Dynamics of Zinc Fractions, Availability to Wheat (*Triticum aestivum* L.) and Residual Effect on Succeeding Maize (*Zea mays* L.) in Inceptisols

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Abstract

The objective of this study was to compare the transformation, redistribution, availability and relative effectiveness of Zn from different fertilizer sources *viz*. Zn-DTPA (Zinc chelated with di-ethylene tri-amine penta-acitic acid), Zn-EDTA (Zinc chelated with ethylene di-amine tetra-acetic acid), Zn-CH (Zinc chelated with a mixture of DTPA & EDTA) and $ZnSO_4.7H_2O$ (Zinc sulphate hepta hydrate) applied at various zinc levels (5, 10 and 20 mg kg^{-1}) to an Inceptisols in a greenhouse experiment. The results of the greenhouse study showed that the application of three zinc sources significantly increased wheat (*Triticum aestivum* L.) and succeeding maize (*Zea mays* L.) dry matter yield and shoot/root ratio compared with the control at increased levels of zinc. Positive, significant correlations were obtained between the zinc concentration in plant and the available zinc as well as the first two sequentially extracted Zn fractions (water soluble plus exchangeable and organically complexed). The positive and significant effect of zinc levels was also found on plant nitrogen and potassium. The zinc fractions in the soil after harvest of both crops were positively and significantly correlated with each other.

Keywords: Dry matter yield, Plant zinc, Zinc fractions

1. Introduction

Micronutrients have assumed increasing importance in crop production under present day exploitative agriculture. Intensive cultivation of high yielding varieties and use of high analysis fertilizers disturb the nutrient balance in soil and micronutrients become limiting factor for crop production. Despite their small content, the micronutrients in soil solution are essential to plant nutrition. The availability of the essential micronutrients to plants is often poorly related to their total quantity in the soil. Excluding iron, zinc is the most abundant metal to be found in living organisms, where it plays a major structural, catalytic and co-catalytic role in enzymes. So the study of zinc transformation in soil is an important component of plant nutrition research. The availability of zinc present in the soil or applied as fertilizer is governed by the net effect of a series of physical, chemical and biological reactions in the soil.

Zinc (Zn) is an essential element for plant growth, crop yield and quality. When the supply of plant-available zinc is insufficient, crop yields are reduced and the quality of crop products is frequently impaired (Alloway, 2003). Natural levels of zinc in the soil range from 10 to 300 mg kg^{-1} with an average of 50 mg kg^{-1} (Mulligan et al*.,* 2001). It is estimated that 30 per cent of the world's cultivated soils are deficient in zinc (Suzuki et al*.,* 2006). Among cereals, wheat and rice in particular, suffer from zinc deficiency. Grain-yield reductions of up to 80 per cent along with reduced grain zinc level have been observed under zinc deficiency (Cakmak et al*.,* 1998). This has serious implication for human health in countries where consumption of cereal-based diets predominate (Welch, 2001). Further, plants grown on zinc-deficient soils tend to accumulate heavy metals, which again is a potential human health hazard (Hart et al*.,* 1998). Zinc deficiency is a common micronutrient deficiency affecting maize grown in different parts of the world (Kabata-Pendias, 2001).

Since zinc is essential in plant nutrition, it has to be supplied to crops in some forms for optimum plant growth where zinc deficiency in the soil is expected. In recent years, the use of various zinc fertilizers to correct zinc deficiency has received widespread interest. In general, application of zinc fertilizers to most soils is relatively ineffective, since it is readily converted to unavailable forms. Zinc deficiency is widespread in the soils having high pH, low organic matter and which are calcareous, sodic, sandy and limed acidic in nature (Rattan and Sharma, 2004). The nature and the amount of various forms of zinc depend on the soil texture, pH, calcium carbonate, organic matter and other soil properties (Sharma et al., 2004).

