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Research Article

Zn Deficiency-Cd Contaminated Soils: The Effect of Zn Fertilization on the Uptake of Cd and Some Nutrient Elements by Wheat (*Triticum aestivum* L.) Plants

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Abstract: In recent years, the use of micronutrients such as Zn has become a practical approach to mitigate the harmful effects of metals. This research aimed to examine the effect of Zn fertilization on the concentrations of Cd and some nutrients in wheat in Cd-contaminated soil with excessive lime and Zn deficiency. Five different Zn doses Zn₀:0, Zn₁:3, Zn₂:6, Zn₃:9, and Zn₄:12 mg kg⁻¹ were applied in three replicates to soils contaminated with 20 mg kg⁻¹ Cd according to a completely randomized design. The study found that while Zn₂ application reduced Cd concentrations, the other Zn applications increased Zn and Fe concentrations in the plants. Zinc showed a positive relationship with Mg in all applications, while Zn showed a positive relationship with K and Ca in all applications except for the Zn₄. Specifically, in the Zn₂, Zn, Cu, K, and Ca were taken up at the highest levels, while Cd, Ni, and P were taken up at the lowest levels. As a result of this study, it was observed that Zn-fertilization in a Zn-deficient, Cd-contaminated soil was insufficient to alleviate Cd uptake in wheat plants, and it can be concluded that the relationship between Zn and Cd and other elements is controversial and may vary depending on the dose, soil properties, the part of the plant, and the growth period. In future studies, applying different Cd and Zn concentrations and measuring them in different plant organs at different stages will contribute to a better understanding of the relationship between Zn and Cd.

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1. Introduction

Modern cities, industrialization, the use of wastewater in agriculture, and pesticide and fertilizer applications are considered the most significant causes of heavy metal pollution in soils, and cadmium (Cd) is among the most toxic of these heavy metals (Jing et al., 2025). Cadmium is readily absorbed by plants due to its high mobility and soil solubility, negatively affecting plant physiological and biochemical processes and product quality. It also poses a risk to humans through bioaccumulation as it enters the food chain (Song et al., 2025).

The accumulation of Cd in agricultural soils has become a major global environmental concern, and various applications have been attempted to reduce Cd toxicity in plants (Rizwan et al., 2019). Exogenous applications may be a viable approach to increase tolerance to certain elements and reduce their concentrations in plants (Huang et al., 2017). Appropriate mineral fertilization may be the most feasible and inexpensive way to control Cd uptake in plants (Rehman et al., 2018). Over recent years, the use of micronutrients such as Zn has become a practical approach globally to mitigate the toxic effects of heavy metals (Farooq et al., 2020; Hassan et al., 2022).

Zinc deficiency is common in agricultural areas of Türkiye, and studies indicate that approximately 55% of soils are deficient in zinc (Saltalı and Alhashemi, 2022). Taşpınar et al. (2025) reported that 55% of the agricultural soils in the Central Anatolia Region were deficient in Zn. Furthermore, it has been reported that high soil pH and lime content can create difficulties in the uptake of micronutrients such as Zn (Abacı Bayar and Demir, 2025). In addition to being an important nutrient for plants, zinc plays a significant role in mitigating the adverse effects of abiotic stresses (Zafar et al., 2017). Cadmium toxicity can be more severe under Zn deficiency conditions (Köleli et al., 2004).

Zinc and Cd, both members of Group 12 (IIB) of the periodic table, exhibit similar chemical and geochemical characteristics (Clemens, 2019; Zhao and Wang, 2020; McLaughlin et al., 2021). Due to its chemical similarity to Cd, Zn may compete with Cd ions for uptake from the soil via roots and may interact with Cd in the phloem-xylem (Fahad et al., 2015). Research has shown that applying zinc (Zn) can alleviate Cd-induced stress in plants such as wheat (Abbas et al., 2017) and rice (Huang et al., 2019). However, Zn has increased Cd concentrations in roots and shoots of maize (Sozubek et al., 2015). The role of Zn in Cd accumulation is controversial. It depends on Zn and Cd concentrations, plant species, and growth conditions (Rizwan et al., 2019). It has been reported that when Cd and Zn are applied together, they exhibit both antagonistic (Murtaza et al., 2017) and synergistic (Cojocaru et al., 2016) effects on each other during their uptake by plants.

