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A global meta-analysis of fertiliser management on soil available and total zinc

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Abstract: Soil available and total zinc are important indicators of soil zinc status, yet the global effects of different fertilisation practices on soil available and total zinc and the drivers of their variation remain insufficiently quantified. We conducted a global meta-analysis based on data extracted from published field studies. A total of 1 240 paired observations of soil available zinc from 94 studies and 364 paired observations of soil total zinc from 44 studies published between 1993 and 2024 were compiled. The effects of eight fertiliser types (mineral fertilisers without zinc [CF], compost, manure, zinc fertiliser, CF combined with either compost [CFC] or manure [CFM] or zinc fertiliser [CFZn], and compost combined with zinc fertiliser [CZn]) on the soil available and total zinc content were assessed by meta-analysis. The results indicated that compared to the control group, soil available zinc content increased significantly under treatments CZn, CFZn, zinc fertiliser, CFM, manure, CFC, and compost by 158, 134, 133, 84, 78, 43, and 35%, respectively. Additionally, manure, CFM, zinc fertiliser, CFZn, and CZn treatments significantly enhanced soil total zinc content, with increases ranging from 25% to 32%. Applying zinc fertiliser at > 20 kg Zn/ha significantly increased soil-available zinc. In the medium-rate CZn class (10–20 kg Zn/ha), soil available zinc increased from 0.78 mg/kg in the control soils to 3.46 mg/kg in the treated soils. Among crop systems, wheat showed a stronger response in soil-available zinc, whereas rice-growing systems showed relatively larger increases in soil-total zinc under manure and CFM treatments. Fertilisation intensity, crop types, soil organic carbon, and soil pH emerged as key drivers of variation in soil available zinc, whereas the main drivers of soil total zinc varied among fertiliser types and were more often associated with fertiliser rate and crop types. When soil organic carbon was ≤ 12 g/kg or soil pH was > 7.5, applying CZn at 10–20 kg Zn/ha showed greater potential to increase soil available zinc. These findings suggest that soil zinc management should be optimised based on fertilisation intensity, crop type, soil organic carbon, and soil pH to improve zinc availability while avoiding excessive accumulation.

Keywords: zinc deficiency; organic fertilisers; dose-response; soil properties; zinc accumulation risk

Zinc (Zn) is a crucial micronutrient that contributes to a variety of biological and physiological processes (Bashir et al. 2021). It contributes to key cellular processes, including DNA replication, gene transcription, and expression, primarily by regulating the activity of over 1 000 transcription factors and

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more than 200 enzymes (MacDonald 2000, Prasad 2009). Currently, nearly 17% of the global population experiences health problems associated with "hidden hunger", including zinc deficiency (Chasapis et al. 2020, Ramzan et al. 2020, Ishfaq et al. 2023). A major strategy to combat "hidden hunger" is through the combination of zinc-enriched crops (Gruter et al. 2017), with soil serving as the principal source of zinc for plants (Liu et al. 2024). Zinc-deficient soils reduce zinc uptake in plants, thereby lowering photosynthetic efficiency and hindering plant growth (Noman et al. 2019). The soil's available zinc content determines its capacity to supply zinc. From an agronomic perspective, soil available zinc is generally considered deficient when it falls below the critical threshold, but relatively sufficient for crop growth when it reaches or slightly exceeds that threshold. Reported critical thresholds of diethylenetriaminepentaacetic acid-extractable zinc vary among major agricultural soil types, being about 1.03 mg/kg in noncalcareous mollisols (Martínez Cuesta et al. 2021), 1.23–1.35 mg/kg in calcareous salt-affected soils (Khoshgoftarmansh et al. 2012), and 0.80–0.85 mg/kg in floodplain soils (Rahman et al. 2021). By contrast, soil total zinc refers to the overall zinc content in soil, including both available and unavailable forms (Xue et al. 2020), and is more suitable for evaluating potential accumulation risk. For example, the United States Environmental Protection Agency has proposed an ecological soil screening level of 160 mg/kg dry soil for terrestrial plants (Agency 2007). At the crop level, zinc nutritional status is commonly assessed by measuring tissue or grain zinc content. For major cereal crops, commonly cited grain zinc targets are about 40 mg/kg for wheat grain (Hui et al. 2025), 38 mg/kg for maize grain (Kihara et al. 2024), and 24–28 mg/kg for polished rice (Sanjeeva Rao et al. 2020). While soil available and total zinc content typically change slowly under natural conditions, human interventions, especially fertilisation, can significantly and rapidly alter them (Bączek-Kwinta and Antonkiewicz 2022, Hui et al. 2025). Therefore, a deeper understanding of how soil available and total zinc respond to different fertilisation practices is essential for enhancing soil fertility and agricultural productivity.

Fertilisation is a key management practice influencing soil available and total zinc content (Felipe-Sotelo et al. 2025). Different fertilisation treatments can affect zinc content directly through zinc input or indirectly by modifying soil physical and chemical properties (Qin et al. 2025). For instance, zinc fertiliser and organic fertilisers can significantly enhance available zinc content due to their zinc content (Yan et al. 2021). Organic materials in compost and manure produce a variety of organic acids through microbial metabolism and chemical transformation, which can form complexes with zinc, increasing its solubility and mobility in the soil (Piri et al. 2019). Manure is generally more effective than compost in increasing soil available zinc content because it contains higher levels of zinc and decomposes more rapidly, releasing dissolved organic carbon that forms stable complexes with zinc ions (Cai et al. 2019, Ren et al. 2024). The effects of mineral fertiliser (CF) on soil available zinc content remain highly controversial, with studies reporting positive (Chen et al. 2020, Zhang et al. 2025), negative (Chen et al. 2018), or no significant effects (Adhikari et al. 2020, Zhang et al. 2021). Moreover, in cropping systems without zinc fertilisation, continuous plant uptake can lead to nutrient mining and long-term depletion of soil zinc reserves (Impa and Johnson-Beebout 2012). The global understanding of how fertilisation practices influence soil available and total zinc content remains limited, which limits efforts to promote sustainable agriculture through optimised fertilisation strategies.

The responses of soil available and total zinc content to different fertilisation practices are governed by fertilisation intensity, crop types, and soil physicochemical properties. First, because of the conditions required for the dissolution, adsorption, and migration of zinc in soil, fertilisation intensity can have varying impacts. For instance, low-intensity fertilisation may slightly increase soil-available zinc content, whereas the effects of high-intensity fertilisation remain uncertain (Liu et al. 2018). Second, under identical fertilisation regimes, different crops exhibit varying capacities to chelate soil available and total zinc ions, largely due to differences in the composition and quantity of root exudates (Zhang et al. 2019). Soil pH is another critical factor in determining zinc solubility and activity. In alkaline conditions, zinc ions tend to precipitate as sparingly soluble hydroxides or oxides, significantly reducing their solubility (Sturikova et al. 2018, Yu et al. 2024). Moreover, soil organic matter provides numerous adsorption sites that effectively retain zinc, thereby enhancing soil available zinc levels (Zeng et al. 2011). In soils with high bulk density, reduced pore space and limited gas diffusion, especially under wet conditions, localised reducing microsites may form that promote the reductive dissolution of Fe and manganese (Mn) oxides and the release of previously sorbed zinc into the soil solution (Alnaimy et al. 2023). As most previous studies have examined isolated factors or limited datasets, there is a pressing need to comprehensively investigate the key drivers of soil available and total zinc content responses to different fertiliser types. Such understanding is essential for the optimal management of soil available and total zinc content.

Understanding how various fertilisation strategies affect soil available and total zinc content lays the groundwork for optimising fertiliser management and enhancing its efficiency, thereby supporting sustainable agricultural development. Therefore, this study conducted a global meta-analysis based on published field studies to quantitatively evaluate the effects of eight fertiliser types on soil available and total zinc at the global scale. In addition, we aimed to identify the key environmental factors regulating these responses under different fertilisation categories. Specifically, this study aimed to: (1) quantify the effects of mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn) on soil available and total zinc; (2) compare how these responses vary with fertilisation intensity, crop types, soil organic carbon, and soil pH; and (3) identify the key environmental factors associated with these responses at the global scale.