Zinc is known to occur in soil in a number of discrete chemical forms differing in their solubility and thus availability to plants. Further, zinc exists in five distinct pools in soils, namely (a) water soluble (b) exchangeable (c) adsorbed, chelated or complexed (d) held in secondary clay minerals and in metal oxides by occlusions and (e) associated with primary minerals. Water soluble, exchangeable and chelated zinc pools have been considered to be in reversible equilibrium with each other and zinc in these pools is said to be readily available to plants (Viets, 1962). The studies that determine how changes in properties bring zinc into available form are of utmost importance, especially to determine from which form it becomes available and what changes are necessary to cause redistribution. Thus, not only are the forms themselves important, but the potential changes among forms due to outside influences possibly having even greater significance. In other words, nutrient transformation is dynamic in nature, which gives rise to a range of inter-linked nutrient forms. Much of the zinc associated with the solid phase is not available for plant uptake (Lake et al., 1984). Infact, <10 per cent, generally is in soluble and exchangeable form.

The continuous application of large amounts of zinc chelates to soil has raised concern regarding the possible accumulation of trace elements and potential harm to the environment, as zinc can be transported downward in soil and may deteriorate ground water quality (Li and Shuman, 1997). Hence, its migration, redistribution and leaching needs to be investigated. Soil properties, element characteristics and environmental factors influence zinc concentrations and loads in surface runoff or leachate (He et al., 2004). In general, chelating agents, such as DTPA and EDTA have been shown to contribute largely to zinc movement in soil under conditions of excessive rainfall or irrigation (Alvarez et al., 1996).

The objectives of this study were to determinethe distribution of different factions of zinc in soil and to investigate the effectiveness of the three different types of zinc fertilizers and to determine the relationship between different forms of zinc in soil and zinc content in crop plants by growing wheat and succeeding maize crop.

2. Materials and Methods

2.1 Study Site

The experiment was conducted for a period of four months (Nov., 2009 to March, 2010) in the greenhouse of the Department of Agricultural Chemistry and Soil Science, Rajasthan College of Agriculture, Udaipur in a sandy clay loam soil (Typic Ustochrepts). The region falls under sub-humid southern plain and Aravali hills (Agro-climatic zone IV-A of Rajasthan) with a typical sub-tropical climate.

2.2 Pot Experiment

The experiment was laid out in completely randomized design (CRD) with three replications. 8 kg of air dried soil was placed in lysimeter pots over washed gravel at the bottom. Soil was treated with different sources of zinc @ 5, 10 and 20 mg Zn kg^{-1} (Source: http://www.avachemicals.com/) with treatment combinations T_1, Zn-DTPA$_5$; T_2 Zn-DTPA$_{10}$; T_3, Zn-DTPA$_{20}$; T_4, Zn-EDTA$_5$; T_5, Zn-EDTA$_{10}$; T_6, Zn-EDTA$_{20}$; T_7, Zn-CH$_5$ (DTPA + EDTA); T_8, Zn-CH$_{10}$ (DTPA + EDTA); T_9, Zn-CH$_{20}$ (DTPA + EDTA); T_{10}, ZnSO$_4$-Zn$_5$; T_{11}, ZnSO$_4$-Zn$_{10}$; T_{12}, ZnSO$_4$-Zn$_{20}$ and T_{13}, Zn$_0$ (control). Basal dose of N @ 60 mg N kg^{-1}, P @ 20 mg P$_2$O$_5$ kg^{-1} and K @ 15 mg K$_2$O kg^{-1} for wheat and N @ 45 mg N kg^{-1}, P @ 18 mg P$_2$O$_5$ kg^{-1} and K @ 15 mg K$_2$O kg^{-1} for maize were used at the time of sowing. Seven seeds of wheat (Raj-4037) and seven seeds of maize (Pratap Makka Chari-6) were sown per pot (total 39 pots) and maintained three seedlings in each pot after ten days of sowing. The crops were grown for 60 days and harvested. Leaf, stem and root samples were collected and soil samples were also collected after crop harvest and analysed using standard methods of analysis.