Wheat (*Triticum aestivum* L.), one of the three major cereals, accounts for 37.5% of global cereal cultivation area and 28.7% of total cereal production, providing approximately 40% of the world's zinc intake (Zhu et al., 2025). Today, it is estimated that nearly half of the world's wheat-growing soils are deficient in bioavailable Zn, and in Zn-deficient soils in Türkiye, the Zn content in cereals is less than 10 mg kg⁻¹, while in areas fertilized with Zn, the Zn content in cereals is above 20 mg kg⁻¹ however, it is known that the recommended amount for healthy nutrition in humans is in the range of 40-50 mg kg⁻¹ (Cakmak and Kutman, 2018). Therefore, zinc fertilization, particularly in soils deficient in zinc and contaminated with Cd, has the potential to reduce Cd concentrations in plants while also providing the necessary zinc concentrations for humans. Additionally, Sarwar et al. (2015) reported that Zn application to Cd-contaminated soils increased mineral content in wheat shoots and grains, including P, K, and Zn.

This research is designed to determine the effect of different concentrations of Zn applications on the uptake of Cd and certain nutrients by wheat plants grown in soil deficient in Zn, contaminated with Cd, alkaline in pH, and high in lime content.

2. Materials and Methods

2.1. Material

The study was conducted in 2024 as a pot trial in the garden of the Doğu Akdeniz Geçit Kuşağı Agricultural Research Institute. The Zn-deficient soil to be used in the study was selected based on preliminary studies of soil samples collected from different locations. The soil was collected from 0-30 cm depth (37.591667°N, 36.823611°E), dried in the shade, and sieved through a 4 mm sieve.

Some characteristics of the soils used in the study: the texture is sandy loam, the pH is slightly alkaline (Alpaslan et al., 1998), and it is classified as slightly saline (Dellavalle, 1992). They have low organic matter content (Güçdemir, 2006) and high lime content at a calcareous level (Hızalan and Ünal, 1966). According to Alpaslan et al. (1998), potassium (K) extractable with ammonium acetate is at a sufficient level, while calcium (Ca) and magnesium (Mg) are abundant. The extractable phosphorus (P) content determined with sodium bicarbonate is low. Extractable iron (Fe), manganese (Mn), and copper (Cu), determined with diethylenetriaminepentaacetic acid (DTPA), are sufficient, while zinc (Zn) is

deficient in soils at 0.62 mg kg^{-1} . The nickel (Ni) content of the soil was determined to be 0.73 mg kg^{-1} and Cd 0.04 mg kg^{-1} (Table 1).

Table 1. Some physical and chemical properties of the soil used in the experiment

Clay (%)	Silt (%)	Sand (%)	pH	EC ($\mu\text{S cm}^{-1}$)	Lime (%)	O.M (%)	P (mg kg^{-1})	K (mg kg^{-1})
5	25	70	7.87	762	17.50	1.25	6.17	132.35
Ca (mg kg^{-1})	Mg (mg kg^{-1})	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Ni (mg kg^{-1})	Cd (mg kg^{-1})	
7570	1350	5.81	0.62	1.74	8.55	0.73	0.04	

The study was designed according to a completely randomized design (CRD), and 500 g of soil sample was weighed into plastic pots. Before sowing, $3\text{Cd}_3\text{SO}_4 \cdot 8\text{H}_2\text{O}$ ($\text{Cd}_3[\text{SO}_4]_3[\text{H}_2\text{O}]_8$) was added to the soil at a rate of 20 mg kg^{-1} Cd to all pots. Zinc was applied to Cd-contaminated soil at doses of Zn: 0 mg kg^{-1} , Zn₁: 3 mg kg^{-1} , Zn₂: 6 mg kg^{-1} , Zn₃: 9 mg kg^{-1} , and Zn₄: 12 mg kg^{-1} ; the experiment was conducted in a total of 15 pots with three replicates for each dose. Zinc sulfate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) in powder form was used as the Zn source. Triple superphosphate (TSP) was applied at a rate of 20 mg P kg^{-1} to compensate for phosphorus deficiency observed before wheat sowing, while nitrogen was applied at a rate of 32 mg N kg^{-1} ammonium sulfate at sowing and 40 mg N kg^{-1} urea fertilizer at tillering, according to the wheat plant's requirements (72 mg N kg^{-1}). The winter wheat variety Esperia, which is widely used and commercially available in our country, was used in the study.

Four seeds were sown in each pot and thinned out so that two wheat plants remained per pot after germination. The wheat plants were harvested after approximately 60 days, with all above-ground parts (stem and leaves) remaining. Plant samples harvested from each pot (two wheat plants) were combined to obtain a single composite sample. After harvesting, the wheat plants were first washed in tap water, then carefully rinsed several times with distilled water. The plant samples were then dried in an oven at 65°C until constant weight, ground with a plant grinder, and prepared for analysis.

