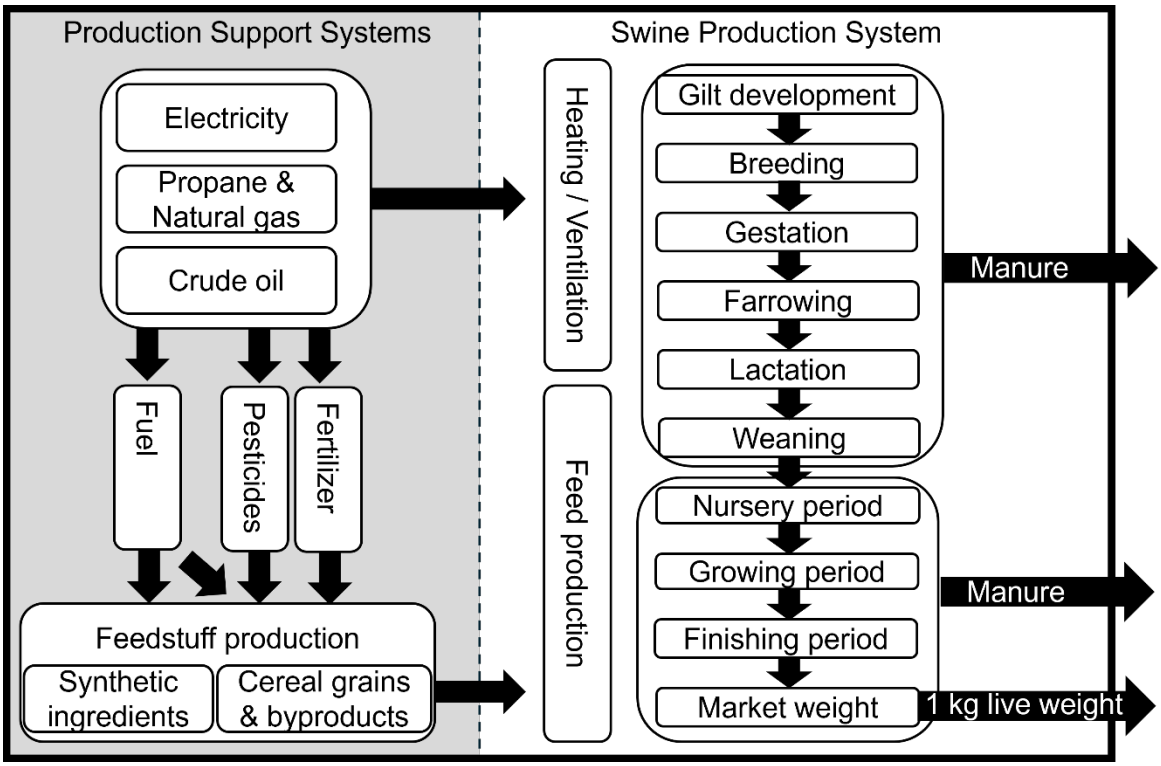


Figure 1. LCA overview and boundaries for the swine production system. The schematic shows the foreground (swine production system) and background (production support systems) components of the modeled swine system analyzed.

In the US-ecoinvent 2.2 framework, zinc oxide exists as a white powder and is produced via the indirect (or French) process, wherein secondary zinc materials undergo oxidation at high temperatures to form ZnO. The functional unit for the ZnO LCA was defined as 1 kg of solid ZnO powder, including upstream processes such as raw material extraction, transportation to the production site, and estimated energy demand, while

excluding solid waste considerations (Supplementary Table S3). The LCIA of major feed ingredients used in the model was presented in Supplementary Table S4.

2.6. Statistical Analysis

Nursery pig growth performance data were first evaluated for homogeneity of variance using the UNIVARIATE procedure in SAS (version 9.4; SAS Institute Inc., Cary, NC). Subsequently, data were analyzed using the MIXED procedure under a randomized complete block design, with pen as the experimental unit. The statistical model included treatment as a fixed effect, while block and room were treated as random effects. For time-dependent variables, phase was included as a repeated measure, and initial body weight served as a covariate. Pair-wise comparisons using the Tukey test were used to evaluate differences in treatment means. To test the hypotheses, $p < 0.05$ was considered significant. If pertinent, trends ($0.05 \leq p < 0.10$) are also reported.

