

Contamination Level Determines Whether Soil-Applied Zinc Oxide Nanoparticles Limit Cadmium Uptake in Maize

Miebaka Emmanuel Ikiriko^{1*} , Isaac Glory Chimamanda¹ , and Idiami Victoria Ogie² 

Abstract. Cadmium (Cd) persists in agricultural soils and maize, a staple cereal, takes it up readily. Zinc oxide nanoparticles (ZnO NPs) are widely proposed as a remedy, yet most supporting evidence comes from foliar sprays or from soils with little Cd. We grew maize (*Zea mays* L.) in a strongly acidic loamy sand amended with Cd at 150, 250 and 350 mg kg⁻¹ and treated it with soil-applied ZnO NPs at 100, 150 and 200 mg kg⁻¹, in a screen-house factorial experiment with an untreated control. Cd reduced growth in proportion to dose; plants at the highest rate were 42% shorter than those at the lowest. No ZnO NP rate restored growth to control levels, and 100 mg kg⁻¹ gave taller plants and longer roots than 150 or 200 mg kg⁻¹. The effect of ZnO NPs on tissue Cd depended on contamination. At 150 mg kg⁻¹ Cd, raising ZnO NPs from 100 to 200 mg kg⁻¹ lowered shoot Cd by 51%. At 250 and 350 mg kg⁻¹ Cd, higher ZnO NP rates were instead associated with higher root and shoot Cd. The translocation factor stayed below 1 in every treatment and was lowest at 200 mg kg⁻¹ ZnO NPs. Soil-applied ZnO NPs cannot be relied on as a general control on Cd uptake by maize. Where they lowered shoot Cd, at the lowest contamination level tested, they did so at a cost to growth.

Keywords: cadmium, zinc oxide nanoparticles, maize, translocation factor, soil contamination, nanoremediation

Introduction

Cadmium (Cd) is a Group 1 human carcinogen (IARC, 2012) with no known function in plants. It reaches people mainly through crops grown on polluted soil. A recent global synthesis of 796,084 soil samples estimated that 14–17% of the world's cropland is affected by toxic metal pollution, and that 0.9–1.4 billion people live in regions of elevated risk (Hou et al., 2025); Cd is one of the seven metals it covers. How much of the Cd in a soil reaches a crop depends on soil chemistry. Cd mobility is governed by pH, organic matter and competition from other cations, and acidic soils release more of it to roots (Kubier et al., 2019).

Maize is a staple cereal across sub-Saharan Africa, which makes its Cd content a matter of food safety. The root is the first organ to meet Cd. Cd slows root elongation and alters root anatomy (Lux et al., 2011), and it changes the uptake of other metals (Wang et al., 2007). Cd also resembles zinc (Zn) chemically, and the two elements compete for uptake, which is why Zn supply has long been considered a way of limiting Cd entry (Rizwan et al., 2019b).

¹Department of Crop and Soil Science, Faculty of Agriculture, University of Port Harcourt, Choba, Rivers State, Nigeria

²Department of Soil Science, Faculty of Agriculture, Ignatius Ajuru University of Education, Port Harcourt, Nigeria

*Corresponding Author. E-mail: miebaka.ikiriko@uniport.edu.ng

Received: 13 April 2026; Accepted: 9 September 2026; Published online: 25 October 2026

© The Author(s) 2026. This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).

The root can, in addition, hold Cd back from the shoot: high Cd in the rhizosphere accelerates the maturation of apoplastic barriers in the root (Lux et al., 2011). Zinc oxide nanoparticles (ZnO NPs) have attracted interest as a vehicle for that Zn. In wheat, ZnO NPs applied through soil or as a foliar spray lowered grain Cd by 16–78% and 30–77%, respectively, and improved growth (Hussain et al., 2018). In maize, foliar ZnO NPs have been reported to reduce Cd accumulation, alone or combined with biochar (Rizwan et al., 2019a; Zha et al., 2022), and to lessen Cd-induced oxidative and metabolic damage in seedlings (Hussain et al., 2024).

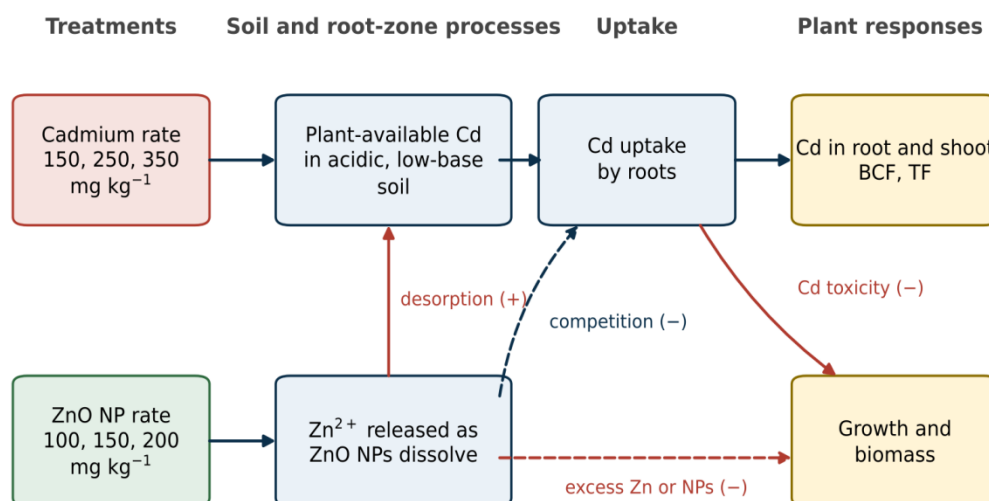
The evidence is, however, conditional. A review by Rizwan et al. (2019b), concluded that the effect of Zn on Cd accumulation is inconsistent and depends on the concentrations of both metals, the exposure period, the species and the growth conditions. In rice, Zn and Cd were antagonistic in roots and shoots, yet higher Zn activity increased the transfer of Cd from root to shoot, and the net effect depended on genotype (Cai et al., 2019). Soil-applied ZnO NPs raised rice growth under Cd stress but, at high doses, also raised the bioavailable Cd in the rhizosphere (Zhang et al., 2019).