2.3 Soil and Plant Analysis

The analysed soil having OC, 0.53% (Piper, 1960); EC, 0.63 dSm^{-1} (Richards, 1954); CaCO$_3$, 3.10% (Hutchinson and Mclennan, 1914); pH, 8.11 (Richards, 1954); available nitrogen, 287.22 kg N ha^{-1} (Subbiah and Asija, 1956); P$_2$O$_5$, 26.22 kg ha^{-1} (Olsen et al., 1954); K$_2$O, 311.56 kg ha^{-1} (Richards, 1954); Zn, 0.584 mg kg^{-1} (Lindsay and Norvell, 1978) and sequentially extracted zinc fractions, WSEX-Zn (Water soluble + exchangeable zinc), 0.497 mg kg^{-1} (Shuman, 1985); OC-Zn (Organically complexed zinc), 2.174 mg kg^{-1} (Shuman, 1985); MnOX-Zn

(Manganese oxide bound zinc), 0.418 mg kg^{-1} (Chao, 1972); AFeOX-Zn (Amorphous iron oxide bound zinc), 4.221 (Shuman, 1985); CFeOX-Zn (Crystalline iron oxide bound zinc), 9.473 mg kg^{-1} (Shuman, 1985); CARB-Zn (Carbonate bound zinc), 1.621 mg kg^{-1} (Tessier et al., 1979) and RES-Zn (Residual zinc), 123.582 mg kg^{-1} (Tessier et al., 1979). The plant (leaf, stem and root) samples of both crops (wheat and maize) were also analysed for nitrogen (Snell and Snell, 1959), phosphorus & potassium (Jackson, 1973) and zinc (Lindsay and Norvell, 1978).

2.4 Statistical Analysis

The data of different fractions of zinc were statistically analyzed by using analysis of variance techniques as given by Panse and Sukhatme (1967). Test of significance (T-test) was used for estimation of the treatment differences as described by Cochran and Cox (1959). Critical differences (CD) were calculated to assess the significance between soils wherever they were found significant with F-test. Linear correlation values (r) were computed between various zinc fractions according to procedures as outlined by Snedecor (1961).

3. Results and Discussion

3.1 Dry Matter Yield

Data presented in the Table 1 showed that the shoot and root dry matter of wheat (60 DAS) significantly increased with increased application of zinc and was respectively, 43 and 33 per cent increased at 20 mg Zn kg^{-1} under Zn-DTPA as compared to control while zinc sulphate was less effective as compared to chelated zinc fertilizers in producing shoot and root dry matter (33 and 28 per cent over control at 20 mg Zn kg^{-1}, respectively). Thus, the data analysis revealed that the shoot/root ratio of both (wheat and maize) crops significantly increased with the application of zinc in soil. These results are in accordance with the findings of Cakmak (2004) and Singh et al. (2004).

Data further showed that residual effect of zinc on dry matter production of shoot and root of fodder maize significantly increased with applied zinc. The dry matter of shoot and root of maize (60 DAS) was respectively, 31 and 21 per cent more at 20 mg Zn kg^{-1} level of Zn-DTPA over control, whereas zinc sulphate produced shoot and root dry matter respectively to the extent of 17 and 18 per cent over control. According to Maftoun and Karimian (1989) plants supplied with Zn produced more stem and leaf's dry weights and contained more Zn than those grown without Zn. Moreover, Zn-EDTA was generally more effective than ZnSO$_4$ in increasing Zn concentration and Zn uptake by stems and leaves. Similar results were also reported by Obrador et al. (2003).