3. Results

Supplementation with a high dosage of ZnO in nursery diets during the 6 weeks post weaning significantly improved ($p < 0.05$) the BW, ADG, and ADFI across all nursery phases, as well as the G–F ratio in Phase 1 compared to other treatments (Table 3). The intermediate ZnO treatment showed greater ($p < 0.05$) final BW, ADG, ADFI, and pen weight gain for the overall period than the low-ZnO treatment. Regarding pig health, low-ZnO treatment exhibited the highest mortality rate and incidence of lameness throughout the experimental period.

Table 3. Effect of dietary zinc oxide levels on growth performance and mortality of nursery pigs.

Item	Treatment [1]			SEM [2]	*p*-Value
	Low ZnO	Intermediate ZnO	High ZnO		
BW, kg					
0 weeks	5.88	5.88	5.88	0.288	0.999
2 weeks	7.44 ^{b}	7.80 ^{b}	8.76 ^{a}	0.247	0.002
4 weeks	12.50 ^{c}	14.04 ^{b}	16.21 ^{a}	0.325	<0.001
6 weeks	22.73 ^{c}	24.56 ^{b}	27.17 ^{a}	0.322	<0.001
ADG, g/d					
Phase 1	111 ^{b}	137 ^{b}	206 ^{a}	17.7	0.002
Phase 2	361 ^{c}	446 ^{b}	532 ^{a}	21.2	<0.001
Phase 3	731 ^{b}	752 ^{ab}	783 ^{a}	12.7	0.022
Overall	401 ^{c}	445 ^{b}	507 ^{a}	11.3	<0.001
ADFI, g/d					
Phase 1	182 ^{b}	200 ^{b}	239 ^{a}	8.9	<0.001
Phase 2	439 ^{c}	514 ^{b}	655 ^{a}	16.9	<0.001
Phase 3	1173 ^{c}	1254 ^{b}	1322 ^{a}	20.8	<0.001
Overall	598 ^{c}	656 ^{b}	739 ^{a}	11.6	<0.001
G:F ratio					
Phase 1	0.527 ^{b}	0.641 ^{b}	0.846 ^{a}	0.0710	0.011
Phase 2	0.823	0.879	0.816	0.0361	0.410
Phase 3	0.624	0.603	0.594	0.0142	0.324
Overall	0.658	0.708	0.752	0.0318	0.115
Pen weight, kg					
0 weeks	342.3	342.9	342.9	16.79	0.999
2 weeks	434.7	454.9	510.7	30.26	0.200
4 weeks	694.9 ^{b}	797.7 ^{b}	938.7 ^{a}	37.95	<0.001

Table 3. *Cont.*

Item	Treatment [1]			SEM [2]	*p*-Value
	Low ZnO	Intermediate ZnO	High ZnO		
6 weeks	1221.8 [b]	1385.7 [b]	1574.3 [a]	58.93	<0.001
Overall weight gain (0–6 weeks)	878.5 [c]	1042.8 [b]	1231.4 [a]	47.34	<0.001
Mortality, head					
Phase 1	7	2	1		
Phase 2	5	3	0		
Phase 3	0	0	0		
Overall	12	5	1		
Overall mortality, %	8.3	3.5	0.7		
Lameness, head	8	5	4		

[abc] Within a row, means without a common superscript differ ($p < 0.05$). [1] High ZnO: a corn–SBM-based basal diet with ZnO supplementation at pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), intermediate ZnO: a basal diet with ZnO supplementation at intermediate level between pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and low ZnO: a basal diet with ZnO supplementation at EU recommendation (150 ppm) throughout the entire nursery period. [2] Standard error of the mean.

The growth performance estimates for the growing–finishing phases using the NRC growth model [17] are presented in Table 4. The number of feeding days from the end of the 6-week feeding trial to reaching market weight (130 kg) was 127, 124, and 120 days for low-, intermediate-, and high-ZnO treatments, respectively. Consequently, the total feeding duration from weaning to market weight was 169, 166, and 162 days for low-, intermediate-, and high-ZnO treatments, respectively. As a result, high-ZnO treatment showed a greater pen carcass weight compared with other treatments, which is due to both higher survival rates and faster growth.

Table 4. Estimation of feeding days to market weight using NRC growth model [2].