2.2. Method

Soil texture was determined by hydrometer analysis of sand, silt, and clay fractions, and the results were classified according to the soil textural triangle (Gee and Bauder, 1986). Soil pH and electrical conductivity (EC) were measured in a 1:2.5 (w/v) soil-to-water suspension using calibrated pH and EC meters, respectively (Richards, 1954). Prior to measurements, the instruments were calibrated using standard buffer solutions (pH 4.0, 7.0, and 10.0). Soil organic matter content was determined using the modified Walkley–Black method (Nelson and Sommers, 1996). In this procedure, soil samples were subjected to wet oxidation with potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) and sulfuric acid (H_2SO_4), and the remaining dichromate was determined by titration. Soil calcium carbonate (CaCO_3) content was determined using a Scheibler calcimeter, based on the measurement of CO_2 gas volume released after treatment with dilute HCl (Allison and Moodie, 1965). The evolved CO_2 was collected in a closed system and measured volumetrically. Phosphorus can be extracted from soils using 0.5 M NaHCO_3 (pH:8.5) and determined colorimetrically using a UV-VIS spectrophotometer (Optima SP-3000 Nano) (Olsen and Sommers, 1982). The instrument was calibrated with a series of phosphorus standard solutions ranging from 0 to 10 mg L^{-1} , achieving a calibration curve with $R^2 = 0.999$, and quality control was ensured through the use of blanks and replicate samples (Olsen and Sommers, 1982). Determination of Mg, Ca, and K in soils; determined by Richards (1954) using atomic absorption spectrophotometry (ASS; Agilent Technologies 200 Series, USA) on the filtrate obtained by extraction with 1 N ammonium acetate (pH: 7.0). Fe, Zn, Cu, Mn, Ni, and Cd in soils were determined according to the DTPA method developed by Lindsay and Norvell (1978) to determine extractable concentrations in near-neutral pH and calcareous soils. Plant samples were incinerated using the wet digestion method (Jones, 2001), and P concentrations were determined using vanadomolybdenophosphoric acid (Kuo, 1996). In plant samples, Ca, K, Mg, Zn, Fe, Cu, Mn, Ni, and Cd were measured using atomic absorption spectrophotometry (AAS).

2.3. Statistical Analysis

In the study conducted according to a completely randomized design, the data were subjected to analysis of variance (one-way ANOVA with Zn as the factor) using JMP statistical software, and statistically significant differences ($p < 0.05$) were compared using the Tukey test (JMP, 2018). Data on Cd, Fe, Cu, Mn, Ni, P, K, Ca, and Mg concentrations measured as a result of Zn applications were normalized between 0 and 1 and then converted into graphs using the Python seaborn library to interpret the relationship between Zn and these elements (Python Software Foundation, 2025).

3. Results

3.1. Cd and Zn concentration in plant tissues (mg kg^{-1})

The results of the analysis of variance (ANOVA) for Cd and Zn concentrations measured in the tissues of wheat plants grown in Cd-contaminated soil following Zn applications at different levels were found to be significant at the $p < 0.01$ level. The means and groups are presented in Table 2.

Table 2. Effect of Zn applications at different levels on Cd and Zn contents in wheat

Zn doses	Cd (mg kg^{-1})	Zn (mg kg^{-1})
Zn ₀	2.17±0.28b	27.00±1.50b
Zn ₁	2.67±0.28ab	38.25±8.75ab
Zn ₂	2.00±0.00b	49.25±5.25a
Zn ₃	3.17±0.27a	39.25±0.75ab
Zn ₄	2.67±0.25ab	43.25±5.75a
LSD _{0,05}	0.70	14.22
P-value	0.002**	0.006**

**: $p < 0.01$.

The highest Cd concentration (3.17 mg kg^{-1}) was measured in the Zn₃ application, while the lowest Cd concentrations (2.17 and 2.0 mg kg^{-1}) were measured in the Zn₀ and Zn₂ applications. Specifically, Zn₃ application increased Cd in wheat plant above-ground tissue. Zinc treatments significantly increased Zn content in plant tissues.

Figure 1 shows the variation in Cd and Zn concentrations in plant tissues resulting from Zn applications at different levels.