MATERIAL AND METHODS

Data collection and preparation. A global-scale dataset was established to systematically evaluate how different fertilisation practices influence soil available and total zinc content. An extensive literature search was conducted using the Web of Science (https://www.webofscience.com) and the China Knowledge Resource Integrated Database (https://www.cnki.net/) to identify relevant studies published through March 2024. "zinc" OR "Zn") AND ("soil") AND ("fertilizer" OR "fertilization" OR "manure" OR "compost" OR "chemical fertilizer" OR "organic fertilizer" OR "combined fertilization"). The Boolean operators "AND" and "OR" were used to combine terms and broaden the search scope. The articles included in the analysis were peer-reviewed journal publications published between 1993 and 2024. To ensure appropriate data selection and reduce publication bias, specific inclusion criteria were adopted: (1) only field trials were considered, studies based on meta-analysis or review articles were excluded; (2) all selected studies included both control (no fertiliser treatment) and at least one fertiliser treatment, each treatment included a minimum of three replications; (3) in cases where authors conducted multiple experimental sets (e.g., different fertilisation years or growth stages), each treatment was considered an independent observation in the database; (4) fertilisation treatments involving biochar or non-zinc metal element additions (e.g., copper (Cu) and boron (B)) were excluded; (5) studies were required to report the mean and standard deviation (SD). When only the standard error (SE) was provided, the SD was derived according to the equation $SD = SE\sqrt{n}$ (Zhou et al. 2023), where n denotes the sample size. Regarding sewage sludge, related studies were identified during data screening, but the eligible observations were too limited to support robust quantitative synthesis.

In the included studies, soil samples were generally collected after crop harvest, and the present study extracted the reported soil sampling and analytical data from the original publications. For multi-year trials, final-year data were used to ensure temporal comparability. Based on these criteria, we compiled a global dataset consisting of 94 research papers with 1 240 paired observations for soil available zinc and 44 papers with 364 paired observations for soil total zinc. In addition to zinc content, the dataset includes comprehensive metadata on experimental sites (e.g., longitude, latitude, and altitude), fertilisation treatments (e.g., including fertiliser types, fertiliser rate, fertiliser timing, and crop types), climatic variables (e.g., mean annual temperature and mean annual precipitation), and soil characteristics. Soil chemical properties included soil pH (H_2O) (determined using the potentiometric method) and soil organic carbon (determined using a CN automatic analyser). Soil physical properties included bulk density measured using the core method, and soil texture components – clay, silt, and sand – determined using pipette and hydrometer methods. In most studies, soil-available zinc was determined using the diethylenetriaminepentaacetic acid (DTPA) extraction method. In contrast, soil-total zinc was measured after mixed-acid digestion using commonly used acid systems, including HNO_3–HF–HCl. The soil-available and total zinc reported in this meta-analysis were expressed on a dry-soil basis, using air-dried or oven-dried soil samples in the original studies.

Table 1. Summary of site information and selected climate, soil physical, and chemical properties. No. represents the number of independent experiments

Indexes	Unit	No.	Mean	Standard deviation	Median	Min.	Max.	95%*CI* (lower)	95%*CI* (upper)
Longitude	°	1 604	78.31	63.14	112.92	–106.00	126.83	75.22	81.40
Latitude	°	1 604	32.06	17.39	36.90	–29.71	56.44	31.21	32.92
MAT	°C	1 604	13.13	5.16	13.34	–0.03	27.90	12.88	13.39
MAP	mm	1 604	865.07	453.34	667.00	149.00	2 425.00	842.86	887.27
Altitude	m	1 604	341.49	409.80	200.00	2.50	2 339.00	321.42	361.56
Sand	%	1 604	40.92	16.25	36.00	0.00	96.70	40.13	41.72
Silt	%	1 604	35.94	12.94	40.00	0.80	54.00	35.31	36.58
Clay	%	1 604	22.75	12.40	21.00	1.43	92.68	22.14	23.35
SOC	g/kg	360	15.30	15.34	12.12	1.54	132.25	13.71	16.89
Soil pH		568	6.42	1.21	6.43	3.60	8.58	6.32	6.52
BD	g/cm^3	1 604	1.40	0.11	1.39	1.14	1.73	1.40	1.41

MAT – mean annual temperature; MAP – mean annual precipitation; SOC – soil organic carbon; BD – bulk density

A summary of these variables is presented in Table 1. In cases where only soil organic matter was reported, it was converted to soil organic carbon using the following equation: soil organic carbon = soil organic matter/1.724 (Van Bemmelen 1890, Cai et al. 2023). Missing climate data were supplemented using the WorldClim database (https://www.worldclim.org/) and the Climate Database (Zomer et al. 2022). The geographical range of the experimental sites spans latitudes from –29.71° to 56.44° and longitudes from –106° to 126.83° (Figure 1A).

We categorised fertilisation into eight distinct treatments: mineral fertilisers (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn). In this study, CF refers to mineral fertilisers applied without zinc addition, including single-nutrient fertilisers and compound fertilisers as reported in the original studies. Fertiliser application rates were extracted from the primary studies, expressed as total seasonal/annual amounts, and grouped into low, medium, and high classes. CF application rates were grouped into low (< 100 kg/ha), medium (100–200 kg/ha), and high (> 200 kg/ha). Zinc fertiliser, CFZn, and CZn rates were grouped into low (< 10 kg Zn/ha), medium (10–20 kg Zn/ha), and high (> 20 kg Zn/ha) (Liu et al. 2020a), based on the reported zinc input. Compost, manure, CFC, and CFM rates were grouped into low (< 5 t/ha), medium (5–10 t/ha), and high (> 10 t/ha). For compost- and manure-based inputs (including CFC and CFM), rates were recorded on a dry-weight basis when explicitly reported; otherwise, they were retained on an as-applied basis to avoid unverified conversions. Because data for other crops were limited across treatments and regions, wheat, maize, and rice were selected to ensure robust and representative analyses. Because soil organic carbon data were available for only 360 comparisons and further subdivision would substantially reduce fertiliser-specific subgroup sample sizes, initial soil organic carbon was classified into two levels, ≤ 12 and > 12 g/kg (Zhou et al. 2023). Initial soil pH was classified into three categories: acidic (< 6.5), neutral (6.5–7.5), and alkaline (> 7.5) (Du et al. 2020).

Meta-analysis. Meta-analysis is a statistical method that systematically integrates and quantitatively synthesises results from multiple independent studies to estimate overall effects and associated uncertainties. This approach reveals consistent patterns and variations across studies and helps identify potential moderating factors (Cai et al. 2023, Ren et al. 2024). Effect sizes and their 95% confidence intervals were calculated using OpenMEE software (https://www.cebm.brown.edu/openmee/). The formula below presents the natural logarithm transformation of the response ratio (ln*RR*) and its 95% confidence interval (ln(95%*CI*)):

$$\ln RR = \ln(X_t/X_c) = \ln(X_t) - \ln(X_c) \tag{1}$$

where: X_t and X_c – average values for the treatment and control groups, respectively. ln*RR* was used as the effect size and was further expressed as the relative change in soil zinc content under fertilisation compared with the unfertilised control for ease of interpretation. The variance of ln*RR* is

Table 2. Fail-safe number (*N*) for the effect sizes of soil available and total zinc

Indicator	*n*	*N*
Soil available zinc	94	79 885 822.6
Soil total zinc	44	782 970.8

calculated as follows:

$$i.v_i = SD_t^2/N_tX_t^2 + SD_c^2/N_cX_c^2 \quad (2)$$

where: N_t and N_c – sample size of the treatment and control groups, respectively. SD_t^2 and SD_c^2 – standard deviation (SD) of the treatment and control groups, respectively. The weighting factor (W_i) and the natural logarithm of the 95% confidence interval (ln(95%*CI*)) were computed as follows:

$$W_i = 1/V_i \quad (3)$$

$$\ln(95\%CI) = \ln RR \pm 1.96\sqrt{1/\textstyle\sum_{i=1}^{m}\sum_{j=1}^{ki}W_i} \quad (4)$$

where: W_i ($i = 1, 2 \ldots, m$; $j = 1, 2 \ldots, ki$)

where: *m* – number of groups; *ki* – number of comparisons in the group. Effect sizes and the percentage change in the 95% confidence intervals were calculated using the following formula: (exp(ln*RR*) –1) × 100. A significant effect was considered present ($P < 0.05$) if the corresponding 95% confidence interval did not overlap with zero.