Item	Treatment [1]		
	Low ZnO	Intermediate ZnO	High ZnO
BW at 6 weeks	22.73	24.56	27.17
Feeding days to market weight (130 kg)	127	124	120
Average feed intake + wastage, kg/d	2.238	2.265	2.300
Average BWG, g/day	849	855	863
Feeding days from weaning to market, d			
Nursery period	42	42	42
Growing 1 (6 wks to 40 kg)	26	23	19
Growing 2 (40–60 kg)	24	24	24
Finishing 1 (60–80 kg)	23	23	23
Finishing 2 (80–100 kg)	23	23	23
Finishing 3 (100–130 kg)	31	31	31
Overall	169	166	162
No. of pigs/pen at the end of Finishing 3, head [2]	10.46	11.01	11.33
Market pig weight, kg	130.0	130.0	130.0
Pen market weight, kg	1360	1431	1473
Carcass yield, % [3]	76.8	76.8	76.8
Pen carcass weight, kg	1044	1099	1131

[1] High ZnO: a corn–SBM-based basal diet with ZnO supplementation at pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), intermediate ZnO: a basal diet with ZnO supplementation at intermediate level between pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and low ZnO: a basal diet with ZnO supplementation at EU recommendation (150 ppm) throughout the entire nursery period. [2] Assumed 1.315% of pig mortality rate during the growing–finishing period. [3] Dressing percent value is referenced from the corn–SBM-based diet feeding program of Yang et al. [21].

The calculated total zinc intake and fecal zinc excretion of pigs during the nursery and growing–finishing periods are presented in Table 5. In the nursery period, high-ZnO

treatment had the highest zinc intake and fecal zinc excretion across all phases, due to the elevated zinc concentration (from ZnO) in the diets. Moreover, high-nursery-ZnO treatment resulted in significantly greater overall zinc excretion through feces compared to the intermediate- and low-ZnO treatments, with 5.8-fold and 15.7-fold increases, respectively. In the growing–finishing period, low-nursery-ZnO-treatment pigs showed greater zinc intake and fecal zinc excretion over the entire growing–finishing phase compared to the intermediate- and high-nursery-ZnO treatment due to the longer feeding duration during growing Phase 1. Over the entire period (weaning to market), the fecal zinc excretion per pig was 54,125, 59,485, and 106,043 mg for the low-, intermediate-, and high-ZnO treatments, respectively.

Table 5. Fecal zinc excretion of a pig during nursery period and growing–finishing period, calculated using a modified equation from Gourlez et al. [16].

Item	Treatment [1]		
	Low ZnO	Intermediate ZnO	High ZnO
Nursery Phase 1			
Zinc intake, mg	382	3360	10,038
Fecal zinc excretion, mg	349	3070	9777
Nursery Phase 2			
Zinc intake, mg	922	4318	27,510
Fecal zinc excretion, mg	842	3945	26,795
Nursery Phase 3			
Zinc intake, mg	2463	2633	22,210
Fecal zinc excretion, mg	2251	2406	20,295
Nursery period			
Zinc intake, mg	3767	10,311	59,758
Fecal zinc excretion, mg	3442	9421	56,867
Growing–finishing period [2]			
Zinc intake, mg	53,507	52,854	51,917
Fecal zinc excretion, mg	50,682	50,063	49,176
Weaning to market			
Zinc intake, mg	57,275	63,165	111,675
Fecal zinc excretion, mg	54,125	59,485	106,043
Zinc retention in pig, mg	3150	3680	5632

[1] High ZnO: a corn–SBM-based basal diet with ZnO supplementation at pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), intermediate ZnO: a basal diet with ZnO supplementation at intermediate level between pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and low ZnO: a basal diet with ZnO supplementation at EU recommendation (150 ppm) throughout the entire nursery period. [2] Growing Phase 1: feeding days to reach 40 kg of live BW for low-, intermediate-, and high-ZnO treatments were 26, 23, and 19 days, respectively.

In the nursery pig production model, the low-ZnO treatment had the lowest environmental impact per nursery pig (6 weeks post weaning) in most LCIA impact categories amongst the treatments, except for stratospheric ozone depletion, mineral resource scarcity, and water consumption (Table 6). The high-ZnO treatment in the nursery feeding phase resulted in the highest effects on human non-carcinogenic toxicity (71.1%), freshwater ecotoxicity (59.6%), marine toxicity (57.9%), and terrestrial ecotoxicity (47.4%) compared to the low-ZnO treatment. Furthermore, the high-ZnO treatment had the greatest effect on fossil resource scarcity (19.5%), terrestrial acidification (14.1%), fine particulate matter formation (13.5%), ozone formation (terrestrial ecosystems, 13.2%), ozone formation (human health, 11.5%), freshwater eutrophication (11.0%), and human carcinogenic toxicity (10.7%) impact categories compared to the low-ZnO treatment. Also, it resulted in increased impacts on ionizing radiation (6.9%), global warming (4.1%), marine eutrophication (3.8%), land use (3.3%), water consumption (2.8%), mineral resource scarcity (2.7%), and stratospheric ozone depletion (1.5%) compared to the low-ZnO treatment.