The maize studies cited above used foliar sprays at 25–100 mg L⁻¹ or, in one case, seedlings in nutrient solution at 0.6 mM Cd (Hussain et al., 2024), and the soil-based rice work used Cd at 1.0–5.0 mg kg⁻¹ (Zhang et al., 2019). We found no study that tested soil-applied ZnO NPs in maize across a wide gradient of soil Cd.

This gap has practical consequences. Neither the nanoparticle rate that best serves maize nor the Cd level beyond which the treatment stops working has been established. Advisers working on land polluted by mining, industrial effluent or waste need to know whether a nanoparticle amendment deserves a recommendation, at what rate, and for what degree of pollution. Applying it without that knowledge risks paying for a treatment that, under some conditions, may increase Cd in the crop. A dose–response test across contamination levels, in a soil of the kind on which maize is commonly grown in the humid tropics, is therefore needed.

We framed the study around three processes that operate when ZnO NPs enter an acidic soil carrying Cd (Fig. 1). First, the nanoparticles dissolve and release Zn²⁺. Second, Zn²⁺ competes with Cd²⁺ for uptake sites at the root surface, which lowers Cd entry (Rizwan et al., 2019b; Cai et al., 2019). Third, Zn²⁺ may displace Cd from soil exchange sites and raise the amount available to roots, since competition between cations is a recognised route of Cd release (Kubier et al., 2019; Zhang et al., 2019), and excess Zn or nanoparticles may damage roots directly (Lin & Xing, 2007).

The first process favours lower tissue Cd; the second and third work against it. Their balance should depend on how much Cd the soil carries and how much ZnO is added, and root retention then determines how much of the absorbed Cd reaches the shoot (Lux et al., 2011). Tissue Cd and its partitioning, expressed as the bioconcentration factor (BCF) and translocation factor (TF), are therefore the response variables that show which process dominates, and growth shows the cost to the plant. The framework does not assume that ZnO NPs protect maize. It treats protection as one possible outcome.



Red arrows: processes expected to raise Cd availability or damage growth. Dashed blue arrow: Zn²⁺ competition expected to lower Cd uptake.

Figure 1

Conceptual framework. ZnO NPs release Zn²⁺, which may lower Cd uptake by competition at the root surface, raise Cd availability by displacing Cd from exchange sites, or harm growth directly at high rates. Tissue Cd, BCF and TF show which process dominates; growth shows the cost to the plant.

The main objective of this study was to determine how soil-applied ZnO NPs at three rates affect Cd uptake by maize grown at three levels of Cd contamination. The specific objectives were to (i) determine the effect of ZnO NP rate on the growth and biomass of maize exposed to different levels of Cd; (ii) evaluate the influence of ZnO NPs on Cd accumulation in the roots and shoots across the Cd gradient; and (iii) calculate the BCF and TF of Cd in maize under each combination of ZnO NP and Cd.

Materials and Methods

Site and Soil

The experiment was carried out in the screen house of the Department of Crop and Soil Science, Faculty of Agriculture, University of Port Harcourt, Choba, Rivers State, Nigeria (about 4°53'–4°54' N, 6°54'–6°55' E), in the humid tropical rainforest zone. Surface soil (0–30 cm) was taken from an uncultivated part of the Faculty's Teaching and Research Farm, bulked, cleaned of debris, air-dried for seven days and sieved (2 mm). A subsample was analysed before treatment in triplicate. Particle size was determined by the hydrometer method (Bouyoucos, 1962); pH in a 1:1 soil–water suspension; electrical conductivity in a 1:2 suspension; organic carbon by dichromate wet oxidation (Walkley & Black, 1934); total nitrogen by macro-Kjeldahl digestion (Bremner & Mulvaney, 1982); available phosphorus by Bray P-1 extraction (Bray & Kurtz, 1945) with molybdenum-blue colorimetry (Murphy & Riley, 1962); exchangeable bases in 1 N neutral ammonium acetate, with potassium read by flame photometry and calcium and magnesium by atomic absorption spectrophotometry (AAS); and background Cd after aqua regia digestion, by AAS at 228.8 nm.