In addition, to assess the robustness of the meta-analysis results, we calculated Rosenthal's fail-safe number (*N*), as follows:

$$N > 5n + 1 \quad (5)$$

where: *n* – number of included studies. Overall, the results of the meta-analysis were stable and reliable, with no evidence of publication bias (Table 2) (Ding et al. 2024). Additionally, between-group heterogeneity tests (Q_b tests) were employed to examine heterogeneity between groups and determine how responses varied with fertiliser management practices. A statistically significant Q_b statistic ($P < 0.05$) denotes considerable variation in effect sizes among the predefined groups (Table 3) (Hedges et al. 1999).

Statistical analyses. All statistical analyses were performed using RStudio software (Posit Software, PBC, Boston, USA). Statistical analyses were conducted to explore the relationship between soil available and total zinc content and multiple influencing factors. Initially, forest plots were used to assess the effects of fertiliser type, fertilisation intensity, crop type, soil organic carbon, and soil pH on soil available and total zinc content. Subsequently, environmental variables were then grouped into five categories, namely climate (mean annual temperature and mean annual precipitation), biological factors (crop types), topographic factors (altitude), management measures (fertiliser rate and fertiliser timing), and soil properties (pH, soil organic carbon, bulk density, clay, silt, and sand), to determine which categories had the most significant influence on soil available and total zinc under different fertilisation treatments. To identify key environmental drivers, we used the "glmulti" package in RStudio to model and rank variables based on their effects on soil available and total zinc content within each environmental category. The threshold for the sum of Akaike weights was set at 0.8 to distinguish between important and unimportant environmental variables (Su et al. 2024, Chen et al. 2025).

RESULTS

Effects of fertiliser types on soil available and total zinc. Across all control observations, baseline soil-available zinc ranged from 0.13 to 47.42 mg/kg, with a median of 1.03 mg/kg. The interquartile range

Table 3. Between-group heterogeneity (Q_b) under the random-effects model

Moderator	Outcome	*df*	Q_b	*P*
Fertilisation type	soil available zinc	7	699.83	< 0.001
	soil total zinc	7	47.39	< 0.001
Fertilisation intensity	soil available zinc	15	865.63	< 0.001
	soil total zinc	13	123.24	< 0.001
Crop types	soil available zinc	19	1 011.86	< 0.001
	soil total zinc	13	41.56	< 0.001
Soil organic carbon	soil available zinc	15	868.88	< 0.001
	soil total zinc	13	86.82	< 0.001
Soil pH	soil available zinc	20	860.40	< 0.001
	soil total zinc	18	71.41	< 0.001

df – degrees of freedom

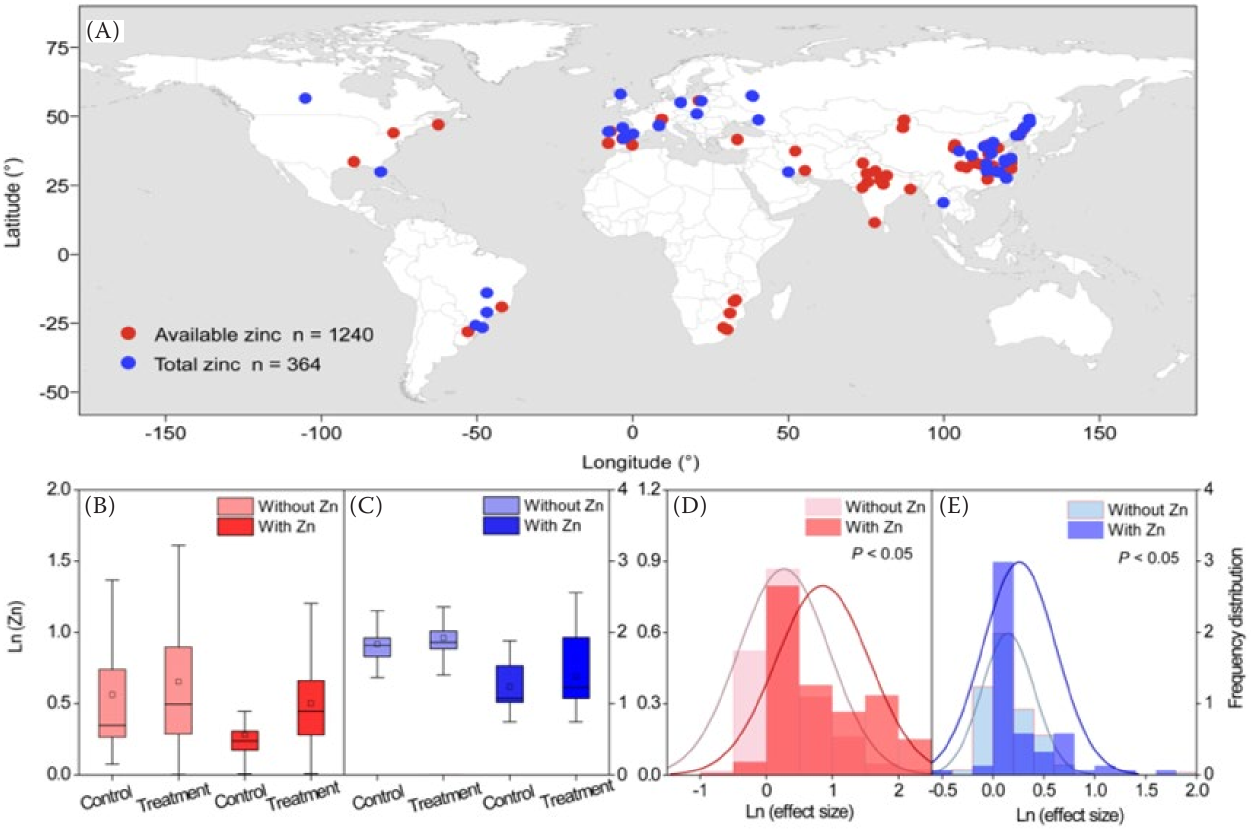

Figure 1. Geographic distribution of extracted data points on soil available and total zinc from the studies included in this meta-analysis. Panel (A) shows the geographic distribution of the compiled observations. Without Zn: fertilization treatments excluding zinc fertilizer treatments; With Zn: only zinc fertilizer treatments. Compare the differences in soil available zinc (B) and total zinc (C) contents between control and treatment groups; the frequency distributions of the effect sizes for soil available zinc (D) and total zinc (E). In Figure 1B and 1C, the lower and upper edges of the boxes represent the 25th and 75th percentiles, respectively, with the lines and squares inside the boxes indicating the medians and means. Figure 1D and 1E indicate that the effect sizes for soil available and total zinc do not follow a normal distribution

was 0.67–2.57 mg/kg. For soil total zinc, baseline values ranged from 4.56 to 201.20 mg/kg, with a mean of 58.30 mg/kg and an interquartile range of 34.55–74.90 mg/kg. Compared to the control group, the soil available zinc content increased significantly under CZn, CFZn, zinc fertiliser, CFM, manure, CFC, and compost treatments, with increases of 158, 134, 133, 84, 78, 43, and 35%, respectively. In contrast, the CF treatment had no significant effect on the soil available zinc content (Figure 2A). Regarding soil total zinc content, all treatments except CF, compost, and CFC showed a significant positive effect. The effect sizes of manure, CFM, zinc fertiliser, CFZn, and CZn treatments were 25, 29, 29, 32, and 26%, respectively (Figure 2B).

