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Zinc Availability in Reclaimed Sodic Soil under Rice-Wheat Cultivation Following Conservation Agriculture-Based Nutrient Management Practices

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Abstract

The deficiency of available Zn in soil is a major constraint to crop productivity and quality, and has contributed to widespread human malnutrition. To address this issue, the present study examined Zn adsorption and availability in soil under a rice-wheat cropping system following conservation agriculture (CA)-based nutrient management practices. The initial Zn concentration was directly proportional to per cent saturation and the supply parameter, but inversely related to the differential buffering capacity (DBC) of the soil. This relationship indicated greater Zn adsorption with a decreasing rate at higher initial Zn concentrations, along with an increase in the quantity factor (solid-phase Zn). Approximately 100% Zn saturation was achieved at an initial Zn concentration of ~150 mg L^{-1}, while the DBC was maximum (646 and 1441 L kg^{-1} at 25°C and 40°C, respectively) under full conservation agriculture with inorganic nutrient management. Among the management practices, full conservation agriculture and higher temperature conditions promoted stronger Zn adsorption, thereby restricting its availability in soil. Although the effect of organic manure application on Zn availability was not clearly evident in the present study, the supply parameter was higher under organic manuring than under conventional and full conservation agriculture practices. Overall, partial conservation agriculture practices resulted in greater available Zn concentrations, whereas soils under full conservation agriculture require higher Zn fertilization due to their elevated differential buffering capacity.

Keywords: Available soil Zn, Buffering capacity, Partial conservation agriculture, Per cent saturation, Supply parameter

Introduction

Zinc (Zn) is an essential micronutrient for plants, animals, and humans (Noulas *et al*., 2018). However, its widespread deficiency in soils remains a major constraint to crop productivity and produce quality. The availability of Zn in the soil–plant system is primarily governed by the soil solution phase, where its concentration is regulated by adsorption-desorption and precipitation-dissolution processes (Noulas *et al*., 2018).

Based on soil pH, Zn availability in neutral to alkaline soils is predominantly controlled by precipitation-dissolution reactions, whereas adsorption–desorption processes regulate solution Zn concentration below pH 7.0 (Brümmer *et al*., 1983). Furthermore, adsorption dominates at lower Zn concentrations, while precipitation occurs after saturation of adsorption sites, which requires relatively high Zn concentrations (> ~100 mg L^{-1}) (Brümmer *et al*., 1983). This suggests that adsorption is the principal mechanism governing Zn availability at low application rates, such as $ZnSO_4 \cdot 7H_2O$ @ 25 kg ha^{-1}, which supplies only 5.25 kg Zn ha^{-1}.

Soil components contributing to Zn adsorption include aluminosilicate clay minerals, organic matter, and amorphous oxides of Fe, Al, and Mn. Among these, oxides and humic substances exhibit the greatest Zn-binding capacity (Brümmer *et al*., 1983). The adsorption-desorption behaviour of Zn is further influenced by soil pH, total Zn concentration, and soil composition, including mineral phases and organic matter (Girija *et al.*, 2014). Application of organic matter enhances Zn availability by releasing Zn during mineralization and through the formation of soluble complexes with low-molecular-weight organic acids (Girija *et al.*, 2014).

The widespread Zn deficiency in the Indo-Gangetic Plains (IGP), particularly under intensive rice-wheat cultivation, makes this region suitable for studying Zn bioavailability in soil. The rice-wheat system in the IGP faces sustainability challenges, including declining soil fertility, reduced organic matter content, falling groundwater levels, and labour constraints. However, conservation agriculture (CA) practices-such as minimum tillage, residue retention, and crop diversification-have improved system productivity (Chaki *et al.*, 2021). Organic inputs, including crop residues and *Sesbania* incorporation, contribute to soil carbon and fertility while improving physical properties such as bulk density, structure, aggregation, and infiltration rate (Jat *et al.*, 2024). These benefits can be further enhanced through integrated nutrient management using both organic sources (farmyard manure and vermicompost) and inorganic fertilizers.

In this context, the present study aimed to determine percent saturation (%), differential buffering capacity (DBC), and the supply parameter of Zn in soil at two temperatures (25°C and 40°C). The objective was to evaluate Zn adsorption and availability under different CA-based nutrient management practices in rice. It was hypothesized that Zn bioavailability in soil can be enhanced through CA-based nutrient management practices in the rice-wheat cropping system.