Table 6. Life cycle impact assessment (LCIA) of dietary treatment in nursery pig production system (final product: a nursery pig, data from 6-week feeding trial) [1].

Item	Treatment [2]		
	Low ZnO	Intermediate ZnO	High ZnO
Impact category [3] (% change from low-ZnO treatment)			
Global warming, kg CO_2 equiv.	93.10	93.15 (0.1)	96.96 (4.1)
Stratospheric ozone depletion, kg CFC11 equiv.	0.001	0.001 (−0.4)	0.001 (1.5)
Ionizing radiation, kBq Co-60 equiv.	1.062	1.071 (0.8)	1.135 (6.9)
Ozone formation (human health), kg Nox equiv.	0.099	0.101 (1.8)	0.111 (11.5)
Fine particulate matter formation, kg PM2.5 equiv.	0.067	0.069 (3.6)	0.076 (13.5)
Ozone formation (terrestrial ecosystems), kg Nox equiv.	0.113	0.115 (2.0)	0.128 (13.2)
Terrestrial acidification, kg SO_2 equiv.	0.242	0.251 (3.9)	0.276 (14.1)
Freshwater eutrophication, kg P equiv.	0.014	0.014 (2.9)	0.015 (11.0)
Marine eutrophication, kg N equiv.	0.059	0.059 (0.6)	0.061 (3.8)
Terrestrial ecotoxicity, kg 1,4-DCB	29.73	31.77 (6.8)	43.83 (47.4)
Freshwater ecotoxicity, kg 1,4-DCB	0.738	0.818 (10.9)	1.178 (59.6)
Marine ecotoxicity, kg 1,4-DCB	0.558	0.606 (8.6)	0.881 (57.9)
Human carcinogenic toxicity, kg 1,4-DCB	0.304	0.311 (2.3)	0.337 (10.7)
Human non-carcinogenic toxicity, kg 1,4-DCB	−17.28	−15.68 (9.3)	−4.98 (71.1)
Land use, m^2a crop equiv.	133.73	134.17 (0.3)	138.15 (3.3)
Mineral resource scarcity, kg Cu equiv.	0.109	0.109 (−0.2)	0.112 (2.7)
Fossil resource scarcity, kg oil equiv.	9.82	10.34 (5.3)	11.74 (19.5)
Water consumption, m^3	0.990	0.988 (−0.2)	1.018 (2.8)

[1] The LCIA was performed using the method of ReCiPe 2016 Midpoint (H) V1.09/World (2010)H. [2] High ZnO: a corn–SBM-based basal diet with ZnO supplementation at pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), intermediate ZnO: a basal diet with ZnO supplementation at intermediate level between pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and low ZnO: a basal diet with ZnO supplementation at EU recommendation (150 ppm) throughout the entire nursery period. [3] CO_2: carbon dioxide, CFC11: chlorofluorocarbons (known as trichlorofluoromethane), Co-60: cobalt-60, Nox: nitrogen oxides, PM2.5: particulate matter 2.5, SO_2: sulfur dioxide, P: phosphorus, N: nitrogen, 1,4-DCB: 1,4-dichlorobenzene, and Cu: copper.

In the weaning to market phases, the high-ZnO treatment resulted in the largest changes, particularly in human non-carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity by −40.3%, 24.2%, 15.6%, and 12.5%, respectively, compared to the low-ZnO treatment (Table 7; final product: 130 kg market pig). However, unlike the nursery pig scenario (Table 6; final product: 6 weeks post-weaning pig), the high-ZnO treatment reduced global warming (−4.1%), stratospheric ozone depletion (−2.4%), mineral resource scarcity (−2.1%), land use (−1.6%), marine eutrophication (−1.6%), ionizing radiation (−1.3%), and water consumption (−0.3%) impacts compared to the low-ZnO treatment. This study demonstrates the complexity of managing zinc nutrition in pigs under a One Health framework, where decisions to improve animal growth and survival simultaneously influence environmental and public health risks. The low-ZnO treatment had the greatest effect on global warming, stratospheric ozone depletion, ionizing radiation, marine eutrophication, mineral resource scarcity, and water consumption environmental impacts. In addition, the intermediate-ZnO treatment resulted in the least significant effects on ozone formation (human health and terrestrial ecosystems), marine eutrophication, human carcinogenic toxicity, and water consumption impacts amongst treatments.