Effects of fertilisation intensity on soil available and total zinc. Soil available zinc generally increased from low to high fertilisation intensity classes under compost, manure, CFC, CFM, and zinc fertiliser treatments, with effect sizes ranging from 15–182%. Conversely, although CFZn and CZn generally produced positive increases in soil available zinc (38–330%), the magnitude of the pooled effect decreased with increasing fertilisation intensity. Specifically, in the CZn subgroup at 10–20 kg Zn/ha, mean soil available zinc increased from 0.78 mg/kg in the control soils to 3.46 mg/kg in the treated soils. The CF treatment showed no significant effect on soil available zinc, regardless of intensity (Figure 3A). Regarding soil total zinc content, CF, compost, and CFC treatments had no effect size differences across intensities. Under CFM and zinc fertiliser treatments, soil total zinc ranged from 1–86% across intensity classes. For manure, soil total zinc increased by 33,

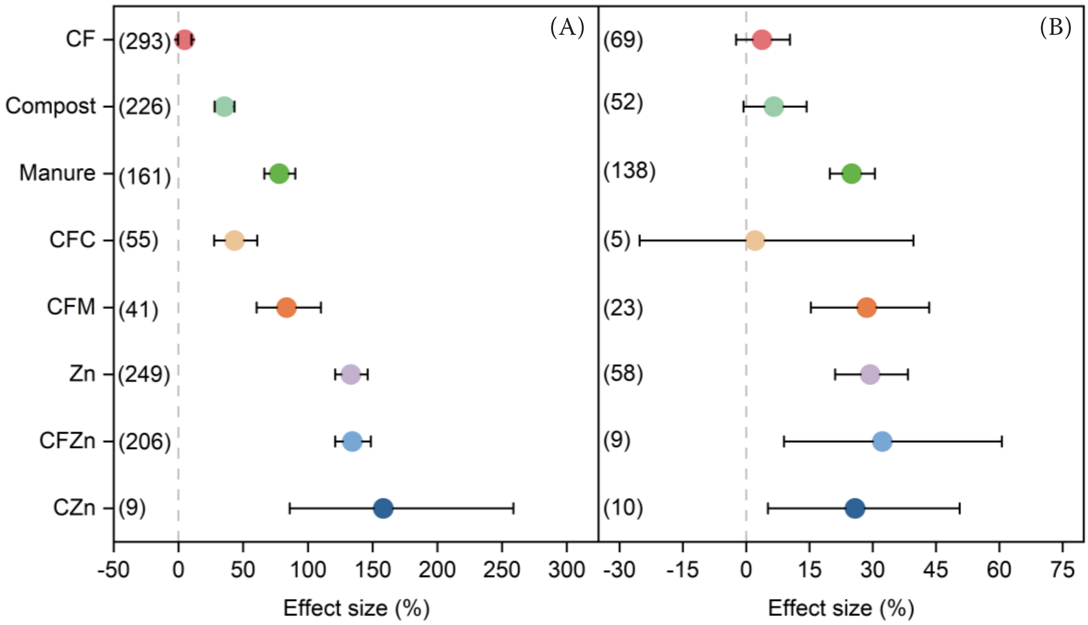

Figure 2. Effects of fertilisation type on (A) soil available zinc and (B) soil total zinc based on observations compiled from the published studies included in this meta-analysis. Points and black lines indicate the mean and 95% confidence interval of the effect size. The vertical dashed line indicates no significant effect. If the 95% confidence interval does not overlap with the vertical dashed line, the effect size is statistically significant ($P < 0.05$). The values in parentheses indicate the sample size. The *y*-axis represents the fertiliser types, which include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

30, and 19% at low, medium, and high fertilisation intensities, respectively (Figure 3B).

The effect sizes of soil available and total zinc under various crop types. Baseline soil available zinc in the control groups had medians of 0.80, 0.86, and 0.63 mg/kg for wheat, maize, and rice, respectively, whereas baseline soil total zinc had medians of 70.94, 68.45, and 58.35 mg/kg, respectively. Under compost, zinc fertiliser, and CFZn treatments, the soil available zinc effect sizes followed the order wheat > maize > rice. For manure, CFC, and CFM treatments, the soil available zinc effect sizes were higher for maize than for rice. The CF treatment showed no significant differences in soil available zinc among crop types (Figure 4A). For soil total zinc, CF, compost, and CFC treatments showed no significant differences among crop types. For the manure treatment, the soil total zinc content followed the order rice (21%) > maize (19%) > wheat (14%). In the CFM treatment, rice (37%) exhibited a higher effect size than maize (23%) (Figure 4B).

The effect sizes of soil available and total zinc under various soil organic carbon and soil pH levels. Baseline soil available and total zinc in the control groups had medians of 0.94 and 61.72 mg/kg under soils with soil organic carbon ≤ 12 g/kg, respectively, and 1.20 and 70.40 mg/kg under soils with soil organic carbon > 12 g/kg, respectively. Baseline soil available and total zinc in the control groups had medians of 1.16 and 65.35 mg/kg under acidic (pH < 6.5) soils, 0.88 and 11.00 mg/kg under neutral (6.5–7.5) soils, and 0.88 and 70.40 mg/kg under alkaline (pH > 7.5) soils, respectively. The effect size of soil available zinc was larger in soils with high soil organic carbon (> 12 g/kg) than in those with low soil organic carbon (≤ 12 g/kg) under manure, CFM, and zinc fertiliser treatments. In contrast, soil available zinc effect sizes were higher in soils with low soil organic carbon than in those with high soil organic carbon under compost, CFC, CFZn, and CZn treatments (Figure 5A). For soil total zinc, effect sizes under zinc fertiliser and CZn were greater in soils with high soil organic carbon than in those with low soil organic carbon (Figure 5B). Relative to the control, effect sizes for soil available zinc were higher in acidic than in alkaline soils under CFC and CFM, with 47% *vs* 38% for CFC and 142% *vs* 82% for CFM. In contrast, zinc fertiliser and CFZn showed greater effects on soil available zinc in alkaline than

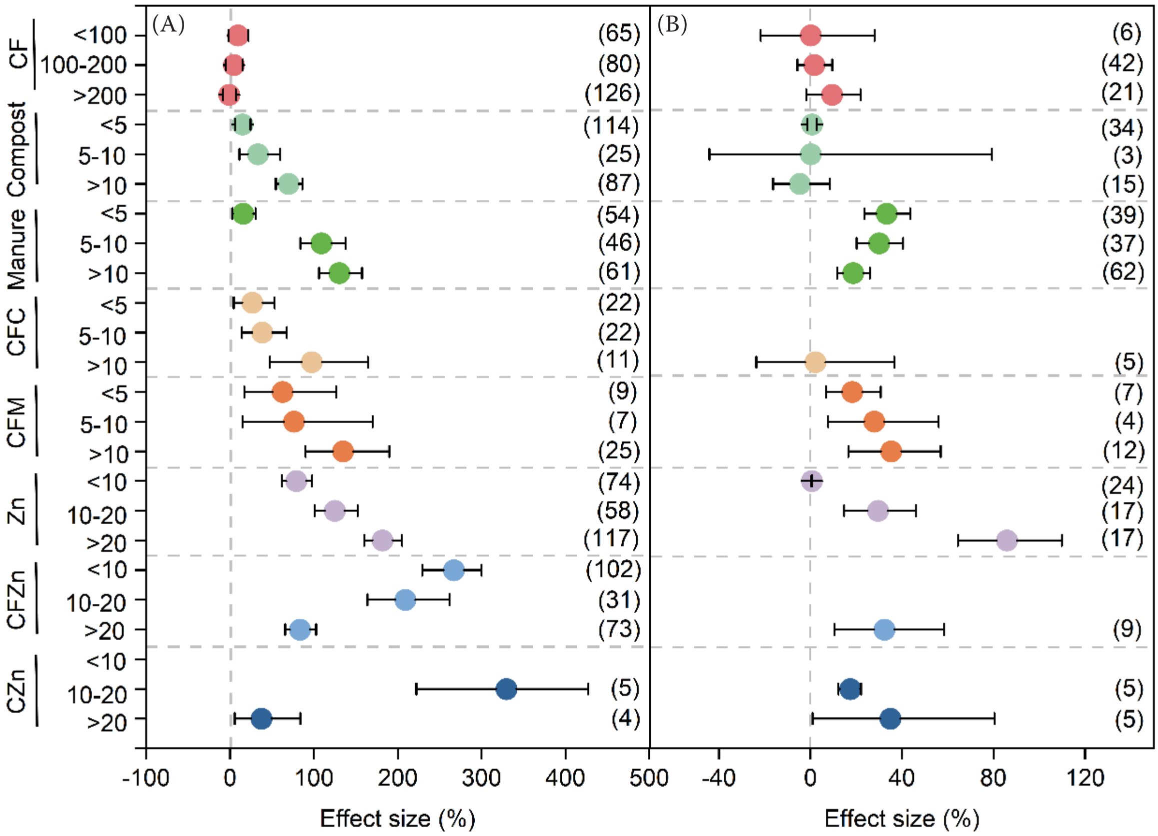

Figure 3. Effects of fertilisation intensity on (A) soil available zinc and (B) soil total zinc based on observations compiled from the published studies included in this meta-analysis. Points and black lines indicate the mean and 95% confidence interval of the effect size. The vertical dashed line indicates no significant effect. If the 95% confidence interval does not overlap with the vertical dashed line, the effect size is statistically significant ($P < 0.05$). The values in parentheses indicate the sample size. The unit of fertiliser rate is kg/ha for mineral fertilisers without zinc (CF), zinc fertiliser, CF combined with zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn); the unit of fertiliser rate for compost, manure, CF combined with compost (CFC), and CF combined with manure (CFM) is t/ha. For zinc-containing treatments, low, medium, and high input levels corresponded to < 10, 10–20, and > 20 kg Zn/ha, respectively