3.2 Nutrient Content in Plant

The zinc content in wheat leaves, stem and roots (60 DAS) significantly increased with increased levels of zinc in soil (Tables 2 and 3), similarly, residual effect on zinc content in succeeding maize leaves, stem and roots (60 DAS) was also significant. The zinc content in plant (wheat and maize) varied with application of different Zn fertilizers and was more with chelated zinc (Zn-DTAP, Zn-EDTA and Zn-CH) than zinc sulphate. Dang et al. (2010) also observed that the concentration of Zn in various above-ground organs of wheat was 9.5 to 112.5 mg kg^{-1} at different growing stages. All the organs were ordered in such a sequence with respect to Zn content that leaf blades > spikes > leaf sheaths > stems according to the net absorption and transportation of Zn as well as their contribution to Zn accumulation in grains. Vasconcelos et al. (2011) also reported that the zinc concentration in roots and shoots of maize plants were increased by Zn application both in soil and leaves.

It is revealed from the data (Table 3) that the concentration of Zn in maize was 2.8 times higher over control when the high Zn (20 mg kg^{-1}) was applied through the zinc sulphate to previous crop (wheat), this value did not reach 50 mg kg^{-1} (dry matter), which is given by some authors as the minimum necessary for using this plant (maize) as feeding fodder for ruminant animals (McDonald et al., 1981). However, zinc concentrations of >50 mg kg^{-1} were obtained with 10 mg Zn kg^{-1} dosage applied as chelated zinc fertilizers (Zn-DTPA, Zn-EDTA and Zn-CH). Srivastava and Gupta (1996) reported the critical limit of zinc deficiency in maize as 20 and 22 mg Zn kg^{-1} dry matter of early leaf initial silk and whole plant, respectively. Brennan and Bolland (2002) also reported the critical limit of zinc deficiency in wheat (spring) as 32 mg Zn kg^{-1} dry matter of shoot.

The data further showed that nitrogen and potassium content in both crops significantly increased with increased levels of zinc in soil, whereas phosphorus content increased up to 10 mg Zn kg^{-1} only and decreased thereafter at increased levels of zinc. These results corroborate to the previous findings of Verma and Minhas (1987) who reported that the P concentration in wheat and maize plants decreased with the increasing levels of applied zinc. Furthermore, Zhu et al. (2001) also reported that the Zn supply had little effect on tissue P concentration and P uptake per unit of root weight in cultivars under study irrespective of nitrogen supply. An increase in P availability caused a significant reduction in Zn uptake per unit of root weight, and tissue concentration of Zn in cultivars of spring wheat.

3.3 Distribution of Zinc Fractions in Soil after Harvest of Crop

It is evident from the data presented in Tables 4 and 5 that the distribution of different fractions of zinc in soil were significantly affected by zinc sources and found in order: RES >> CFeOX > AFeOX > OC > CARB > WSEX > MnOX with all Zn sources at 5 and 10 mg Zn kg^{-1} and at 20 mg Zn kg^{-1} by zinc sulphate only and same order was also in control, whereas, distribution changed at 20 mg Zn kg^{-1} under chelated zinc fertilizers (Zn-DTPA, Zn-EDTA and Zn-CH) and the fractions were in the order: RES >> CFeOX > AFeOX > OC > WSEX > CARB > MnOX after harvest of wheat (60 DAS), similarly, after harvest of maize (60 DAS), the zinc fraction distribution order was same in all treatments. Thus, it could be inferred that WSEX zinc is at optimum levels at 20 mg Zn kg^{-1} under chelated zinc fertilizers. Such distribution of zinc fractions depends on many factors *viz.* fertilizer source, crop type/variety/species and properties of soil etc.

The distribution of Zn among various chemical forms may vary significantly in response to changing soil properties (Adhikari and Rattan, 2007). Kiekens (1980) stated that there appeared to be two different mechanisms involved in the adsorption of zinc by clays and organic matter. One mechanism operates mainly in acid conditions and is closely related to cation exchange, and the other mechanism operates in alkaline conditions and mainly involves chemisorption and complexation by organic ligands. Apart from reversible adsorption by cation exchange, zinc can also be sorbed irreversibly by lattice penetration in clay minerals. The latter mechanism fixes amounts of zinc in excess of the cation exchange capacity and may be due to sorption of zinc in a hydrolysed form and precipitation of $Zn(OH)_2$. This 'fixation' of zinc tends to increase over time and can affect the long-term availability of zinc fertilisers. At low pH, Zn is considered to be held in an exchangeable form at basal planes of clay minerals, whereas at higher pH, Zn could be adsorbed by edge sites of clay minerals (McBride, 1994).