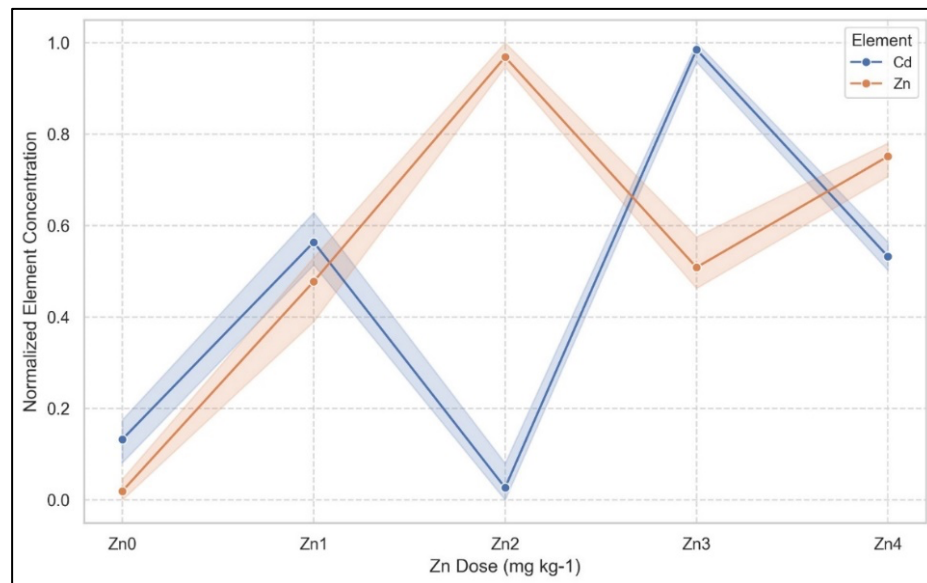


Figure 1. The Graph showing the effect of Zn_{0,1,2,3,4} applications on Cd and Zn contents in wheat.

As shown in Figure 1, the Zn_1 application showed a positive correlation in Zn and Cd levels, while the other Zn applications ($Zn_{2,3,4}$) caused exhibited an inverse relationship in these two elements.

3.2. Fe, Cu, Mn, and Ni concentration in plant tissues (mg kg⁻¹)

The means and groups of the variance analysis results for Fe, Mn, Cu, and Ni measured in wheat plant tissues grown in Cd-containing soils following Zn applications at different levels are presented in Table 3. According to the ANOVA results, Cu and Mn were significant at $p < 0.01$, Fe at $p < 0.05$ and Ni was not significant.

Table 3. Effect of Zn applications at different levels on the Fe, Cu, Mn, and Ni contents of wheat

Zn doses	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Ni (mg kg ⁻¹)
Zn₀	72.75±0.75b	8.50±0.00b	9.00±0.00c	8.33±0.80
Zn₁	81.75±4.25a	8.67±0.28b	12.17±0.80a	8.00±1.50
Zn₂	79.00±3.00ab	9.67±0.26a	10.67±0.30b	7.00±0.00
Zn₃	78.50±3.50ab	8.83±0.30b	9.00±0.50c	8.17±0.30
Zn₄	76.00±2.00ab	8.33±0.29b	7.50±0.50d	8.00±0.00
LSD _{0,05}	7.96	0.70	1.30	-
P-value	0.04*	0.0008**	<.0001**	0.030 ^{ns}

**, $p < 0.01$, *, $p < 0.05$, ns: non-significant.

The highest Fe content (81.75 mg kg⁻¹) was determined in the Zn_1 application, while the lowest Fe content (72.75 mg kg⁻¹) was determined in the control group. The highest Cu concentration in the plant (9.67 mg kg⁻¹) was measured in the Zn_2 application, while the other Zn applications were lower and grouped similarly. The highest Mn content in the plant (12.17 mg kg⁻¹) was determined in the Zn_1 application, whereas the lowest (7.50 mg kg⁻¹) was determined in the Zn_4 application. The Ni contents of the plants were not found to be statistically significant.

Figure 2 shows the variation in Fe and Cu concentrations in plant tissues resulting from Zn applications at different levels.

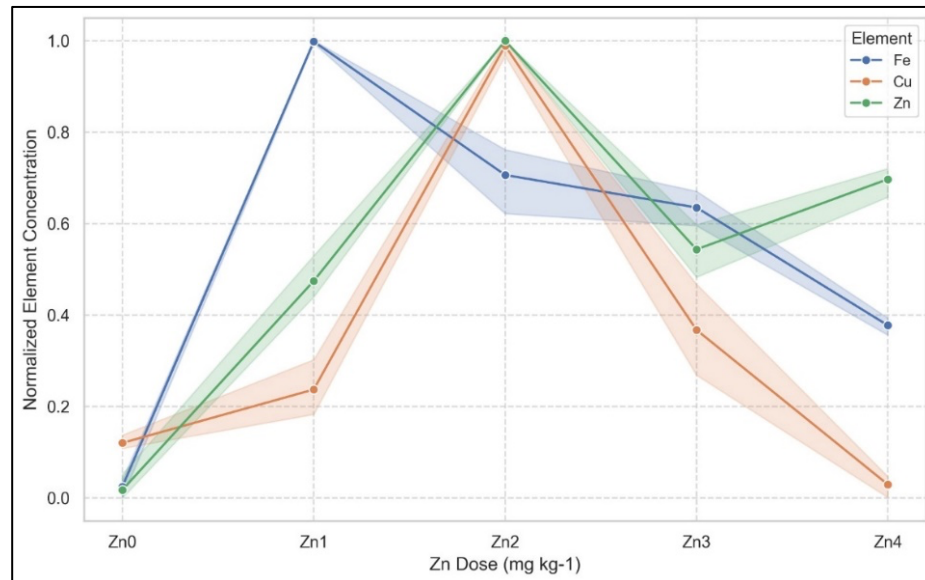


Figure 2. Graph showing the effect of $Zn_{0,1,2,3,4}$ applications on Fe, Cu, and Zn contents in wheat.