Treatments and Design

Cd was added as analytical-grade CdCl₂·2.5H₂O at 150, 250 and 350 mg Cd kg⁻¹ soil. ZnO NPs (average particle size 10–30 nm, purity 99.8%, according to the manufacturer; SkySpring Nanomaterials, Houston, USA) were added at 100, 150 and 200 mg kg⁻¹. The nine Cd × ZnO NP combinations, plus an untreated control, were arranged in a completely randomised design with four replicate pots each (40 pots analysed here). Ten kilograms of soil were placed in each perforated 10-

litre bag, with a bowl beneath to collect leachate, which was returned to the same bag so that no Cd, Zn or nutrients were lost. The Cd salt was dissolved in 100 mL of distilled water, sprinkled over the soil and mixed in. Pots were brought to field capacity and left to equilibrate for two weeks. ZnO NPs were then dispersed in 20 mL of deionised water, sonicated for 30 minutes, mixed into the soil, and the pots were left for three days before sowing. Cd-only and ZnO-only pots included in the original plan were not part of the analysis reported here.

Crop Management and Measurements

Three seeds of maize variety Oba Super 6 were sown per pot at 3 cm depth and thinned to two plants two weeks after sowing. Pots were watered to near field capacity and weeded by hand. Plant height, leaf number (fully opened green leaves) and stem girth (Vernier caliper, 5 cm above the soil) were recorded at 2, 4, 6 and 8 weeks after planting. Plants were harvested at 8 weeks. Shoot length, root length, and fresh shoot and root weights were recorded, and tissues were dried at 70 °C to constant weight (about 72 h) for dry weights. Dried tissue was ground (0.5 mm), digested in a 4:1 mixture of concentrated HNO₃ and HClO₄, and Cd was read by AAS at 228.8 nm against standards prepared from a certified 1,000 mg L⁻¹ stock, with reagent blanks and a drift check every ten samples. The bioconcentration factor was calculated as root Cd divided by soil Cd, and the translocation factor as shoot Cd divided by root Cd (Yoon et al., 2006).

Statistical Analysis

Data were subjected to two-way analysis of variance for a factorial experiment in a completely randomised design, testing the main effects of Cd rate and ZnO NP rate and their interaction, with the contrast between control and treated plants also evaluated. Growth data were analysed separately for each sampling date. Means were separated by Duncan's multiple range test at $P \leq 0.05$. Pearson correlation was used to relate tissue Cd to growth and biomass traits ($n = 40$). Analyses were run in SAS version 9.4.

Results and Discussion

Soil Conditions Favour Cd Mobility

The experimental soil was a loamy sand (81.0% sand, 12.8% silt, 6.2% clay) and strongly acidic (pH 5.21). Organic matter was high for the texture (104.0 g kg⁻¹), but exchangeable bases were low (2.09 cmol kg⁻¹) and the background Cd concentration was 0.07 mg kg⁻¹ (Table 1). With so little clay, the capacity of this soil to hold added Cd rests largely on its organic matter, and at pH near 5 a considerable share of added Cd is expected to remain available to roots (Kubier et al., 2019). The scarcity of base cations has a second consequence. Zn released from the nanoparticles would meet little competition from calcium, magnesium and potassium and could therefore act directly on Cd at exchange sites and at the root surface.

Table 1

Properties of the experimental soil before treatment (means of three determinations)

Property	Value
pH (H ₂ O)	5.21
Sand / silt / clay (%)	81.0 / 12.8 / 6.2
Textural class	Loamy sand
Total organic carbon (g kg ⁻¹)	61.8
Organic matter (g kg ⁻¹)	104.0
Total nitrogen (g kg ⁻¹)	6.8
Available phosphorus (mg kg ⁻¹)	14.20
Exchangeable Ca, Mg, K, Na (cmol kg ⁻¹)	1.60, 0.34, 0.06, 0.09

Property	Value
Total exchangeable bases (cmol kg ⁻¹)	2.09
Cadmium, background (mg kg ⁻¹)	0.07

Values are those reported in the dissertation (Isaac, 2026).

Cadmium Suppresses Growth in Proportion to Dose

Cd rate was the dominant influence on growth. By 8 weeks after planting (WAP), mean plant height fell from 36.33 cm at 150 mg kg⁻¹ Cd to 25.42 cm at 250 mg kg⁻¹ and 21.08 cm at 350 mg kg⁻¹, a loss of 42.0% across the range, and the three rates differed significantly at every sampling date. Leaf number (10.25 versus 6.50), shoot fresh weight (17.33 versus 10.33 g), root dry weight (3.70 versus 2.26 g) and root length (16.25 versus 9.92 cm) followed the same direction, with reductions of 37–40% between the lowest and highest rate (Table 2). Stem girth was the least responsive trait. Cd affected it at 2 and 8 WAP only, and the difference at 8 WAP was confined to the highest rate (1.92 cm, against 2.60 and 2.38 cm at the two lower rates).

Compared with the untreated control, no treatment combination came close. From 4 WAP onwards the control was taller and carried more leaves than every Cd-treated combination. At 8 WAP the best combination (150 mg kg⁻¹ Cd with 100 mg kg⁻¹ ZnO NPs) was still 25.8% shorter than the control, carried about half as many leaves (12.50 against 23.50) and produced 29.3% less shoot fresh weight. The worst combination (350 mg kg⁻¹ Cd with 200 mg kg⁻¹ ZnO NPs) reached one-third of control height and 71% less shoot fresh weight (Table 2; Fig. 2).