in acidic soils, with 173% *vs* 129% for zinc fertiliser and 174% *vs* 39% for CFZn (Figure 6A). For soil total zinc, the effect sizes under manure, CFM, and zinc fertiliser declined across soil pH classes (Figure 6B).

Predicted effect sizes of soil available and total zinc. Crop types were identified as the key driver of the effect size for soil available zinc under CF, compost, manure, zinc fertiliser, and CFZn treatments. Fertiliser rate was the key driver of the effect size for soil available zinc under CFC, CFM, and zinc fertiliser treatments. Soil pH was the dominant factor influencing the soil available zinc effect size under CF, compost, manure, and CFZn treatments. Additional driving factors under CF treatment included soil organic carbon, Sand, fertiliser timing, and mean annual precipitation. For compost and manure treatments, bulk density, soil organic carbon, and fertiliser timing were the primary drivers (Figures 7A–G). For soil total zinc content, fertiliser rate was the significant driver under compost, manure, and zinc fertiliser treatments, whereas crop types were the significant driver under CF and compost treatments. Soil pH, soil organic carbon, mean annual temperature, and mean annual precipitation were the significant drivers of the effect size for soil total zinc under CF treatment (Figures 7H–K).

DISCUSSION

Effect sizes of soil available and total zinc under different fertiliser types. Except for CF, compost, and CFC, the other five fertilisation treatments significantly enhanced soil available and total zinc

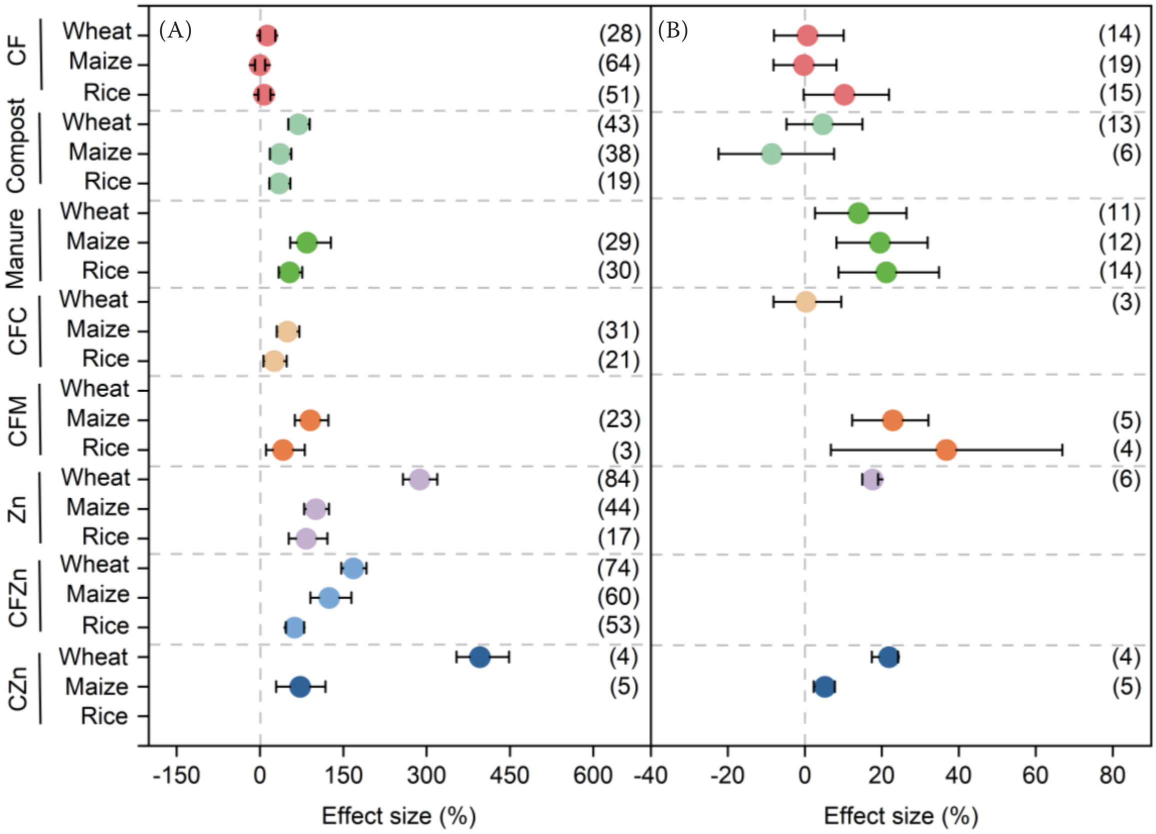

Figure 4. Effects of fertilisation on (A) soil available zinc and (B) soil total zinc under various crop types based on observations compiled from the published studies included in this meta-analysis. Points and black lines indicate the mean and 95% confidence interval of the effect size. The vertical dashed line indicates no significant effect. If the 95% confidence interval does not overlap with the vertical dashed line, the effect size is statistically significant ($P < 0.05$). The values in parentheses indicate the sample size. The y-axis represents the fertiliser types, which include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

content (Figure 2). The nine-year field trial by Liu et al. (2020b) demonstrated that the sole application of compound fertiliser (N-P-K: 15.0-6.5-12.4) had no significant effect on soil available and total zinc content, consistent with our CF treatment results. This finding likely reflects the fact that soil total zinc tends to remain largely unchanged in the absence of net exogenous zinc inputs (Leksungnoen et al. 2022). Meanwhile, compound fertiliser may transiently increase soil available zinc *via* acidification-driven dissolution of insoluble zinc compounds (Wyszkowski et al. 2023). However, continued crop uptake maintains a dynamic equilibrium, thereby leaving soil available zinc largely unchanged over the long term (Stanton et al. 2022). Compost and CFC treatments significantly increased soil available zinc by 35% and 43%, respectively, but had no significant effect on soil total zinc. This is likely because zinc in compost is relatively mobile and dissolves readily into the soil solution (Maturi et al. 2021, Klein et al. 2023). These treatments promote soil available zinc content by transforming zinc forms in the soil without altering the soil total zinc content (Zarrabi et al. 2018). In contrast, manure, CFM, zinc fertiliser, CFZn, and CZn treatments significantly increased soil available and total zinc content. This enhancement can be attributed to the following mechanisms. First, these fertilisation practices introduce zinc directly into the soil (Hodomihou et al. 2020, Yan et al. 2021). Second, in treatments with organic amendments (e.g., manure- and compost-based mixtures), the decomposition of organic fertilisers releases water-soluble compounds that bind with zinc, forming stable complexes, thereby enhancing zinc solubility, mobility, and bioavailability (Gramlich et al. 2013). Additionally, organic acids released during decomposition lower the soil pH,