In the Zn_1 application, Fe and Cu concentrations also increased with Zn; in the Zn_2 application, Cu increased while Fe decreased with Zn; in the Zn_3 application, Fe and Cu concentrations decreased with Zn; and in the Zn_4 application, Fe and Cu concentrations decreased with Zn.

Figure 3 shows the variation in Mn and Ni concentrations in plant tissues resulting from Zn applications at different levels, relative to Zn concentration.

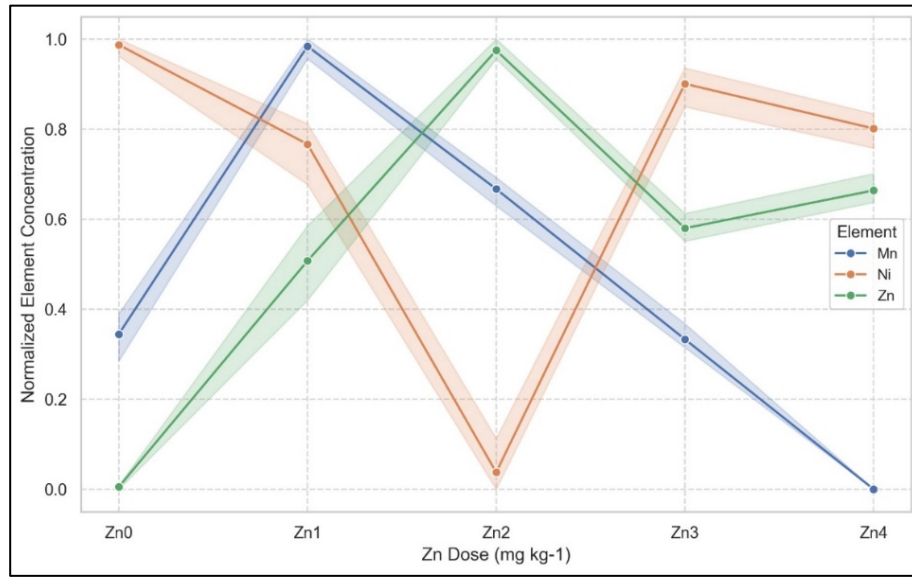


Figure 3. Graph showing the effect of Zn_{0,1,2,3,4} applications on Mn, Ni, and Zn contents in wheat.

In the Zn₁ application, as the Zn concentration increased, the Mn concentration also increased, but the Ni concentration decreased. In the Zn₂ application, as the Zn concentration increased, the Mn and Ni concentrations decreased. In the Zn₃ application, as Zn decreased, Mn concentration decreased, while Ni concentration increased. In the Zn₄ application, as the Zn content increased, the Mn and Ni contents decreased.

3.3. Levels of P, K, Ca, and Mg in plant tissues (%)

The means and groups of the variance analysis results for P, Ca, K, and Mg levels measured in the tissues of wheat plants grown in Cd-contaminated soil as a result of Zn applications at different levels are presented in Table 4. According to the ANOVA result, K and Ca were found to be significant at the $p < 0.01$ level, while P and Mg were not significant.

Table 4. Effect of Zn applications at different levels on the P, K, Ca, and Mg contents of wheat

Zn doses	P (%)	K (%)	Ca (%)	Mg (%)
Zn ₀	0.31±0.00	1.30±0.10d	0.61±0.02c	0.26±0.01
Zn ₁	0.37±0.05	1.62±0.06bc	0.71±0.02b	0.28±0.02
Zn ₂	0.29±0.01	2.02±0.04a	0.77±0.01a	0.30±0.01
Zn ₃	0.34±0.02	1.73±0.03b	0.74±0.03ab	0.28±0.01
Zn ₄	0.30±0.03	1.47±0.01c	0.70±0.00b	0.29±0.02
LSD _{0,05}	-	0.15	0.05	-
P-value	0.05 ^{ns}	<.0001 ^{**}	<.0001 ^{**}	0.11 ^{ns}

^{**}: $p < 0.01$, ^{ns}: non-significant.