Table 2

Growth and biomass of maize at 8 weeks after planting (WAP), by treatment combination

Treatment (mg kg ⁻¹)	Plant height (cm)	Leaves (no.)	Stem girth (cm)	Shoot fresh wt (g)	Root length (cm)	Root dry wt (g)
Control	60.00±3.74 ^a	23.50±3.00 ^a	5.83±0.45 ^a	33.25±11.35 ^a	26.50±4.04 ^a	6.58±2.36 ^a
Cd 150 + ZnO 100	44.50±6.56 ^b	12.50±4.04 ^b	2.80±0.70 ^b	23.50±7.90 ^b	20.00±4.08 ^b	4.68±2.30 ^b
Cd 150 + ZnO 150	31.75±3.86 ^c	10.25±4.99 ^{bc}	2.40±0.36 ^{bc}	14.75±2.22 ^c	14.75±1.26 ^c	3.58±0.95 ^{bc}
Cd 150 + ZnO 200	32.75±1.50 ^c	8.00±1.41 ^{cd}	2.60±0.36 ^{bc}	13.75±3.20 ^c	14.00±1.63 ^{cd}	2.85±0.73 ^{bc}
Cd 250 + ZnO 100	28.25±3.86 ^{cd}	7.25±1.50 ^{cd}	2.43±0.72 ^{bc}	13.25±3.10 ^c	12.25±1.89 ^{cde}	3.05±0.90 ^{bc}
Cd 250 + ZnO 150	24.00±4.32 ^{de}	6.50±1.29 ^{cd}	2.28±0.43 ^{bc}	12.25±1.26 ^c	11.25±2.63 ^{cde}	3.08±0.72 ^{bc}
Cd 250 + ZnO 200	24.00±4.62 ^{de}	5.75±0.96 ^d	2.43±0.26 ^{bc}	12.00±2.31 ^c	11.50±1.91 ^{cde}	2.63±0.35 ^c
Cd 350 + ZnO 100	22.25±5.06 ^{de}	7.00±1.41 ^{cd}	2.05±0.26 ^{bc}	11.25±2.63 ^c	10.25±2.06 ^{de}	2.23±0.86 ^c
Cd 350 + ZnO 150	21.00±1.15 ^e	6.75±0.96 ^{cd}	1.83±0.65 ^c	10.25±0.50 ^c	10.00±0.82 ^e	2.20±0.26 ^c
Cd 350 + ZnO 200	20.00±2.45 ^e	5.75±0.96 ^d	1.88±0.53 ^c	9.50±1.00 ^c	9.50±1.73 ^e	2.35±0.35 ^c

Values are means $\pm$ SD of four replicate pots. Means in a column sharing a letter do not differ at $P \leq 0.05$ (Duncan's multiple range test). Treatments are Cd rate + ZnO NP rate in mg kg^{-1} .

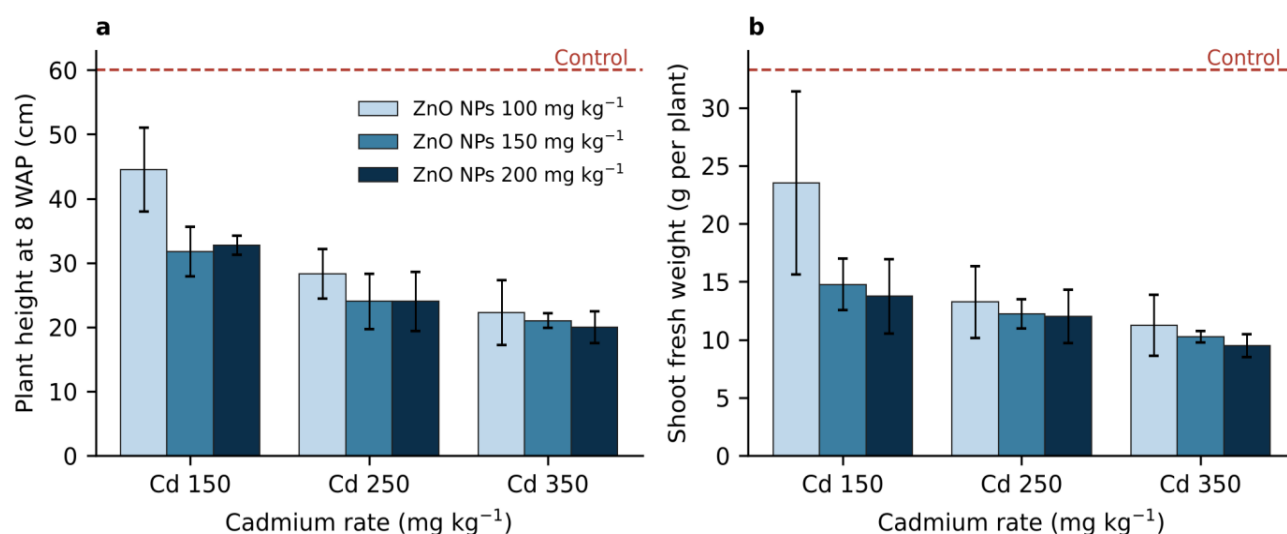


Figure 2

Growth of maize at 8 WAP under three Cd rates and three ZnO NP rates. a, Plant height. b, Shoot fresh weight. Bars show means and error bars show SD (four replicate pots); the dashed line marks the untreated control mean. ZnO NP rate is given in mg kg^{-1} .