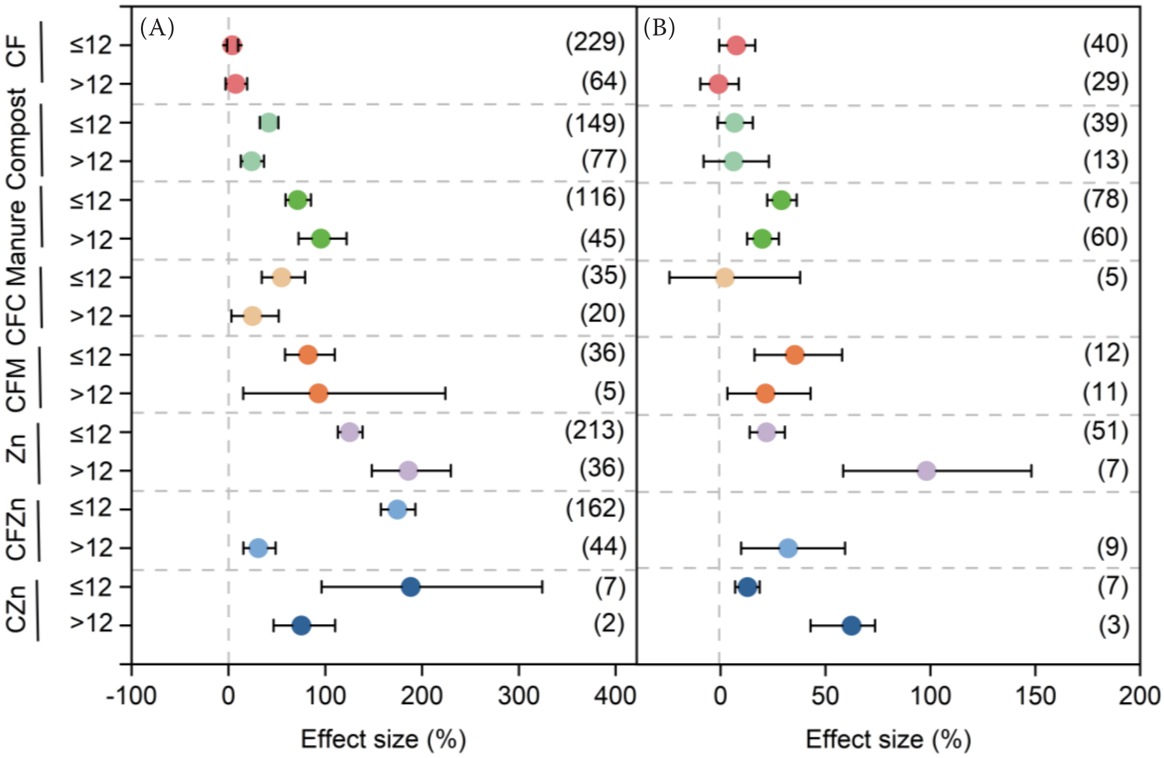

Figure 5. Effects of fertilisation on (A) soil available zinc and (B) soil total zinc under different soil organic carbon levels based on observations compiled from the published studies included in this meta-analysis. Points and black lines indicate the mean and 95% confidence interval of the effect size. The vertical dashed line indicates no significant effect. If the 95% confidence interval does not overlap with the vertical dashed line, the effect size is statistically significant ($P < 0.05$). The values in parentheses indicate the sample size. The *y*-axis represents the fertiliser types, which include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

thereby further enhancing soil available zinc content (Soltani et al. 2014). Meanwhile, zinc fertiliser increases both exchangeable and water-soluble forms of zinc, thereby directly increasing soil available zinc content. Finally, the CZn treatment combines the respective advantages of compost and zinc fertiliser, synergistically boosting soil available and total zinc content (Xiong et al. 2023). The zinc fertilisation category in the compiled studies mainly represented commonly used zinc sources, such as zinc sulfate and chelated zinc fertilisers, and, where explicitly reported in the original studies, other soluble zinc salts. Differences in solubility and reactivity among zinc sources may partly explain variation in effect sizes, but the overall positive response indicates that direct exogenous zinc input was the dominant mechanism driving increases in soil available and total zinc. Collectively, these findings provide useful insights for optimising fertiliser selection and application strategies to improve soil available zinc while maintaining long-term soil zinc balance.

Driving factors of soil available and total zinc under different fertiliser types

Effects of fertilisation intensity on soil available and total zinc. Management practices encompass fertilisation intensity and fertiliser timing. However, fertiliser timing had a relatively minor effect on soil available and total zinc content (Figure 7). Therefore, this study primarily focused on the role of fertilisation intensity. Higher fertilisation intensity tended to enhance soil available and total zinc contents (Figure 3). Soil available zinc increased with higher application rates of CFC, with effect sizes of 27, 38, and 97% under low, medium, and high fertilisation intensities, respectively. A similar increasing trend was observed under CFM, with effect sizes of 63, 76,

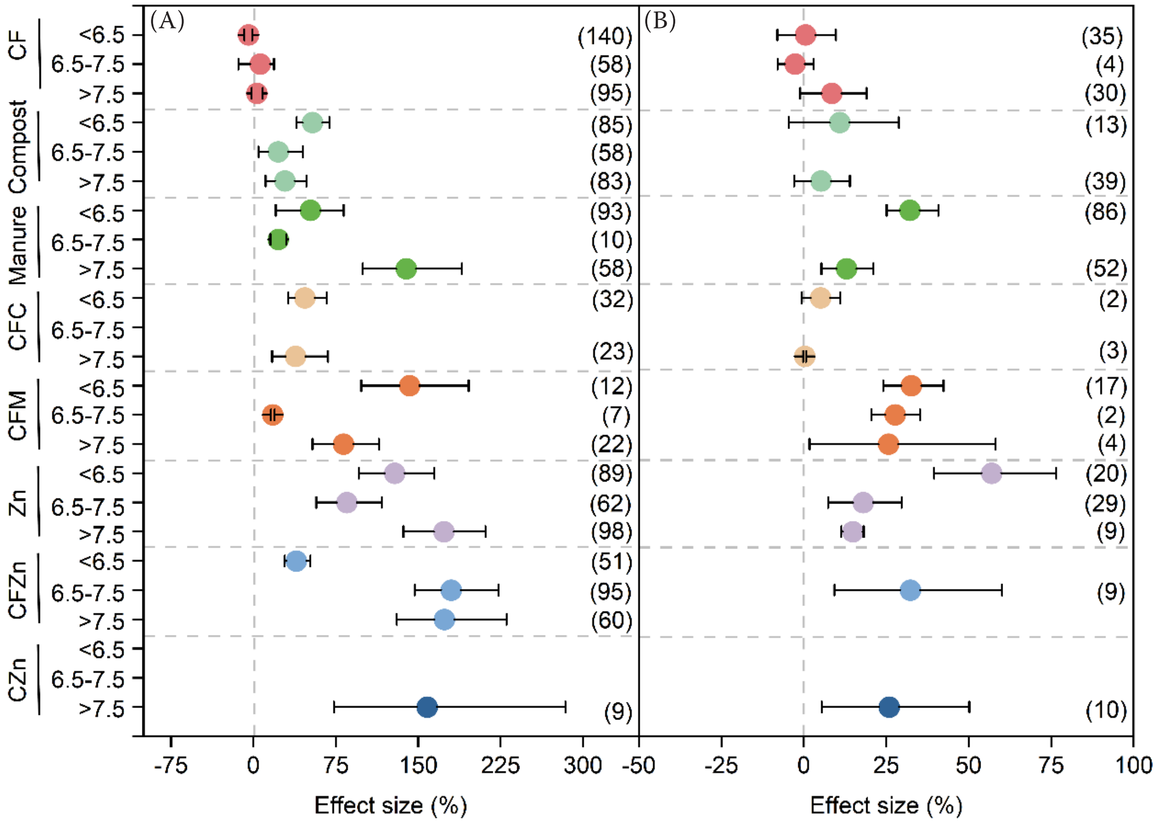

Figure 6. Effects of fertilisation on (A) soil available zinc and (B) soil total zinc under different soil pH levels based on observations compiled from the published studies included in this meta-analysis. Points and black lines indicate the mean and 95% confidence interval of the effect size. The vertical dashed line indicates no significant effect. If the 95% confidence interval does not overlap with the vertical dashed line, the effect size is statistically significant ($P < 0.05$). The values in parentheses indicate the sample size. The *y*-axis represents the fertiliser types, which include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