Data (Tables 6 and 7) further showed that the zinc fractions in the soil after harvest of wheat (60 DAS) were positively and significantly correlated with each other, whereas correlation coefficient slightly changed with time and was negative and non-significant between WSEX and CARB, CFeOX and DTPA-available, CARB and DTPA-available, while other fractions were positively and significantly correlated. Therefore analysed from the data (Table 8) it can be concluded that positive correlations with higher or lower levels of significance existed between zinc concentration in plant with the extracted fractions, except with the zinc associated with MnOX, AFeOX and CFeOX. The most positive and meaningful correlations were obtained with WSEX and OC zinc fractions, as well as with the DTPA-extractable Zn fraction. Similar results were also observed by Behera et al. (2008).

A perusal of the data (Tables 6 and 7) indicated that the DTPA-available zinc in soil significantly increased with increased levels of zinc after harvest of wheat (60 DAS). The residual value of available zinc was also significant after harvest of succeeding fodder maize (60 DAS). Thus, the highest content of available zinc was obtained with chelated zinc fertilizers. The relatively higher maintenance of Zn in soil due to applied chelated-Zn may be attributed from the very little or no interaction between soil components preventing various harmful reactions occurring in soil as compared to soil treated with $ZnSO_4$ which enhances greater fixation, adsorption etc., resulting from the greater interaction between soil components (Karak et al., 2005).

The effectiveness of zinc fertilizers was in order: Zn-DTPA ≥ Zn-CH ≥ Zn-EDTA > $ZnSO_4$ after harvest of both (wheat and maize) crops. These results are in accordance with the work of Mehdi et al. (1990) who also reported the relative effectiveness in order as Zn-EDTA > $Zn(NO_3)_2$ > $(NH_4)_2ZnO_2$ > $ZnSO_4$ > $ZnCl_2$. Karak et al. (2005) also observed that the residual effect of chelated Zn (Zn-EDTA) in maintaining Zn in soil was more than that of $ZnSO_4$. Some studies have indicated that organic sources are more effective fertilizers than inorganic ones. Their effectiveness depends on the rate of their disappearance from the soil solution, which is related to their stability (Alloway, 2008). Zinc chelates differ in physical state, chemical reactivity, cost, bioavailability, and susceptibility to leaching. The chelating agents DTPA, HEDTA and EDTA are some of the strongest synthetic chelating agents; in combination with Zn, they form much stronger chelates than naturally occurring organic ligands (Mortvedt and Gilkes, 1993).

Thus, it could be concluded that available zinc content in soil under study was sufficient for both wheat and maize crops that produced dry matter by balanced uptake of other nutrients, such as phosphorus at 10 mg Zn kg^{-1} using chelated zinc fertilizers (Zn-DTPA, Zn-EDTA and Zn-CH).

Recent recommendations for the treatment of zinc deficiency in wheat in India are 50 kg ha^{-1} zinc sulphate for acute cases and 25 kg ha^{-1} for moderate deficiencies (www.krishiworld.com). Kabata-Pendias (2001) listed threshold total zinc values from the literature for zinc in sensitive plant species as 150 to 200 mg Zn kg^{-1} and 100

to 500 mg Zn kg^{-1} as the range of zinc contents at which the yield of many crops might be reduced by 25 per cent due to toxicity.