These results agree with the established view that Cd restricts maize growth in step with the amount present in the root zone. The root is the first organ to meet Cd, and Cd slows root elongation and alters root anatomy (Lux et al., 2011). A shorter, damaged root system would supply the shoot with less water and fewer nutrients, which is a plausible route to the reduced height and leaf production we observed, although we did not measure water or nutrient status.

Nanoparticle Rate did not Restore Growth, and the Lowest Rate did Best

If ZnO NPs protected maize from Cd, growth should have risen with the nanoparticle rate. It did not. Among ZnO-treated plants, 100 mg kg^{-1} produced the tallest plants at 2, 6 and 8 WAP (31.67 cm at 8 WAP) and the longest roots (14.17 cm), whereas 150 and 200 mg kg^{-1} did not differ from each other (25.58 cm in both cases for height; 12.00 and 11.67 cm for root length). The nanoparticle rate had no significant effect on leaf number, stem girth or any fresh or dry weight, although leaf number fell steadily from 8.92 to 7.83 to 6.50 as the rate rose. The Cd $\times$ ZnO interaction for height was significant only at 2 WAP, when the two lowest-Cd combinations with 100 and 200 mg kg^{-1} ZnO NPs were tallest. It had vanished by 4 WAP, which suggests that any early benefit was overtaken by the cumulative effect of Cd.

This pattern differs from published reports in which ZnO NPs improved the growth of Cd-stressed plants (Hussain et al., 2018; Hussain et al., 2024; Rizwan et al., 2019a; Zhang et al., 2019). The contrast needs careful reading. Those studies compared ZnO-treated plants with plants exposed to Cd alone, and the maize studies applied the nanoparticles to leaves at 25–100 mg L^{-1} , so the root zone never received a large dose. We mixed the whole dose into the soil, and we did not analyse Cd-only pots. Our data therefore cannot show whether ZnO NPs improved growth relative to no nanoparticles. They show something narrower: no rate restored growth to control levels, and rates above 100 mg kg^{-1} were associated with poorer height and root length than the lowest rate.

A direct toxic effect of the nanoparticles is one explanation. Lin and Xing (2007) found that ZnO NPs at 2,000 mg L⁻¹ almost stopped root elongation in several species, maize among them, although the exposure was in suspension and the concentrations are not comparable with ours in soil. In an acidic soil, dissolution of ZnO would release Zn²⁺ quickly, and the two higher rates may have supplied more Zn than the plants could tolerate. We did not measure Zn in soil or tissue, so this explanation remains untested.

The Effect on Tissue Cd Depends on Contamination Level

Cd concentrations in roots, shoots and soil rose significantly with Cd rate ($P < 0.01$ in each case). Root Cd increased from 16.72 mg kg⁻¹ at 150 mg kg⁻¹ Cd to 37.43 mg kg⁻¹ at 350 mg kg⁻¹, a factor of 2.2, and shoot Cd rose from 9.42 to 18.86 mg kg⁻¹. This is the expected dose response, as reported for Cd accumulation in maize by Wang et al. (2007). Concentrations followed the order soil > root > shoot in every treatment.

The nanoparticle effect was not uniform, and the significant Cd × ZnO interaction ($P < 0.01$) shows that it depended on Cd rate (Table 3; Fig. 3). At 150 mg kg⁻¹ Cd, root Cd fell from 20.90 to 16.41 to 12.86 mg kg⁻¹, and shoot Cd from 12.69 to 9.34 to 6.24 mg kg⁻¹, as the ZnO NP rate increased from 100 to 150 to 200 mg kg⁻¹. The shoot value at 200 mg kg⁻¹ was 50.8% lower than at 100 mg kg⁻¹ and was the lowest recorded in the experiment, statistically similar to the control. The result matches the reductions in wheat tissues described by Hussain et al. (2018) and the Zn–Cd antagonism reported for rice by Cai et al. (2019), who attributed lower Cd to competition between the two metals and to dilution through greater biomass.

Table 3

Cadmium concentrations (mg kg⁻¹), bioconcentration factor (BCF) and translocation factor (TF), by treatment combination

Treatment (mg kg ⁻¹)	Root Cd	Shoot Cd	Soil Cd	BCF	TF
Control	15.96±2.57 ^e	7.63±1.27 ^{fg}	31.80±5.06 ^e	0.502±0.002	0.479±0.030 ^{cd}
Cd 150 + ZnO 100	20.90±1.76 ^d	12.69±2.08 ^{cd}	41.80±2.80 ^d	0.500±0.010	0.607±0.080 ^{ab}
Cd 150 + ZnO 150	16.41±3.04 ^e	9.34±2.27 ^{ef}	32.18±5.85 ^e	0.511±0.045	0.566±0.051 ^{bc}
Cd 150 + ZnO 200	12.86±2.14 ^e	6.24±0.80 ^g	25.69±3.36 ^e	0.499±0.030	0.489±0.048 ^{cd}
Cd 250 + ZnO 100	15.42±2.41 ^e	10.37±2.75 ^{def}	30.91±4.58 ^e	0.499±0.011	0.664±0.086 ^a
Cd 250 + ZnO 150	20.62±1.97 ^d	11.66±1.70 ^{de}	41.72±4.20 ^d	0.494±0.007	0.565±0.058 ^{bc}
Cd 250 + ZnO 200	28.16±1.57 ^c	15.38±2.25 ^{bc}	56.43±3.32 ^c	0.499±0.005	0.544±0.053 ^{bc}
Cd 350 + ZnO 100	21.26±2.37 ^d	10.91±1.24 ^{de}	42.19±5.16 ^d	0.505±0.008	0.514±0.043 ^{cd}
Cd 350 + ZnO 150	54.65±2.35 ^a	29.09±1.13 ^a	106.65±5.24 ^a	0.513±0.024	0.533±0.028 ^{bcd}
Cd 350 + ZnO 200	36.38±4.27 ^b	16.59±2.60 ^b	72.19±8.66 ^b	0.504±0.007	0.455±0.032 ^d