and 135% (Figure 3A). On the one hand, increased fertiliser rates of CFC and CFM result in more organic matter. Greater organic matter inputs can enhance zinc complexation with organic ligands, thereby increasing zinc solubility and bioavailability (Piri et al. 2019). On the other hand, organic fertilisers provide a carbon source that stimulates microbial growth and activity (Yang et al. 2016, Wang et al. 2024). Microbial metabolism further generates organic acids and other metabolites that dissolve zinc-containing minerals, thereby increasing soil available zinc content (Hamzah Saleem et al. 2022). Moreover, microbial processes facilitate zinc cycling and transformation within the soil (Sethi et al. 2025). For manure, Sun et al. (2023) reported that soil total zinc increased mainly at medium and high application rates, whereas the response at low rates was weak. In contrast, our meta-analysis demonstrates a significant positive effect of manure application on soil total zinc content regardless of application rate. This discrepancy may be due to differences in study scale and the substantially larger sample size in our analysis, which increases the reliability of the results. Increasing the zinc fertiliser rate directly enhances soil available and total zinc content (Liu et al. 2020b), as it typically elevates all bioavailable zinc fractions in the soil (Lakshmi et al. 2021). These findings indicate that applying appropriate fertiliser types and rates can effectively increase soil zinc content, improve soil quality, and boost agricultural productivity.

Effects of crop types on soil available and total zinc. Fertiliser treatments, including manure, zinc fertiliser, and CFZn, significantly influenced the soil available zinc content across different crop types. Wheat exhibited a greater increase in soil available zinc content compared to maize and rice under com-

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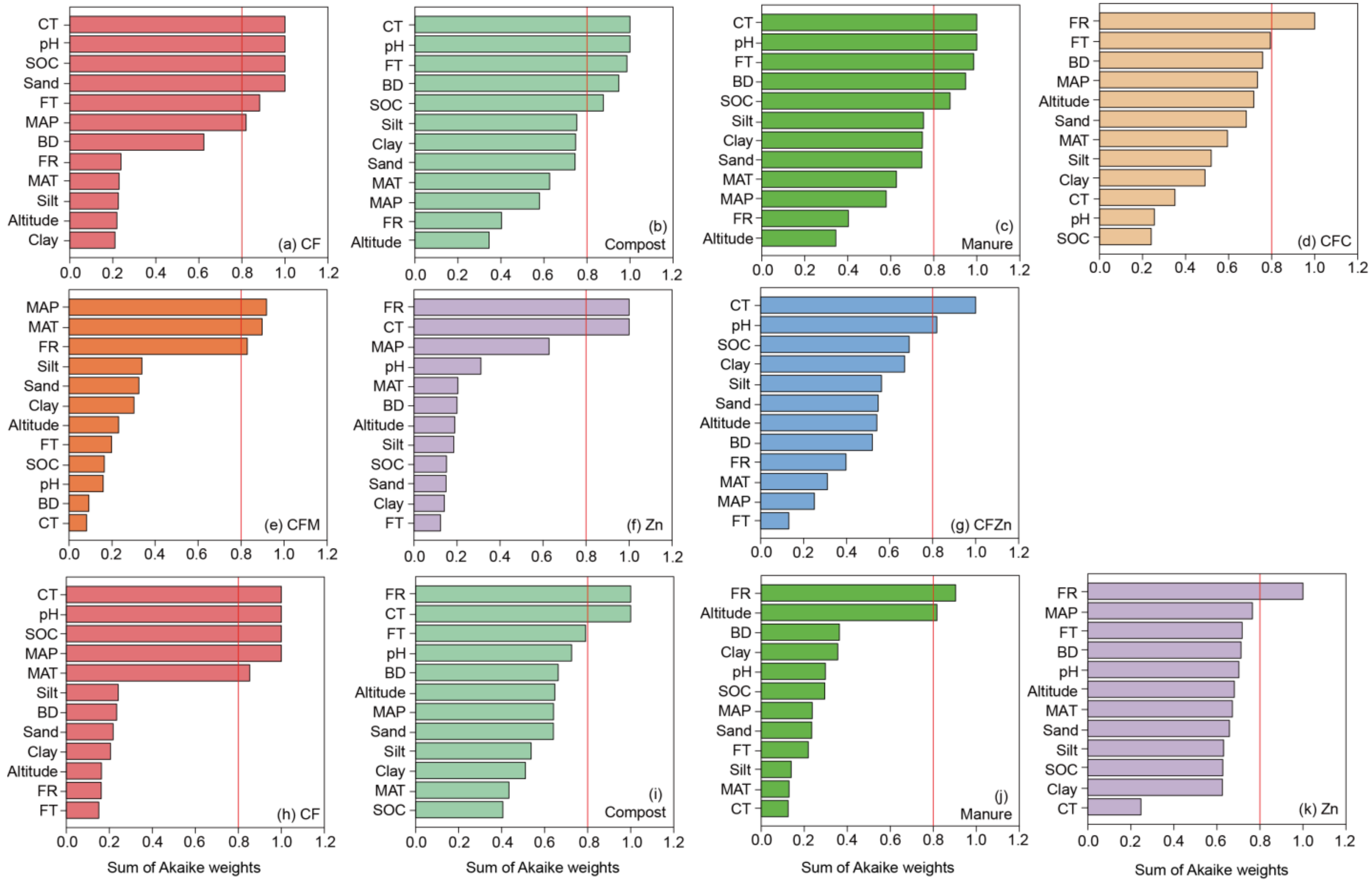

Figure 7. Model average importance of each factor on the effect size of soil available zinc (A–G) and soil total zinc (H–K). The importance is based on the sum of Akaike weights derived from model selection. Cutoff is set at 0.8 (vertical red line) to differentiate between important factors. These factors include altitude, fertiliser rate (FR), fertiliser timing (FT), crop types (CT), mean annual temperature (MAT), mean annual precipitation (MAP), pH, soil organic carbon (SOC), bulk density (BD), clay, silt, and sand. Fertiliser types include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

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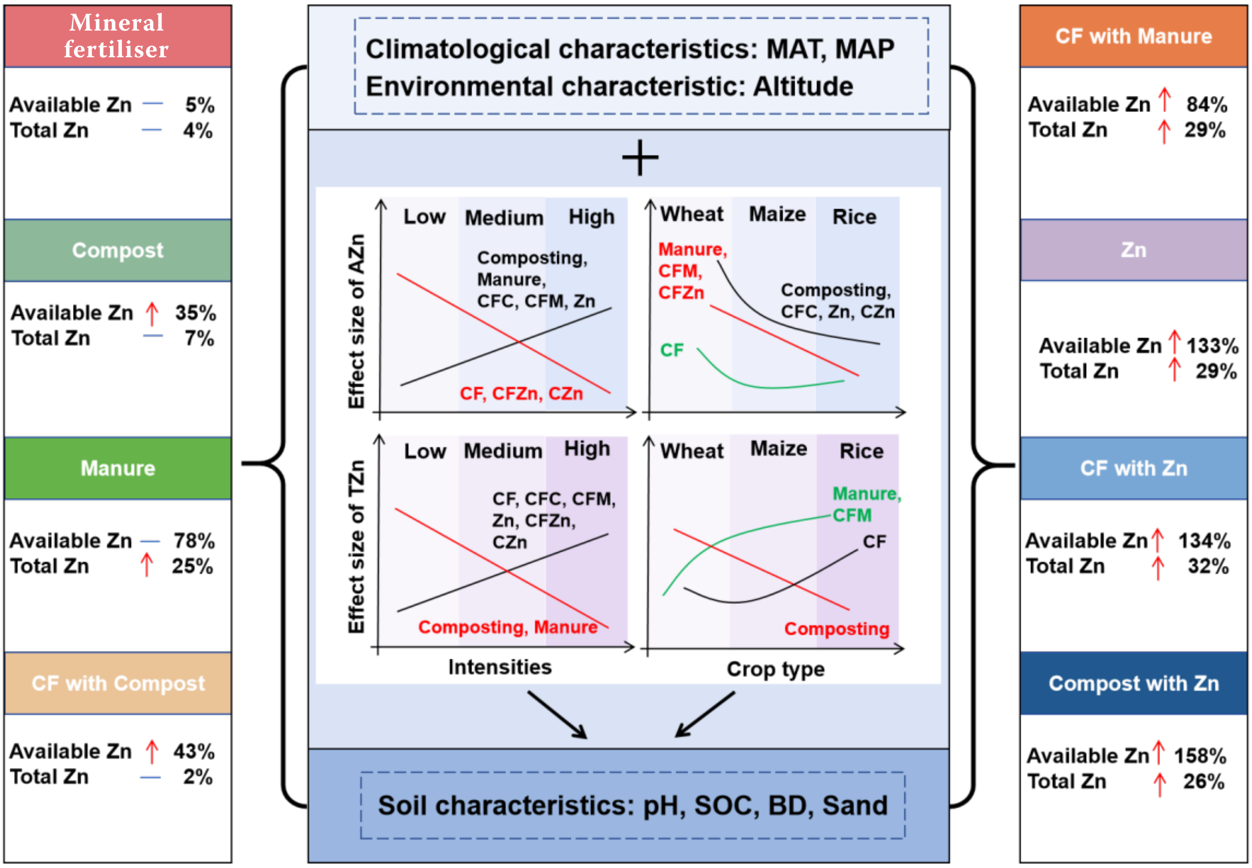