Materials and Methods

The detailed description of the experimental location and management practices is provided in Fig. 1 and Table 1, respectively.

Initial soil physico-chemical analysis

Initial surface (0–15 cm) samples of the reclaimed sodic soil were analyzed for physico-chemical properties. The soil was characterized as silty clay loam in texture, with a neutral to slightly alkaline reaction ($pH_{1:2.5}$: 7.63 ± 0.02), non-saline in nature

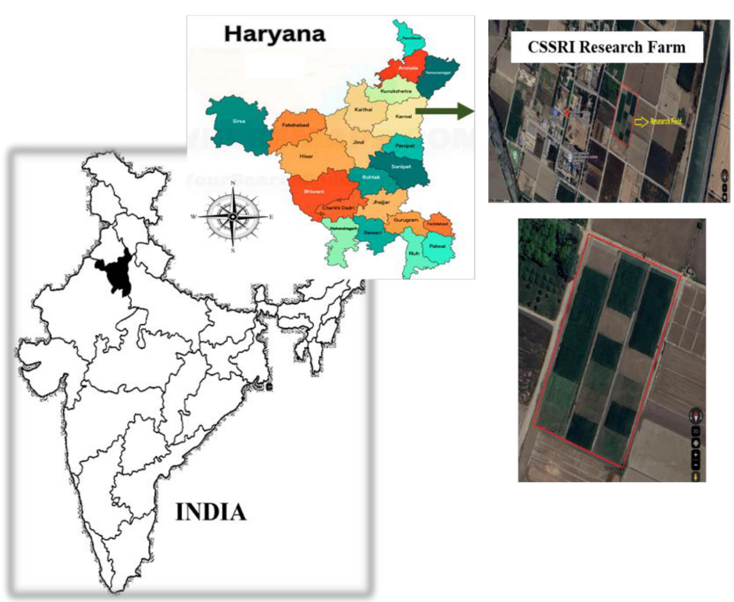

Fig. 1 Description of the experimental location

Table 1. Detailed description of the management practices

Management practices (MP)	Crop rotations	Tillage	Crop establishment method	Residue management	Nutrient (N-P-K) management	
					Quantity (kg ha^{-1})	Source
MP_1	R-W-F	CT-CT	Rice: Transplanting Wheat: Broadcast	All residue removed	Rice: 80-40-0 Wheat: 150-60-0	100% N through chemical fertilizers
MP_2	R-W-S	CT-ZT-ZT	Rice: Transplanting Wheat: Drill seeding *Sesbania*: Drill	75-80 % rice and anchored wheat residue retained on soil surface. Full *Sesbania* residue was incorporated	Rice: 80-40-0 Wheat:150-60-0 *Sesbania*: 0-0-0	100% N through chemical fertilizers
MP_3	R-W-S	CT-ZT-ZT	Rice: Transplanting Wheat: Drill seeding *Sesbania*: Drill	Same as MP_2	Rice: 80-40-0 Wheat:150-60-0 *Sesbania*: 0-0-0	100% N through organic source (FYM/vermicompost)
MP_4	R-W-S	CT-ZT-ZT	Rice: Transplanting Wheat: Drill seeding *Sesbania*: Drill	Same as MP_2	Rice: 80-40-0 Wheat:150-60-0 *Sesbania*: 0-0-0	50% N through organic source (FYM/vermicompost) + 50% N through inorganic fertilizers
MP_5	R-W-S	ZT-ZT-ZT	Rice: Drill seeding Wheat: Drill seeding *Sesbania*: Drill	Same as MP_2	Rice: 80-60-60 Wheat: 150-60-60 *Sesbania*: 0-0-0	100% N through chemical fertilizers

R: Rice; W: Wheat; F: Fallow; S: *Sesbania rostrata*; CT: Conventional tillage; ZT: Zero tillage; FYM: Farmyard manure; N: nitrogen; Surface application of zinc as $ZnSO_4.7H_2O$ was carried out in all the scenarios @ 25 kg ha^{-1} before the sowing of rice.

($EC_{1:2.5}$: 0.73 ± 0.03 dS m^{-1}), and low in organic carbon content (0.49 ± 0.03%).