Values are means ± SD of four replicate pots. Means in a column sharing a letter do not differ at $P \leq 0.05$ (Duncan's multiple range test); BCF did not differ among treatments. Cd × ZnO interaction: $P < 0.01$ for root, shoot and soil Cd. Root and shoot Cd on a dry-weight basis.

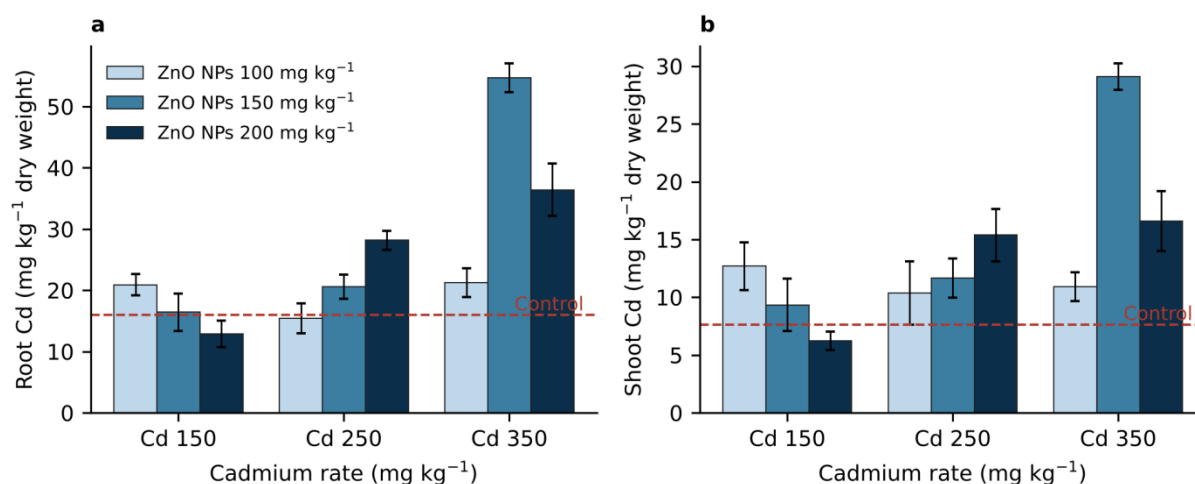


Figure 3

Cadmium concentration in maize tissue at 8 WAP. a, Root Cd. b, Shoot Cd. Bars show means and error bars show SD (four replicate pots); the dashed line marks the untreated control mean. The Cd × ZnO NP interaction was significant ($P < 0.01$). Note that the control was not Cd-free in the measurements (see text).

At the higher Cd rates, the response reversed. At 250 mg kg⁻¹ Cd, root Cd rose from 15.42 to 28.16 mg kg⁻¹ (+82.6%) and shoot Cd from 10.37 to 15.38 mg kg⁻¹ (+48.3%) as ZnO NPs went from 100 to 200 mg kg⁻¹. At 350 mg kg⁻¹ Cd, the 150 mg kg⁻¹ nanoparticle rate produced the highest concentrations of the whole study, 54.65 mg kg⁻¹ in roots and 29.09 mg kg⁻¹ in shoots, which were 157% and 167% above the values at 100 mg kg⁻¹. These results do not support a general protective role for soil-applied ZnO NPs. They fit the conclusion of Rizwan et al. (2019b) that the outcome of Zn supply under Cd stress is inconsistent and conditional, and they parallel the finding of Zhang et al. (2019) that high ZnO NP doses raised bioavailable Cd in the rhizosphere of rice and, in a lightly contaminated soil, raised rice Cd above the Chinese limit of 0.2 mg kg⁻¹.

We think the following account is the most economical, and we offer it as a hypothesis. Where Cd is relatively scarce, competition between Zn²⁺ and Cd²⁺ at the root surface dominates, and more Zn means less Cd entering the plant. Where Cd is abundant, Zn²⁺ released from the nanoparticles may displace Cd from the exchange sites of a soil that has few base cations and little clay, moving Cd into solution faster than the plant's uptake machinery is blocked. Kubier et al. (2019) list competition-induced desorption as one route by which Cd is mobilised in soils. Soil pH, available Cd and available Zn were not measured after the nanoparticles were added, so the mechanism awaits direct testing.