4. Conclusion

The results obtained in the pot experiment provide an explanation of the differences observed in the Zn content in leaves, stem and roots of wheat and maize.The application of different levels of Zn using different Zn sources significantly increased the dry matter (shoot and root) yield and shoot/root ratio of wheat (60 DAS), as compared to control and significant residual effects of Zn on dry matter (shoot and root) yield and shoot/root ratio of succeeding fodder maize were also recorded. The Zn contents in wheat and maize leaves, stem and roots increased significantly with Zn addition over control. N and K content in both crops significantly increased with increased levels of Zn. The distributions of different fractions of Zn in soil were also influenced by the sources of Zn and their levels. Different fractions of Zn in soil were positively and significantly correlated with each other after harvest of wheat (60 DAS), whereas correlation coefficient slightly changed with time and was negative and non-significant between WSEX and CARB, CFeOX and DTPA-available, CARB and DTPA-available, while other fractions were positively and significantly correlated. The effectiveness of Zn fertilizers were in order: Zn-DTPA ≥ Zn-CH ≥ Zn-EDTA > ZnSO$_4$.7H$_2$O after harvest of both (wheat and maize) crops. The available zinc content in soil was sufficient for both crops (wheat and maize) that produced dry matter through balanced uptake of other nutrients, such as phosphorus at 10 mg Zn kg^{-1} using chelated zinc fertilizers (Zn-DTPA, Zn-EDTA and Zn-CH).

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Table 1. Effect of different levels of zinc and zinc sources on dry matter yield (g pot^{-1}) and root shoot : ratio of wheat and its residual effect on succeeding maize

Treatments	Wheat (60 DAS)			Maize (60 DAS)		
	Shoot	Roots	Shoot : Root Ratio	Shoot	Roots	Shoot : Root Ratio
T_1	15.380	8.857	1.736	17.094	9.900	1.727
T_2	16.397	9.077	1.806	17.837	10.080	1.770
T_3	16.713	9.190	1.819	18.100	10.163	1.781
T_4	15.230	8.823	1.726	17.027	9.893	1.721
T_5	16.200	9.063	1.787	17.680	10.070	1.756
T_6	16.477	9.163	1.798	17.893	10.150	1.763
T_7	15.323	8.820	1.737	17.050	9.910	1.721
T_8	16.287	9.090	1.792	17.843	10.043	1.777
T_9	16.600	9.180	1.808	18.060	10.157	1.778
T_{10}	14.780	8.507	1.738	15.850	9.607	1.650
T_{11}	15.337	8.763	1.750	16.120	9.757	1.652
T_{12}	15.567	8.867	1.755	16.273	9.847	1.653
T_{13}	11.663	6.923	1.707	13.870	8.380	1.658
SEm±	0.2421	0.1682	0.0237	0.2767	0.1885	0.0157
CD (p = 0.05)	0.7036	0.4891	0.0690	0.8045	0.5479	0.0457

Where, DAS=Days After Sowing.

Table 2. Effect of different levels of zinc and zinc sources on content of N, P, K and Zn in wheat (60 DAS)