Sample collection for laboratory experiment

The adsorption experiment was conducted using surface soil samples (0–15 cm) collected after the third rice–wheat cropping cycle with a stainless-steel auger. The collected samples were air-dried, processed, and properly labelled for subsequent laboratory experiments and analyses. The obtained data were evaluated using the Langmuir adsorption isotherm (Saroha *et al.*, 2025), and the corresponding parameters (Equations 1–3) were determined to assess the effect of initial Zn concentration on Zn adsorption and its bioavailability (Diatta and Kocialkowski, 1998).

$$\text{Percent saturation (\%)} = \frac{Q}{Q_m} \times 100 \qquad \text{Eq. 1}$$

$$\text{Differential buffering capacity (L kg}^{-1}) = \frac{Q_m.K_L}{(1+K_L.C_e)^2} \qquad \text{Eq. 2}$$

$$\text{Supply parameter (mmol kg}^{-0.25}\text{L}^{-2.25}) = \sqrt{\frac{Q_e.C_e}{\sqrt{Q_m.K_L}}} \qquad \text{Eq. 3}$$

Here, Q is the amount of Zn adsorbed at equilibrium at any concentration (mg kg^{-1}), Q_m is the maximum adsorption capacity (mg kg^{-1}), K_L is the bonding energy coefficient (L mg^{-1}) in the Langmuir adsorption isotherm, C_e is the equilibrium Zn concentration (mg L^{-1}), and Q_e is the amount of Zn adsorbed per unit of soil at equilibrium (mg kg^{-1}).

Statistical analysis

The data are presented as the mean of three replications along with their corresponding standard deviations (values following ±). Statistical analysis was performed using analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) with the AgroR package in R software (version 4.2.1) at a 5% level of significance (R Core Team, 2023).

Results and Discussion

The effects of initial Zn concentration and management practices on Zn adsorption in soil are presented and discussed in this section. Data obtained from the Zn adsorption isotherm experiment were used to determine percent saturation (%), differential buffering capacity (L mg^{-1}), and supply parameter (mmol $kg^{-0.25}$ $L^{-2.25}$) at two different temperatures (25°C and 40°C) using Equations 1-3 (Fig. 2).

Per cent saturation represents the Zn adsorption capacity of the soil (Diatta and Kocialkowski, 1998). It increased with increasing initial Zn concentration at both temperatures, indicating enhanced Zn adsorption (Figs. 2a and 2a'). However, percent saturation exceeded 100% at approximately 150 mg L^{-1} of initial Zn, suggesting the occurrence of multilayer adsorption or co-precipitation of Zn on soil constituents (minerals and organic matter) following monolayer adsorption. Thus, 150 mg L^{-1} may be considered a critical concentration for Zn precipitation in the experimental soil under rice grown with CA-based nutrient management practices. These findings are consistent with Saroha *et al*. (2025), who reported maximum Zn adsorption at an equilibrium concentration of 20 mg L^{-1} corresponding to ~100 mg L^{-1} initial Zn.

Table 2. Average percentage Zn saturation (%) in soil at 25°C and 40°C

Management practices	Percent saturation (%)	
	25°C	40°C
MP_1	40.94 ± 0.25[a]	40.14 ± 0.73[a]
MP_2	40.75 ± 0.07[a]	39.42 ± 0.07[a]
MP_3	40.24 ± 0.25[a]	39.55 ± 0.33[a]
MP_4	40.88 ± 0.01[a]	39.73 ± 1.27[a]
MP_5	40.81 ± 0.01[a]	40.44 ± 0.13[a]

Means with different letters as superscripts are significant ($p < 0.05$), whereas having common letter(s) are not significantly different. The values following ± represent the standard deviation about the mean (n=3).

The average percent saturation across initial Zn concentrations did not differ significantly ($p > 0.05$) among management practices at either temperature (Table 2). It ranged from 39.42% to 40.94%, indicating a negligible effect of temperature on Zn saturation.

Differential buffering capacity (DBC) reflects the resistance of the soil solution to changes in Zn concentration upon addition or removal of Zn (Qiu *et al*., 2010), and represents the quantity–