Cd is Retained in Roots, and the Highest ZnO Rate Retains More

The bioconcentration factor (BCF; root Cd divided by soil Cd) was essentially constant, between 0.494 and 0.513 in all treatments, and did not respond to Cd rate, nanoparticle rate or their interaction. The translocation factor (TF; shoot Cd divided by root Cd) was below 1 everywhere, from 0.455 to 0.664, so roots held more of the absorbed Cd than shoots did. Under the criteria of Yoon et al. (2006), who defined BCF as the ratio of root to soil concentration and TF as the ratio of shoot to root concentration, maize in this experiment qualifies neither for phytoextraction nor for phytostabilisation, both of which, on those criteria, require a BCF above 1. The retention of Cd in roots is consistent with the barrier function of the root endodermis and exodermis, which restricts movement of Cd towards the xylem (Lux et al., 2011).

The TF was significantly lower at 200 mg kg⁻¹ ZnO NPs (0.496) than at 100 mg kg⁻¹ (0.595) or 150 mg kg⁻¹ (0.555), and it was lowest at the 200 mg kg⁻¹ rate within each Cd level. It was also lower at

the highest Cd rate (0.501) than at the two lower rates (0.554 and 0.591). Taken at face value, a large Zn supply reduced the share of absorbed Cd that reached the shoot, even in pots where total tissue Cd was higher. That is the one nanoparticle effect observed at every Cd rate, and for food safety it is the most useful. It runs against Cai et al. (2019), who found in rice that high Zn activity increased Cd transfer from root to shoot, so the effect appears to depend on species, genotype or Zn status, as those authors suggest. The direction of the TF response also needs caution in its own right: the differences were modest (0.455 to 0.664) and the TF of the control did not differ significantly from most treated combinations.

Plant Cd Tracks Growth Loss, but Only Moderately

Across the control and the nine treatment combinations ($n = 40$ pots), all growth and biomass traits were strongly and positively correlated with one another ($r = 0.692$ to 0.966), which indicates that the treatments affected the plants as a whole and not single traits. Shoot Cd correlated negatively and significantly with all eight growth and biomass traits, the strongest with plant height ($r = -0.469$), stem girth ($r = -0.460$) and root length ($r = -0.428$). Root Cd was significantly and negatively correlated with seven of the eight traits; its correlation with shoot dry weight ($r = -0.297$) was not significant. Root, shoot and soil Cd were closely related ($r = 0.966$ to 0.997), whereas BCF and TF were unrelated to any growth trait (r from -0.268 to 0.209).

These coefficients confirm that more Cd in the plant went with less growth. They are also moderate. An r of -0.47 means that tissue Cd accounts for about 22% of the variation in plant height. The remainder reflects the dose of Cd in the pot, the nanoparticle rate and plant-to-plant variation, and the absence of any link between TF and growth shows that how Cd was divided between root and shoot mattered little to growth over eight weeks.

Conclusion and Recommendation

Conclusion

In a strongly acidic, coarse-textured soil, Cd reduced the growth and biomass of maize in proportion to the rate applied, and soil-applied ZnO NPs did not restore growth to the level of the control at any rate tested. The lowest nanoparticle rate (100 mg kg^{-1}) supported taller plants and longer roots than 150 or 200 mg kg^{-1} .

The effect of ZnO NPs on tissue Cd depended on the level of contamination. Only at 150 mg kg^{-1} Cd did raising the nanoparticle rate lower root and shoot Cd, and at 200 mg kg^{-1} it halved shoot Cd relative to 100 mg kg^{-1} . At 250 and 350 mg kg^{-1} Cd, higher nanoparticle rates did not lower Cd uptake and in several cases raised it. Soil-applied ZnO NPs are therefore not a dependable means of limiting Cd uptake by maize across the range of contamination studied. Maize retained most absorbed Cd in its roots (TF below 1 throughout), and the 200 mg kg^{-1} rate lowered the translocation factor at every Cd level. At the lowest Cd level, the rate that gave the least shoot Cd was not the rate that gave the best growth.

Recommendations

1. Soils suspected of Cd contamination, such as those that have received industrial effluent or waste, should be tested before maize is grown on them. Cd reduced growth and accumulated in shoots at every contamination level examined here.
2. Where ZnO NPs are applied to acidic sandy soil contaminated with Cd, the rate should not exceed 100 mg kg^{-1} if the aim is to support growth, because 150 and 200 mg kg^{-1} gave shorter plants with shorter roots.

3. Where contamination is at the lowest level tested ($150 \text{ mg kg}^{-1} \text{ Cd}$) and the priority is a lower shoot Cd, ZnO NPs at 200 mg kg^{-1} may be considered, since this rate halved shoot Cd relative to 100 mg kg^{-1} . The user should expect a growth penalty (plants about 26% shorter at 8 WAP than at 100 mg kg^{-1}) and should confirm grain Cd before any produce is used for food or feed.
4. ZnO NPs should not be relied on as the only remediation measure for soils at or above $250 \text{ mg kg}^{-1} \text{ Cd}$, because they did not lower, and in places raised, Cd uptake at these levels. Such soils should not be used to grow maize for food or feed until they have been remediated.
5. Future trials should include Cd-only and ZnO-only controls, measure soil pH and available Cd and Zn after nanoparticle application, test Cd rates closer to those found on farmland, and report grain Cd. These additions address the main gaps identified in this study.