Table 7. Life cycle impact assessment (LCIA) of dietary treatment in the weaning and growing–finishing phases of the production system (final product: a 130 kg market pig, data from 6-week feeding trial and NRC growth model) [1].

Item	Treatment [2]		
	Low ZnO	Intermediate ZnO	High ZnO
Impact category [3] (% change from low-ZnO treatment)			
Global warming, kg CO_2 equiv.	402.38	386.35 (−4.0)	385.92 (−4.1)
Stratospheric ozone depletion, kg CFC11 equiv.	0.003	0.003 (−1.6)	0.003 (−2.4)
Ionizing radiation, kBq Co-60 equiv.	4.027	3.983 (−1.1)	3.973 (−1.3)

Table 7. *Cont.*

Item	Treatment [2]		
	Low ZnO	Intermediate ZnO	High ZnO
Ozone formation (human health), kg Nox equiv.	0.356	0.354 (−0.6)	0.358 (0.6)
Fine particulate matter formation, kg PM2.5 equiv.	0.183	0.184 (0.4)	0.188 (2.8(
Ozone formation (terrestrial ecosystems), kg Nox equiv.	0.408	0.405 (−0.6)	0.412 (1.0)
Terrestrial acidification, kg SO_2 equiv.	0.610	0.614 (0.6)	0.631 (3.5)
Freshwater eutrophication, kg P equiv.	0.032	0.032 (0.1)	0.033 (2.0)
Marine eutrophication, kg N equiv.	0.145	0.144 (−1.0)	0.143 (−1.6)
Terrestrial ecotoxicity, kg 1,4-DCB	94.56	95.57 (1.1)	106.34 (12.5)
Freshwater ecotoxicity, kg 1,4-DCB	1.583	1.617 (2.2)	1.966 (24.2)
Marine ecotoxicity, kg 1,4-DCB	1.659	1.661 (0.2)	1.917 (15.6)
Human carcinogenic toxicity, kg 1,4-DCB	0.942	0.938 (−0.5)	0.947 (0.5)
Human non-carcinogenic toxicity, kg 1,4-DCB	−30.70	−29.95 (2.5)	−18.32 (40.3)
Land use, m^2a crop equiv.	485.77	481.18 (−0.9)	478.02 (−1.6)
Mineral resource scarcity, kg Cu equiv.	0.362	0.357 (−1.3)	0.354 (−2.1)
Fossil resource scarcity, kg oil equiv.	28.41	28.68 (1.0)	29.73 (4.7)
Water consumption, m^3	2.002	1.987 (−0.8)	1.997 (−0.3)

[1] The LCIA was performed using the method of ReCiPe 2016 Midpoint (H) V1.09/World (2010)H. [2] High ZnO: a corn–SBM-based basal diet with ZnO supplementation at pharmaceutical level (3000, 3000, and 1200 ppm for Phase 1, 2, and 3, respectively), intermediate ZnO: a basal diet with ZnO supplementation at intermediate level between pharmaceutical level and EU recommendation (1200, 600, and 150 ppm for Phase 1, 2, and 3, respectively), and low ZnO: a basal diet with ZnO supplementation at EU recommendation (150 ppm) throughout the entire nursery period. [3] CO_2: carbon dioxide, CFC11: chlorofluorocarbons (known as trichlorofluoromethane), Co-60: cobalt-60, Nox: nitrogen oxides, PM2.5: particulate matter 2.5, SO_2: sulfur dioxide, P: phosphorus, N: nitrogen, 1,4-DCB: 1,4-dichlorobenzene, and Cu: copper.

4. Discussion

Considering the environmental and public health implications associated with supplementing pharmacological levels of ZnO to weaned pigs, many countries have proactively implemented regulations to reduce zinc supplementation in swine diets. In 2022, the EU has implemented regulations limiting zinc inclusion in pig diets to a maximum of 150 mg/kg [19]. In 2018, China decreased the authorized level of zinc supplementation in pig diets from 2250 to 1600 mg/kg for the first 2 weeks of the post-weaning period, and restricted the zinc concentration to 110 mg/kg in all other stages of the wean-to-finish pigs [29]. The primary difference between the EU and Chinese regulations lies in the allowance of high doses of zinc in the weaning pigs' diets for the prevention of PWD. Regarding the regulatory restrictions on zinc dosage in weaned pigs' diets due to environmental and antimicrobial resistance concerns, several alternative strategies have been explored, including organic complexes and modified zinc sources [12,14]. Among various zinc sources, including, inorganic forms (e.g., ZnO and $ZnSO_4$), organic forms (e.g., Zn-Met, Zn-Lys, Zn-Gly, and Zn-proteinate), and further processed forms (e.g., coated, capsulated, and nano-sized), ZnO has been widely used in the U.S. swine production system as a cost-effective strategy for preventing PWD. However, ZnO has a major effect on ecotoxicity, particularly on terrestrial ecotoxicity, human non-carcinogenic toxicity, global warming, and fossil resource scarcity (Supplementary Table S3).