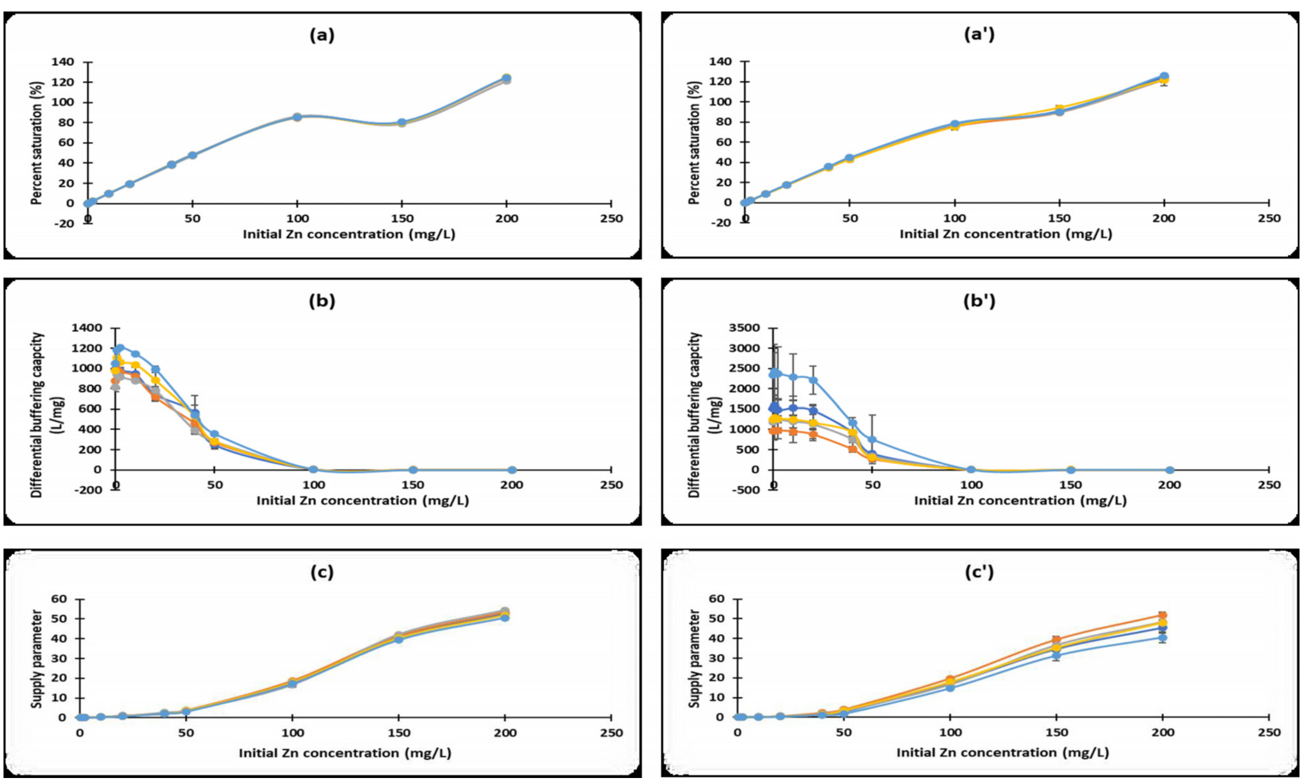

Fig. 2 Effect of initial Zn concentrations on the (**a**) percent saturation (%); (**b**) differential buffering capacity (L mg^{-1}); and (**c**) supply parameter (mmol $kg^{-0.25}$ $L^{-2.25}$) at two temperatures; here, a, b, and c represent 25°C and a', b', and c' represent 40°C. The error bars denote the standard deviation about mean

Table 3. Differential buffering capacity of adsorbed Zn in soil at 25°C and 40°C

Management practices	Differential buffering capacity (L kg^{-1})	
	25°C	40°C
MP_1	553.58 ± 37.80^{bc}	899.74 ± 103.43^{a}
MP_2	526.14 ± 11.58^{c}	550.79 ± 45.76^{a}
MP_3	503.80 ± 9.92^{c}	711.49 ± 63.09^{a}
MP_4	585.04 ± 3.02^{b}	798.13 ± 282.01^{a}
MP_5	646.07 ± 3.66^{a}	1440.99 ± 317.31^{a}

Means with different letters as superscripts are significant ($p < 0.05$), whereas having common letter(s) are not significantly different. The values following ± represent the standard deviation about the mean (n=3).