Treatments	Nitrogen (%)			Phosphorus (%)			Potassium (%)			Zinc (mg kg^{-1})		
	Leaves	Stem	Roots	Leaves	Stem	Roots	Leaves	Stem	Roots	Leaves	Stem	Roots
T_1	1.524	1.469	1.442	0.197	0.195	0.194	1.191	1.123	1.088	58.977	61.120	65.460
T_2	1.561	1.511	1.494	0.191	0.189	0.188	1.226	1.161	1.134	70.637	72.350	76.783
T_3	1.591	1.534	1.526	0.184	0.182	0.180	1.264	1.191	1.172	79.893	81.480	85.490
T_4	1.515	1.463	1.434	0.196	0.194	0.193	1.185	1.128	1.104	59.277	61.250	65.813
T_5	1.571	1.502	1.477	0.190	0.188	0.187	1.222	1.172	1.142	69.643	71.470	75.487
T_6	1.596	1.538	1.519	0.185	0.183	0.181	1.274	1.204	1.161	78.950	80.674	84.150
T_7	1.523	1.466	1.435	0.198	0.196	0.195	1.201	1.139	1.107	59.983	62.537	66.470
T_8	1.577	1.511	1.491	0.191	0.189	0.187	1.242	1.174	1.146	69.980	73.470	77.577
T_9	1.601	1.539	1.523	0.184	0.182	0.181	1.284	1.199	1.182	78.740	81.450	85.943
T_{10}	1.478	1.421	1.424	0.196	0.193	0.186	1.173	1.125	1.073	40.617	42.240	47.237
T_{11}	1.543	1.463	1.464	0.191	0.188	0.185	1.214	1.147	1.124	51.737	53.740	58.583
T_{12}	1.581	1.492	1.491	0.183	0.181	0.180	1.247	1.184	1.158	59.280	61.560	66.480
T_{13}	1.418	1.351	1.325	0.186	0.185	0.183	1.151	1.097	1.067	18.640	20.457	23.130
SEm±	0.0191	0.0201	0.0208	0.0018	0.0013	0.0013	0.0154	0.0136	0.0119	1.1655	0.8576	1.1703
CD(p=0.05)	0.0554	0.0585	0.0604	0.0054	0.0038	0.0039	0.0448	0.0394	0.0346	3.3879	2.4929	3.4020

Where, DAS=Days After Sowing.

Table 3. Residual effect of different levels of zinc and zinc sources on content of N, P, K and Zn in maize (60 DAS)

Treatments	N (%)			P (%)			K (%)			Zn (mg kg^{-1})		
	Leaves	Stem	Roots	Leaves	Stem	Roots	Leaves	Stem	Roots	Leaves	Stem	Roots
T_1	1.377	1.315	1.280	0.201	0.199	0.197	1.230	1.200	1.191	46.753	48.150	53.507
T_2	1.408	1.352	1.312	0.197	0.195	0.194	1.250	1.220	1.210	57.220	59.180	64.240
T_3	1.425	1.374	1.330	0.191	0.189	0.189	1.260	1.230	1.231	65.447	67.593	71.137
T_4	1.379	1.318	1.274	0.202	0.200	0.198	1.230	1.200	1.202	46.247	48.470	52.350
T_5	1.409	1.352	1.316	0.198	0.196	0.194	1.250	1.210	1.214	57.483	59.240	63.240
T_6	1.427	1.378	1.334	0.192	0.189	0.189	1.260	1.220	1.224	66.470	68.480	72.480
T_7	1.381	1.321	1.280	0.202	0.200	0.198	1.240	1.200	1.190	47.180	49.480	52.860
T_8	1.418	1.355	1.317	0.197	0.195	0.193	1.250	1.210	1.211	57.417	58.950	63.337
T_9	1.425	1.367	1.335	0.191	0.189	0.190	1.270	1.220	1.218	65.947	68.160	70.893
T_{10}	1.375	1.315	1.260	0.200	0.198	0.197	1.230	1.190	1.192	35.510	36.220	39.213
T_{11}	1.405	1.343	1.290	0.199	0.196	0.195	1.230	1.200	1.203	42.893	43.670	46.557
T_{12}	1.416	1.361	1.310	0.193	0.191	0.189	1.250	1.210	1.209	47.540	48.950	51.650
T_{13}	1.362	1.313	1.250	0.193	0.192	0.191	1.220	1.190	1.185	16.757	18.250	20.540
SEm±	0.0156	0.0151	0.0148	0.0019	0.0013	0.0012	0.0094	0.0062	0.0096	0.8309	0.7460	0.7365
CD (p = 0.05)	0.0453	0.0440	0.0432	0.0056	0.0038	0.0034	0.0273	0.0180	0.0280	2.4153	2.1686	2.1409

Where, DAS=Days After Sowing.