The effect of different levels of Zn application on the P and Mg content of wheat was not found to be statistically significant. The highest potassium level (2.02 mg kg⁻¹) in plant tissues was determined in the Zn₂ application, while the lowest (1.30 mg kg⁻¹) was determined in the Zn₀ application. Similarly, the highest Ca level (0.77 mg kg⁻¹) was determined in the Zn₂ application, whereas the lowest (0.61 mg kg⁻¹) was determined in the Zn₀ application.

The visual representation of changes in P and K concentrations in plant tissues resulting from Zn applications at different levels is shown in Figure 4.

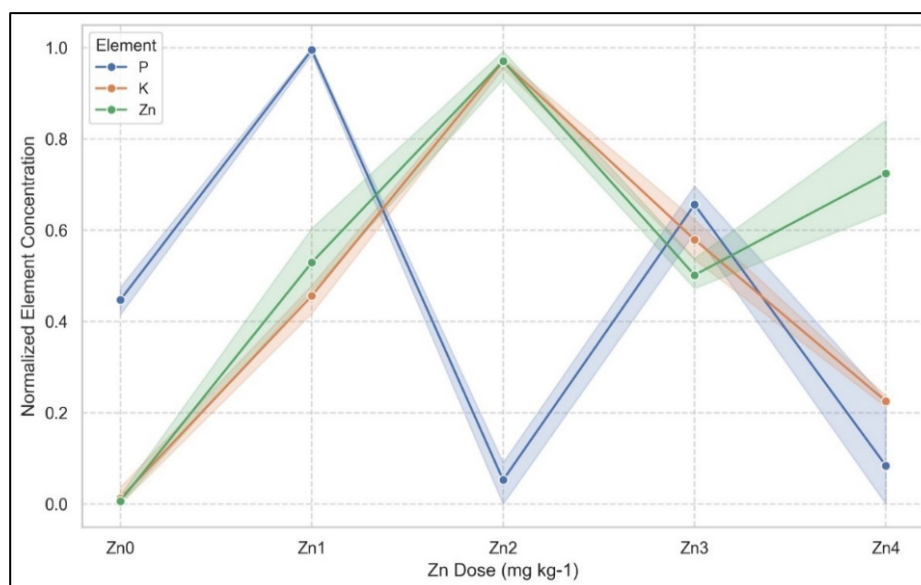


Figure 4. Graph showing the effect of $Zn_{0,1,2,3,4}$ applications on P, K, and Zn contents in wheat.

In the Zn_1 application, as the Zn increased, the K and P levels also increased. In the Zn_2 application, as the Zn concentration increased, the P concentration decreased while the K concentration increased. In the Zn_3 application, as Zn decreased, K concentration also decreased, but P concentration increased. In the Zn_4 application, as Zn increased, K and P levels decreased.

The visual representation of the changes in Mg and Ca concentrations in plant tissues resulting from Zn applications at different levels is shown in Figure 5.

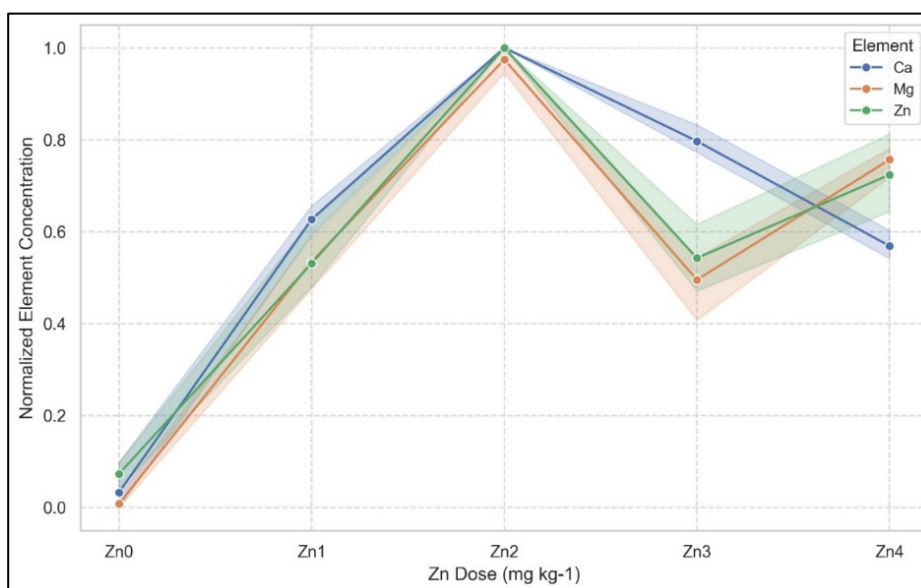


Figure 5. Graph showing the effect of $Zn_{0,1,2,3,4}$ applications on Ca, Mg, and Zn contents in wheat.