Figure. 8. Graphical summary of the main processes of fertilisation type effect on soil available and total zinc. An upward red arrow indicates a significant increase relative to the control ($P < 0.05$); a blue horizontal bar indicates no significant effect. Fertiliser types include mineral fertilisers without zinc (CF), compost, manure, zinc fertiliser, CF combined with either compost (CFC) or manure (CFM) or zinc fertiliser (CFZn), and compost combined with zinc fertiliser (CZn)

post, zinc fertiliser, and CFZn treatments (Figure 4A). This can be attributed to wheat's dense root system and extensive root hairs, which enhance soil-root contact and promote rhizosphere interactions (Ober et al. 2021). During compost decomposition, low molecular weight organic acids are released by microbial activity while wheat roots also secrete carboxylates such as citric acid, malic acid, etc. (He et al. 2021, Nadeem et al. 2024). These organic acids enhance zinc solubility and mobility through acidification and complexation processes (Moreno-Lora and Delgado 2020). In contrast, maize root exudates may be less effective at mobilising zinc. Rice, typically grown in flooded conditions, induces higher soil pH, which suppresses zinc solubility and bioavailability (Zhang et al. 2019). Although zinc fertilisation increases soil available zinc content in rice systems (Lakshmi et al. 2021), the waterlogged environment hinders zinc speciation and transformation, resulting in lower bioavailability relative to wheat. Under zinc fertiliser and CFZn treatments, zinc fertiliser application promotes wheat roots, increasing root dry weight, root length density, and root surface area (Liu et al. 2019, Jiang et al. 2023). These root traits boost the release of exudates such as organic acids, which in turn enhance soil available and total zinc content. Overall, these results underscore the need for site-specific fertilisation programs tailored to different crop systems.

Soil properties influenced soil available and total zinc. Soil properties are crucial determinants of soil available zinc, with soil organic carbon and soil pH identified as two primary factors driving its variation (Figure 7). Soil organic carbon plays an important role in regulating zinc dynamics in soil (Wood et al. 2018). Under manure, CFM, and zinc fertiliser treatments, the soil available zinc content increased with higher soil organic carbon (Figure 5A).

This response can be explained by two main mechanisms. First, functional groups in organic matter can complex with zinc ions, thereby reducing their immobilisation in soil (Sethi et al. 2025). Second, organic acids generated during the decomposition of organic matter can enhance zinc dissolution and subsequently increase its bioavailability (Goodarzi et al. 2020). Under compost treatment, the effect size of soil available zinc decreased from 42% in soils with soil organic carbon ≤ 12 g/kg to 24% in soils with soil organic carbon > 12 g/kg. Under CFC treatment, the corresponding values declined from 55% to 25%. This result differs somewhat from previous studies, which generally report a positive relationship between soil organic carbon and soil available zinc content (Zheng et al. 2021). The discrepancy in the study may be due to the fact that higher soil organic carbon levels are associated with increased humic acid content, which can form insoluble complexes with zinc ions, reducing soil available zinc content (Güngör and Bekbölet 2010, Piri et al. 2019). Soil pH is a key factor affecting the distribution of zinc in the soil (Taspinar et al. 2025). The effects of CFC and CFM treatments on soil available zinc were greater under acidic than under alkaline conditions, with effect sizes of 47% *vs* 38% for CFC and 142% *vs* 82% for CFM, respectively (Figure 6A). This trend is consistent with findings from previous studies, which have shown that low pH facilitates zinc solubilisation in soil, whereas higher pH promotes the conversion of zinc ions into insoluble compounds like $Zn(OH)_2$ and $Zn(OH)_3^-$ (Khongchiu et al. 2025). These results suggest that soil organic carbon and soil pH should be taken into account in fertilisation treatments to improve zinc use efficiency and optimise soil available and total zinc management strategies.

Limitations, future perspectives, and applications

This global meta-analysis evaluated how fertilisation management affects soil available and total zinc, providing an evidence base for enhancing soil zinc management. However, translating these results into practice requires acknowledging key limitations. It also requires defining targeted research priorities and management measures. Regarding these limitations, first, certain fertiliser types (e.g., CFZn, CZn) and crops (e.g., maize, rice) were underrepresented, potentially reducing the statistical power to detect true effects and limiting extrapolation to broader agricultural systems. Moreover, while focusing on soil available and total zinc, the study did not address critical zinc fractions (e.g., exchangeable, water-soluble). Future research should investigate the transformation dynamics among these fractions and integrate microbial activity data. Such integration can clarify mechanisms of zinc cycling, bioavailability, and migration in soil-plant systems.

From an agronomic perspective, the measured control-group values in our dataset indicate that many observations were still at low or marginal zinc status. The median soil available zinc in the control group was 1.03 mg/kg, with an interquartile range of 0.67–2.57 mg/kg. Using this median as a reference, the observed effect sizes correspond to approximate soil available zinc levels of 1.39 mg/kg under compost, 1.47 mg/kg under CFC, 1.83 mg/kg under manure, 1.90 mg/kg under CFM, 2.40 mg/kg under zinc fertiliser, 2.41 mg/kg under CFZn, and 2.66 mg/kg under CZn, whereas CF showed no significant effect. Relative to the commonly reported critical thresholds of soil available zinc, which are approximately 0.80–1.35 mg/kg depending on soil type, compost and CFC generally raised soil available zinc slightly above deficiency thresholds into a relatively adequate range. Manure, CFM, zinc fertiliser, CFZn, and CZn raised soil available zinc more clearly above the commonly reported critical levels. Thus, except for CF, the evaluated organic or zinc-containing treatments generally elevated soil available zinc beyond deficiency thresholds. However, these values should not be interpreted as evidence of generalised excess on the basis of available zinc alone. For soil total zinc, the control-group mean was 58.30 mg/kg, with an interquartile range of 34.55–74.90 mg/kg. Using this mean as a reference, the approximate soil total zinc values were 72.88 mg/kg under manure, 75.21 mg/kg under CFM, 75.21 mg/kg under zinc fertiliser, 76.96 mg/kg under CFZn, and 73.46 mg/kg under CZn. These values remained below the 160 mg/kg dry-soil screening benchmark for terrestrial plants proposed by the United States Environmental Protection Agency. This suggests that the evaluated management practices did not generally cause zinc content to exceed recommended or screening levels. These results therefore support refined and context-specific zinc management strategies rather than a single universal recommendation. Zinc fertiliser, CFZn, and CZn should be prioritised when rapid correction is needed. Manure and CFM are more appropriate for moderate correction, especially in soils with soil organic carbon

> 12 g/kg. CZn is particularly suitable for soils with soil organic carbon ≤ 12 g/kg or pH > 7.5. CFC and CFM are also suitable for acidic soils. Compost and CFC are more appropriate for mild improvement or maintenance. Overall, these findings indicate that zinc-containing fertilisation can improve deficient or marginal zinc status without generally causing zinc content to exceed recommended or screening levels at the dataset scale.

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