Conflict of Interest

The authors declare that they have no conflict of interest regarding this article.

References

- Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal*, 54(5), 464–465.
<https://doi.org/10.2134/agronj1962.00021962005400050028x>
- Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59(1), 39–45. <https://doi.org/10.1097/00010694-194501000-00006>
- Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—Total. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., pp. 595–624). American Society of Agronomy; Soil Science Society of America. <https://doi.org/10.2134/agronmonogr9.2.2ed.c31>
- Cai, Y., Xu, W., Wang, M., Chen, W., Li, X., Li, Y., & Cai, Y. (2019). Mechanisms and uncertainties of Zn supply on regulating rice Cd uptake. *Environmental Pollution*, 253, 959–965.
<https://doi.org/10.1016/j.envpol.2019.07.077>
- Hou, D., Jia, X., Wang, L., McGrath, S. P., Zhu, Y.-G., Hu, Q., Zhao, F.-J., Bank, M. S., O'Connor, D., & Nriagu, J. (2025). Global soil pollution by toxic metals threatens agriculture and human health. *Science*, 388(6744), 316–321. <https://doi.org/10.1126/science.adr5214>
- Hussain, A., Ali, S., Rizwan, M., Zia ur Rehman, M., Javed, M. R., Imran, M., Chatha, S. A. S., & Nazir, R. (2018). Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. *Environmental Pollution*, 242(Part B), 1518–1526.
<https://doi.org/10.1016/j.envpol.2018.08.036>
- Hussain, M., Kaousar, R., Haq, S. I. U., Shan, C., Wang, G., Rafique, N., Shizhou, W., & Lan, Y. (2024). Zinc-oxide nanoparticles ameliorated the phytotoxic hazards of cadmium toxicity in maize plants by regulating primary metabolites and antioxidants activity. *Frontiers in Plant Science*, 15, Article 1346427. <https://doi.org/10.3389/fpls.2024.1346427>
- International Agency for Research on Cancer. (2012). *Arsenic, metals, fibres, and dusts* (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 100C). World Health Organization.
- Isaac, G. C. (2026). *Effect of zinc oxide nanoparticles on cadmium uptake by maize plants (Zea mays L.) under different levels of cadmium contamination* [Bachelor's dissertation, University of Port Harcourt].
- Kubier, A., Wilkin, R. T., & Pichler, T. (2019). Cadmium in soils and groundwater: A review. *Applied Geochemistry*, 108, Article 104388. <https://doi.org/10.1016/j.apgeochem.2019.104388>
- Lin, D., & Xing, B. (2007). Phytotoxicity of nanoparticles: Inhibition of seed germination and root growth. *Environmental Pollution*, 150(2), 243–250.
<https://doi.org/10.1016/j.envpol.2007.01.016>

- Lux, A., Martinka, M., Vaculík, M., & White, P. J. (2011). Root responses to cadmium in the rhizosphere: A review. *Journal of Experimental Botany*, 62(1), 21–37.
<https://doi.org/10.1093/jxb/erq281>
- Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, 27, 31–36.
[https://doi.org/10.1016/S0003-2670\(00\)88444-5](https://doi.org/10.1016/S0003-2670(00)88444-5)
- Rizwan, M., Ali, S., Zia ur Rehman, M., Adrees, M., Arshad, M., Qayyum, M. F., Ali, L., Hussain, A., Chatha, S. A. S., & Imran, M. (2019a). Alleviation of cadmium accumulation in maize (*Zea mays* L.) by foliar spray of zinc oxide nanoparticles and biochar to contaminated soil. *Environmental Pollution*, 248, 358–367. <https://doi.org/10.1016/j.envpol.2019.02.031>
- Rizwan, M., Ali, S., Zia ur Rehman, M., & Maqbool, A. (2019b). A critical review on the effects of zinc at toxic levels of cadmium in plants. *Environmental Science and Pollution Research*, 26(7), 6279–6289. <https://doi.org/10.1007/s11356-019-04174-6>
- Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29–38. <https://doi.org/10.1097/00010694-193401000-00003>
- Wang, M., Zou, J., Duan, X., Jiang, W., & Liu, D. (2007). Cadmium accumulation and its effects on metal uptake in maize (*Zea mays* L.). *Bioresource Technology*, 98(1), 82–88.
<https://doi.org/10.1016/j.biortech.2005.11.028>
- Yoon, J., Cao, X., Zhou, Q., & Ma, L. Q. (2006). Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. *Science of the Total Environment*, 368(2–3), 456–464. <https://doi.org/10.1016/j.scitotenv.2006.01.016>
- Zha, Y., Zhao, B., & Niu, T. (2022). Bamboo biochar and zinc oxide nanoparticles improved the growth of maize (*Zea mays* L.) and decreased cadmium uptake in Cd-contaminated soil. *Agriculture*, 12(9), Article 1507. <https://doi.org/10.3390/agriculture12091507>
- Zhang, W., Long, J., Li, J., Zhang, M., Xiao, G., Ye, X., Chang, W., & Zeng, H. (2019). Impact of ZnO nanoparticles on Cd toxicity and bioaccumulation in rice (*Oryza sativa* L.). *Environmental Science and Pollution Research*, 26(22), 23119–23128.
<https://doi.org/10.1007/s11356-019-05551-x>