In a meta-analysis, Luise et al. [14] found that increased dietary Zn levels significantly improved the ADG and G–F ratio by 20% and 5%, respectively, which could be attributed to increased villus height and width, enhanced intestinal integrity, and the upregulated expression of genes associated with tight junction proteins. Furthermore, they reported that dietary ZnO or Zn, due to its antibacterial activity, could improve intestinal integrity and reduce intestinal inflammation, ultimately contributing to better growth performance in weaned pigs [30–33]. The growth performance result observed in the current study aligned with previous studies [34,35], which demonstrated that pharmaceutical levels of ZnO had a positive effect on the growth performance of weaned pigs. Hansen et al. [35] found that increasing dietary zinc levels from 153 to 2407 mg Zn/kg of feed quadratically increased the ADG of pigs during the first 2 weeks post weaning, with the turning response observed at 1408 mg Zn/kg. Furthermore, Zn supplementation at 2407 mg Zn/kg significantly

reduced the probability of diarrhea during the first 3 weeks post weaning compared with lower Zn levels. Collectively, given the results of current and previous Zn studies, the supplementation of ZnO at a pharmaceutical level (>2500 mg/kg) in weaned pigs for the early post-weaning period would have beneficial effects on growth performance and intestinal health, while preventing PWD and mortality in weaned pigs from the perspective of both animal health and swine producers.

Reducing the dietary zinc intake of pigs obviously decreases the Zn excretion of the pigs [16,35]. Interestingly, the fecal zinc excretion for the high-ZnO treatment during the nursery period accounts for 53% of the total fecal zinc excretion during the whole period and exceeds the total fecal zinc excretion for the low-ZnO treatment. Subsequently applying the pig manure with a high concentration of Zn to the crop field would have toxic effects on plants and soil microorganisms and become an environmental concern in some areas of intensive pig farming [36,37]. Furthermore, zinc in feed can lead to the emergence of antimicrobial resistance genes in the gut microflora of pigs, pig manure, and soil [38,39]. A high level of dietary zinc supplementation (2500 ppm ZnO for four weeks post weaning) has been shown to increase the prevalence of zinc-tolerant *Escherichia coli* strains in piglets. Some of these isolates also harbored antimicrobial resistance genes, indicating a potential risk of co-selection between metal and antibiotic resistance traits [40]. However, the zinc content in soil varies across countries and regions [41,42], and accordingly, the effects of applying zinc-enriched swine manure to soil may vary. Notably, excessive or subsequent zinc supply through manure application could be toxic to crops, such as corn, soybeans, and peanuts [43,44]. Furthermore, we applied a single value for zinc bioavailability during the weaning period in the current study. However, zinc bioavailability with fecal zinc excretion can vary depending on pig age, post-weaning stage, and dietary zinc intake level, as reported in previous studies [45,46]. Therefore, the use of pharmaceutical doses of ZnO in nursery diets should be carefully considered due to its potential effects on crop fields, including risks of plant toxicity, alterations to soil conditions, and effects on ecological diversity.

Investigating the environmental impacts of livestock production systems through LCA has been recognized as an emerging approach for guiding decision-making and supporting the transition toward sustainable food production and consumption patterns [47]. In this context, multi-objective diet formulation has gained consideration as a promising approach, utilizing LCA databases for feed ingredients to optimize animal diets with respect to environmental, nutritional, and economic objectives [48–50]. Furthermore, LCA methodologies have been used to assess evaluate the environmental impacts of various feeding strategies and pork production systems in the U.S. [21,22,51]. Feed ingredients in swine diets typically account for 55–75% of climate change impacts and 85–100% of the land use associated with pork production systems [52–54]. Moreover, feeding programs with multiple phases and diet formulations can result in differences in pig productivity, including pig growth rate, feed efficiency, and total feeding days, ultimately affecting the overall environmental impacts of pork production systems [55]. Andretta et al. [56] indicated that pig diets, including the processes associated with crop cultivation, manufacturing, and transportation, were the primary contributor to the environmental impacts of pork production systems.