In Zn_1 and Zn_2 applications, as the Zn density increased, the Mg and Ca concentrations also increased. In the Zn_3 application, as the Zn concentration decreased, the Ca and Mg concentrations also decreased. While Zn and Mg showed a positive relationship across all applications, Zn and Ca showed a positive relationship in all but the Zn_4 application.

4. Discussion

In this study, Zn applications did not reduce Cd concentration at all application levels, and a reduction was observed only with the Zn₂ treatment (Table 2). Many studies have reported that Zn and Cd exhibit a competitive relationship, which manifests in changes in Zn and Cd uptake and translocation from roots to shoots depending on the concentrations of both metals in the environment (Palusińska et al., 2020). Cadmium and Zn are chemically similar, and therefore they compete for root symplastic and apoplastic uptake, vacuolar storage in root cells, xylem transport from roots to shoots, phloem redistribution, and accumulation in edible parts (Hart et al., 2002). This competition may arise because the same transporter-like proteins (OsZIP7) and heavy metal ATPases (OsHMA2), which are responsible for loading both Zn and Cd into the xylem in roots, are involved (Tan et al., 2020).

Many studies have reported similar results; Saifullah et al. (2014) reported that low zinc concentrations alleviated reductions in growth and stress caused by Cd, but high zinc levels combined with Cd increased Cd concentrations (Cherif et al., 2011). Poblaciones et al. (2017) applied Zn to the leaves of two plant species (*Lolium rigidum* and *Trifolium subterraneum*) in the presence of Cd; compared to the control, Cd decreased in the plants, while Cd concentration increased at higher levels of Zn. Cadmium levels in rice shoots were enhanced by high Zn activity in the nutrient solution (Green et al., 2017). Sozubek et al. (2015) found that Zn application in alkaline soils increased Cd concentrations in 45-day-old maize seedlings compared with the control. Hussain et al. (2016) reported that 30 mg kg⁻¹ Zn application increased Cd levels in spinach plants. Saifullah et al. (2014) reported that when 15 mg kg⁻¹ Zn was applied to soil containing 30 mg kg⁻¹ Cd for wheat plants, Cd concentration in the plant increased compared to other Zn levels, and that this was because Zn increased the transfer of Cd from root tissues to shoots. Studies show that Zn supplementation does not affect Cd concentration in the concentrate. Sarwar et al. (2015) observed that foliar application of zinc at a rate of 3.0 g L⁻¹ during the flowering phase led to a decrease in Cd accumulation in the harvested grains. In contrast, when Zn was supplied to the soil at 15 and 30 mg kg⁻¹, or when higher doses were applied to the foliage, no significant change in grain Cd levels was detected. Collectively, these findings suggest that Zn's influence on Cd uptake in plants is variable and largely determined by the specific levels of both metals in the growth environment. One possible explanation for the elevated Cd observed in some Zn-treated plants is that Zn may displace Cd from soil binding sites, thereby increasing the pool of Cd that is available for plant uptake (Rizwan et al., 2019). The higher uptake of Cd, together with Zn, in the nutrient solution may be due to the greater toxic effects of each element when applied together than when applied alone (Rizwan et al., 2019). The bioavailability of Cd in soil to plants is influenced by various soil and plant factors, including pH, organic matter content, chloride concentration in the soil solution, Fe and Mn hydrated oxides, the Cd:Zn ratio (Chaney et al., 2000; Nan et al., 2002), and plant species. Chaney et al. (2000) reported that the Cd:Zn ratio is a more important factor in determining Cd accumulation in plant shoots than Zn concentration. Hussain et al. (2016) also reported that Cd concentration in spinach leaves was highly correlated with the Cd:Zn ratio in the growth medium. In their study, the highest leaf Cd concentration was observed at a 1:10 Cd:Zn ratio, while at a 1:100 Cd:Zn ratio, leaf Cd concentrations decreased by 46%. A comparison can also be made with the ratios used in our study. In our study, because the Cd:Zn ratio in the aboveground parts of wheat was less than 1:100, Cd accumulation may not have decreased linearly. Moreover, in this study, only the aboveground parts were evaluated, limiting the determination of root retention of Cd and Zn. The findings of this study are generally consistent with the literature; however, some studies have reported that increasing Zn applications can enhance Cd uptake. These differences are thought to depend on both environmental and physiological factors, such as application rates, application method (foliar or soil), plant species, and growth conditions. Boysan Canal et al. (2022) reported that metals are mostly accumulated in the roots.