Table 4. Supply parameter of adsorbed Zn in soil at 25°C and 40°C

Management practices	Supply parameter (mmol kg$^{-0.25}$ L$^{-2.25}$)	
	25°C	40°C
MP_1	13.30 ± 0.26^{a}	11.39 ± 0.24^{a}
MP_2	13.51 ± 0.09^{a}	13.18 ± 0.39^{a}
MP_3	13.46 ± 0.07^{a}	11.96 ± 0.24^{a}
MP_4	13.08 ± 0.05^{ab}	11.91 ± 1.19^{a}
MP_5	12.65 ± 0.02^{b}	10.06 ± 0.76^{a}

Means with different letters as superscripts are significant ($p < 0.05$), whereas having common letter(s) are not significantly different. The values following ± represent the standard deviation about the mean (n=3).

intensity (Q/I) relationship. DBC decreased with increasing initial Zn concentration at both temperatures (Figs. 2b and 2b'), likely due to saturation of adsorption sites and a corresponding increase in the quantity factor (Diatta and Kocialkowski, 1998). Higher DBC at lower Zn concentrations indicates lower Zn availability in the soil solution. At 25°C, mean DBC varied significantly ($p < 0.05$) among management practices, with the highest value under MP_5 (646.07 L kg^{-1}) and the lowest under MP_3 (503.80 L kg^{-1}) (Table 3).

At 40°C, DBC increased across all treatments, indicating enhanced Zn adsorption, but differences among treatments were not statistically significant. The highest DBC was again observed under MP_5 (1440.99 L kg^{-1}). These results suggest that soils under full conservation agriculture with inorganic nutrient management (MP_5) require higher Zn fertilization compared to partial CA with organic (MP_3) and integrated nutrient management (MP_4). Although temperature had little effect on percent saturation, it markedly increased DBC. The limited differentiation between organic and inorganic nutrient management may be attributed to rapid organic matter decomposition under semi-arid subtropical conditions, restricting soil organic carbon build-up.

Zn availability in soil is governed by the combined effects of intensity (solution Zn), quantity (solid-phase Zn), and buffering capacity, collectively represented by the supply parameter (Diatta and Kocialkowski, 1998). The supply parameter increased with increasing initial Zn concentration at both temperatures (Figs. 2c and 2c'), indicating greater Zn bioavailability at higher fertilization rates. At 25°C, the supply parameter was significantly influenced by management practices, ranging from 13.51 mmol kg$^{-0.25}$ L$^{-2.25}$ under MP_2 to 12.65 mmol kg$^{-0.25}$ L$^{-2.25}$ under MP_5 (Table 4). At 40°C, it decreased under all treatments and varied non-significantly between 10.06 and 13.18 mmol kg$^{-0.25}$ L$^{-2.25}$, with the lowest value again observed under MP_5. Lower supply parameter values at higher temperature and under full conservation agriculture indicate stronger Zn adsorption, thereby reducing its bioavailability. This may be attributed to the partial loss of the hydration shell around Zn^{2+} ions, promoting the formation of inner-sphere complexes rather than outer-sphere electrostatic adsorption. Although statistically *at par*, the slight decrease in the supply parameter under MP_3 and MP_4 as compared to MP_2 might be attributed to the organic manuring, which offers additional adsorption sites for Zn and reduces its availability. Overall, Zn bioavailability was relatively higher under partial conservation agriculture compared to full conservation agriculture, with the highest supply parameter consistently observed under MP_2 at both 25°C (13.51 mmol kg$^{-0.25}$ L$^{-2.25}$) and 40°C (13.18 mmol kg$^{-0.25}$ L$^{-2.25}$).

Conclusions

The study demonstrated that Zn adsorption and availability in soil are strongly influenced by initial Zn concentration, temperature, and conservation agriculture (CA)-based nutrient management practices. Per cent saturation increased with increasing Zn concentration, indicating enhanced adsorption, while values exceeding 100% at higher concentrations (~150 mg L^{-1}) suggested the occurrence of multilayer adsorption or co-precipitation of Zn. Differential buffering capacity (DBC) decreased with increasing Zn concentration but increased with temperature, reflecting greater Zn adsorption and reduced availability at higher temperatures.

Among the management practices, full conservation agriculture with inorganic nutrient management exhibited the highest DBC, indicating stronger Zn retention and a greater requirement for Zn fertilization. In contrast, partial CA practices, particularly those involving organic and integrated nutrient management, resulted in relatively higher Zn bioavailability, as reflected by higher supply parameter values. The supply parameter increased with Zn concentration but decreased at elevated temperature, indicating reduced Zn availability due to stronger adsorption and possible formation of inner-sphere complexes.

Overall, partial conservation agriculture combined with organic and integrated nutrient management practices proved more effective in sustaining Zn availability in soil, whereas soils under full conservation agriculture require higher Zn inputs to overcome their greater buffering capacity and ensure adequate Zn availability for crop uptake.

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