In the current study, the high-ZnO treatment resulted in greater environmental impacts compared with the intermediate- and low-ZnO treatments, primarily due to the differences in the feed intake amount and fecal output of the pigs during nursery pig production. Numerous studies have indicated that ZnO or ZnO nanoparticles exhibit cytotoxic effects on marine microalgae, including cyanobacteria, *Chlorella vulgaris*, and diatoms, which are considered a biological model for ecotoxicity in freshwater or marine

ecosystems [57]. The ZnO-nano particles cause toxicity to these organisms by releasing Zn^{2+} ions, leading to cellular damage and mechanical injury [57,58]. Furthermore, zinc-containing substances such as ZnO, Zn chloride, Zn stearate, Zn diethyldithiocarbamate, and 4-chloro-2-nitrobenzenediazonium have been shown to cause chronic toxicities in terrestrial organisms [59,60]. Interestingly, most environmental impacts of the intermediate-ZnO treatment were the lowest, likely due to its relatively lower ZnO and feed intakes, as well as its contribution to reduced pig mortality. Also, the intermediate-ZnO treatment exhibited higher terrestrial ecotoxicity, freshwater ecotoxicity, human non-carcinogenic toxicity, and fossil resource scarcity than the low-ZnO treatment due to the increased use of ZnO. Therefore, the significant increase in ecotoxicity underscores the toxicological effects of higher ZnO dosages on terrestrial, marine, and freshwater ecosystems, as also reflected in the ReCiPe assessment.

In the entire pig production system, including the growing–finishing period using the NRC [2] growth model, the observed differences in the environmental impacts have been due to the differences in feeding days during the growing Phase 1 (26, 23, and 19 days), reaching 40 kg of pig BW, as predicted by the NRC [2] growth model. Post-weaning performance and herd health significantly affect the subsequent growth performance of the pigs until market weight [61]. However, a limitation of the NRC growth model was that it did not account for these factors when estimating body weight gain and feed intake based on the diet formulations and their nutrient compositions by feeding phase. Some environmental impact categories, including fine particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine toxicity, human non-carcinogenic toxicity, and fossil resource scarcity showed similar trends among dietary treatments in the entire pig production system compared with the nursery pig production system. However, certain environmental impact categories, including global warming, stratospheric ozone depletion, ionizing radiation, marine eutrophication, land use, and mineral resource scarcity, showed the least impact in high-ZnO treatment compared to low- and intermediate-ZnO treatments. It implies that the environmental impacts during the growing–finishing period were much larger than those in the nursery period with respect to the amounts of feed intake and manure output. Also, the pig mortality rate during the nursery and growing–finishing period could be a significant factor affecting the environmental impacts of the wean-to-finish pig production system.

Tallaksen et al. [22] noted that the growing–finishing phase accounted for 75.2% of global warming potential (GWP) emissions, whereas the nursery phase accounted for 9.2% of GWP emissions. As a representative LCIA, the GWP impact, which indicates the potential global warming effect due to greenhouse gas emissions into the air, using CO_2 as a standard, observed in the current study (386–402 kg CO_2 equiv./a 130 kg pig), was higher than the estimates of the previous studies for corn–SBM diet feeding programs [21,22,48]. According to Tallaksen et al. [22], the commercial average scenario, which reflected the average pig growth and a corn–SBM-based diet feeding program, resulted in a GWP of 313.3 kg CO_2 equiv./130 kg pig, and Shurson et al. [51], using the FoodS^3 model (Institute on the Environment, University of Minnesota, Saint Paul, MN, USA) reported that corn–SBM diets with a four-phase feeding program resulted in 282 kg CO_2 equiv./market pig in the Midwest region and 339.5 CO_2 equiv./market pig in the overall U.S. geographic region. Yang et al. [21], using Opteinics software (BASF, Ludwigshafen, Germany), reported that a corn–SBM-based diet feeding program resulted in 3470 CO_2 equiv./1000 kg of carcass weight, which is the same as 313.3 kg CO_2 equiv./a market pig (with a hot carcass weight of 94.9 kg per pig); this model also accounted for pig transportation and carcass processing within the LCA scenario. The observed differences in CO_2 emissions between the present and previous studies may be partially attributed to variations in diet formulations,

including differences in ingredient compositions and nutrient contents across nursery and growing–finishing phases, as well as differences in pig production system scenarios, such as pig productivity parameters, life cycle inventory for a weaned pig or a growing pig originating from a farrowing sow or a sow reproduction system, facility energy use, or manure management strategies, etc. Furthermore, other important background factors not specially mentioned here, such as regional crop farming practices, geographical variations affecting resource use efficiency, and methodological differences in LCA models, may also significantly influence emissions outcomes [51].