At the same time, Table 2 shows that Zn concentration in the aboveground parts of wheat increased statistically with increasing application rates in this study. Cadmium and Zn have mostly moved in contrary directions (Figure 1). The effects of Zn nutrition on Cd uptake and accumulation in plants are inconsistent; while there are reports of synergy between Cd and Zn (Köleli et al., 2004), Nan et al. (2002) reported that an increase in Cd application increased zinc concentration in wheat, or that the opposite was true. In this study, it was observed that certain Zn applications (except Zn₂) increased Cd uptake; a probable reason for this is that these Zn applications may have led to an increase in Zn

concentration in the root region and caused Cd to be transferred to the above-ground parts of the plant (cation competition), resulting in an increase in Cd content in the shoots. Additionally, the permissible toxic metal threshold values for Cd and Zn in soil and plants have been reported by WHO/FAO as 3 mg kg⁻¹ Cd and 300 mg kg⁻¹ Zn in soil, and 0.2 mg kg⁻¹ Cd and 60 mg kg⁻¹ Zn in plants (WHO/FAO, 2007; Sönmez and Kılıç, 2021). In Zn applications, although the permissible Zn levels were not exceeded, Cd concentrations in plant tissues exceeded the allowable limits in all treatments.

Copper concentration, on the other hand, showed a steady increase in the above-ground parts of wheat compared to the control until Zn₂ application, after which it decreased (Table 3). Dias and Cicero (2016) reported that zinc and copper compete for the same entry site during uptake by plant roots, both being divalent cationic metals, and that increased Zn applications reduced Cu uptake efficiency, attributed to competitive inhibition. Nik-Khah et al. (2024) reported an antagonistic relationship among Fe, Mn, and Zn at certain concentration levels in maize plants. However, Soltangheisi et al. (2014) reported that Mn concentration in maize shoots showed no relationship with Zn levels in the nutrient solution, whereas Mn levels in roots declined as Zn levels increased.

As shown in Figure 2, Zn and Cu move in parallel except for Zn₄, while Zn and Fe move in reverse directions except for Zn₁. Liščáková et al. (2022) reported that the interaction between Cu and Zn leads to a synergistic effect in some studies (*T. aestivum*/*H. vulgare*) and an antagonistic effect in others (*H. vulgare*/*L. sativa*). Lu et al. (2025) stated that Zn and Fe can synergistically affect Cd uptake by roots and its transport to shoot organs, or sometimes show antagonistic effects.

According to Figure 3, Zn and Ni showed an inverse relationship at all applied Zn dose levels; as one increased, the other decreased. Zinc and Mn, on the other hand, showed parallel movement at Zn_{1,3} and opposite movement at Zn_{2,4}. Cadmium and Zn, along with various microelements including Fe, Cu, and Mn, can interact antagonistically and synergistically in plant uptake and transport (Shahzad et al., 2025).

In the study, K, Ca, and Mg concentrations in the above-ground parts of wheat increased linearly up to the Zn₂ application and reached maximum levels at the application (Table 4). Ghasal et al. (2017) observed that plots receiving zinc treatments exhibited elevated levels of both macro- and micronutrients compared to untreated controls. Similarly, Sarwar et al. (2015) reported a positive association between zinc and potassium concentrations in plant shoots. Pooniya and Shivay (2013) also reported a significant increase in N, P, and K content with Zn application, whereas Ghasal et al. (2017) reported that, although N, P, and K increased with increasing Zn application compared to the control, the increase was not statistically significant.

As shown in Figure 4, the relationship between P and Zn has moved in opposite directions, except for the Zn₁ application. Except for the Zn₄ application, Zn and K showed a positive relationship in all other applications. Phosphorus (P) and zinc (Zn) can interact antagonistically (Nath et al., 2024). Ibourki et al. (2022) found that Zn was positively correlated with K in wild plants.

In Figure 5, most applications showed a positive relationship among Zn, Ca, and Mg. Foliar application of Zn increased Ca and Mg content in sugar beets (Zhao et al., 2024).

Conclusion

As a result, Zn application at a specific level increased the concentration and uptake of essential nutrients, including Zn, Fe, Cu, Mn, K, Ca, and Mg, in the aerial parts (shoots) of wheat plants compared to the control. Although the Zn₂ application reduced Cd uptake in plant tissues, none of the applied Zn levels lowered the measured Cd concentration in the plant below the permissible toxic metal threshold. However, since the relationship between Zn applications and Cd accumulation could not be fully understood in the aboveground parts in this study, future studies should examine plant organs (including root) separately. The lack of measurements of element concentrations in root tissue limits the interpretation of the organ-element relationship, and it is recognized that such measurements will be necessary in future studies. The current soil condition (alkaline pH and high lime content) may limit Zn uptake by plants. Therefore, in future studies, the Zn concentration applied can be increased or applied to the leaves to verify the hypothesis.

Ethical Statement

Ethical approval was not required for this study, as no research involving animals or humans was conducted.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of any images, figures, graphics, tables, or related titles.

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Author Contributions

All authors contributed equally to this work.

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