On the other hand, the trends in environmental impacts associated with global warming, ionizing radiation, land use, and mineral resource scarcity for the high-ZnO treatment showed a reduction compared to the low-ZnO treatment. This difference can be attributed to the fact that these impacts were increased with the high-ZnO treatment during the nursery period; however, the reduced feeding days and lower manure output in growing Phase 1, due to the high-ZnO treatment, resulted in a reduction in these impacts. When estimating the environmental impacts based on a 130 kg market pig, the trends in environmental impacts for dietary treatments partially differed by pig mortality during the nursery and growing–finishing periods, and growth performance during the growing–finishing period. The LCA only evaluates the environmental footprint of the final product within a designated scenario with fixed system boundaries and inventories. It should be noted that high-ZnO treatment could have lower mortality and a greater health status of the pigs during the growing–finishing period, leading to lower resource inputs and environmental footprint per market pig. For example, improved health status in weaned pigs can enhance the growth rate and feed efficiency of the pigs during the growing–finishing period, thereby reducing the total feeding period, overall feed consumption, and manure excretion, which ultimately decreases the environmental impacts associated with feed ingredient production and utilization. Unfortunately, in the current study, the NRC [2] growth model assuming identical growth performance from the growing Phase 2 to the finishing Phase 3 was applied. While the LCA model used in the current study accounted for the environmental burden of zinc primarily at the feed and manure excretion stages, it does not encompass the long-term environmental fate of zinc once pig manure is applied to agricultural land. Specifically, our LCA model does not quantify the accumulation of zinc in soil, its uptake by crops, or its effects on soil microbial communities. It represents a critical limitation in evaluating the One Health implications of zinc supplementation in swine diets. Therefore, further studies are needed to determine whether changes in produced carcass weight, pig feed efficiency, and feed budget accounting for mortality significantly affect environmental impacts per unit of kg of pork carcass produced from a barn or a herd through actual animal feeding trials and to evaluate the potential environmental impacts or antimicrobial resistance risk with manure application to crop fields in order to provide balanced and practical guidelines for stakeholders. Furthermore, future modeling efforts should integrate flow dynamics of zinc or trace minerals, along with ecological and microbiological endpoints, to better understand the downstream and cross-sectional risks associated with zinc use in swine production systems.

5. Conclusion

Supplementation with pharmacological levels of ZnO, ranging from 2000 to 3000 mg Zn/kg of diet, has been shown to improve the growth performance and survivability of weaned pigs, supporting enhanced productivity extending into the growing–finishing period. However, these nutritional benefits were accompanied by markedly increased zinc intake and fecal excretion, with zinc excretion nearly doubling compared to pigs fed based on EU-recommended zinc inclusion levels. Elevated zinc excretion contributed to

greater environmental impacts in the nursery production system, particularly increasing freshwater and marine ecotoxicity potential. Yet, when impacts were expressed per market pig produced, improved feed efficiency and reduced mortality under high ZnO inclusion partially mitigated environmental burdens across other impact categories, including global warming potential and land use.

These findings highlight the trade-offs inherent in zinc supplementation decisions, underscoring the need for integrated frameworks that account for animal health, environmental sustainability, and public health outcomes. By combining nutritional response modeling with life cycle assessment, this study illustrates a systems-based approach to evaluating zinc supplementation through a One Health lens. The integration of animal performance, environmental emissions, and ecosystem risks reveals the interconnected consequences of nutrient management strategies across biological and ecological domains.

This work reinforces the imperative for sustainable nutrient management practices that align animal health benefits with environmental and public health protection. Policies and practices that reduce zinc excretion while preserving piglet health—such as precision feeding, alternative zinc sources, or complementary gut health interventions—are critical for achieving One Health objectives in swine production systems. Integrated assessment tools bridging nutritional, environmental, and public health domains will be essential for guiding sustainable livestock production and minimizing ecological and societal risks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments12080279/s1, Table S1: Ingredients and nutrient composition of growing-finishing diets; Table S2: Sensitivity analysis with mortality rate in growing-finishing period; Table S3: Environmental impacts per kg of ZnO (LCIA); Table S4: Environmental impacts per kg of major feed ingredients.

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Abbreviations

The following abbreviations are used in this manuscript:

ADFI	Average daily feed intake
ADG	Average daily gain
BW	Body weight
G:F ratio	Gain to feed ratio
GWP	Global warming potential
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
PWD	Post-weaning diarrhea
SBM	Soybean meal
ZnO	Zinc oxide

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