Table 4. Effect of different levels of zinc and zinc sources on fractions of zinc (mg kg^{-1}) in soil after harvest of wheat (60 DAS)

Treatments	WSEX	OC	MnOX	AFeOX	CFeOX	CARB	RES	DTPA-Available
T$_1$	1.680	2.200	0.433	4.147	9.273	1.917	124.650	1.865
T$_2$	2.017	2.390	0.520	4.350	9.383	2.120	126.237	2.385
T$_3$	2.377	2.520	0.633	4.503	9.637	2.240	127.683	3.088
T$_4$	1.663	2.207	0.417	4.157	9.277	1.907	124.320	1.858
T$_5$	1.987	2.367	0.520	4.337	9.403	2.113	126.140	2.363
T$_6$	2.387	2.530	0.637	4.510	9.587	2.200	127.273	3.075
T$_7$	1.680	2.203	0.420	4.160	9.275	1.917	124.277	1.867
T$_8$	1.977	2.380	0.530	4.344	9.343	2.110	125.153	2.375
T$_9$	2.377	2.527	0.640	4.500	9.637	2.213	127.287	3.075
T$_{10}$	1.353	2.187	0.530	4.145	9.280	1.983	124.783	1.344
T$_{11}$	1.967	2.360	0.613	4.335	9.410	2.197	126.450	1.785
T$_{12}$	2.167	2.517	0.670	4.493	9.647	2.287	129.150	2.109
T$_{13}$	0.480	2.145	0.403	4.143	9.193	1.577	123.546	0.538
SEm±	0.0207	0.0285	0.0077	0.0352	0.1086	0.0378	1.1487	0.0292
CD (p= 0.05)	0.0602	0.0829	0.0223	0.1024	0.3156	0.1098	3.3392	0.0850

Where, DAS=Days After Sowing, WSEX=Water soluble + exchangeable zinc, OC=Organically complexed zinc, MnOX=Manganese oxide bound zinc, AFeOX=Amorphous iron oxide bound zinc, CFeOX=Crystalline iron oxide bound zinc, CARB=Carbonate bound zinc, RES=Residual zinc.

Table 5. Residual effect of different levels of zinc and zinc sources on fractions of zinc (mg kg^{-1}) in soil after harvest of maize (60 DAS)

Treatments	WSEX	OC	MnOX	AFeOX	CFeOX	CARB	RES	DTPA-Available
T$_1$	1.580	2.180	0.320	3.810	9.060	1.730	126.450	1.540
T$_2$	1.823	2.320	0.410	3.910	9.120	2.083	129.140	1.920
T$_3$	1.910	2.470	0.470	3.990	9.180	2.103	131.450	2.335
T$_4$	1.573	2.170	0.330	3.790	9.080	1.730	126.480	1.532
T$_5$	1.807	2.310	0.420	3.900	9.127	2.080	129.123	1.915
T$_6$	1.880	2.480	0.470	3.990	9.170	2.097	131.470	2.318
T$_7$	1.587	2.170	0.320	3.810	9.060	1.730	125.840	1.542
T$_8$	1.787	2.315	0.410	3.900	9.130	2.080	128.657	1.916
T$_9$	1.823	2.500	0.490	3.990	9.187	2.107	130.677	2.325
T$_{10}$	1.260	2.182	0.380	4.020	9.547	1.870	126.510	1.236
T$_{11}$	1.660	2.330	0.450	4.180	9.687	2.181	129.907	1.461
T$_{12}$	1.793	2.510	0.520	4.320	9.810	2.240	131.843	1.813
T$_{13}$	0.430	1.940	0.382	3.720	9.123	1.470	123.949	0.526
SEm±	0.0383	0.0533	0.0084	0.0799	0.0654	0.0283	1.7509	0.0114
CD (p= 0.05)	0.1114	0.1549	0.0245	0.2323	0.1900	0.0823	5.0899	0.0331

Where, DAS=Days After Sowing, WSEX=Water soluble + exchangeable zinc, OC=Organically complexed zinc, MnOX=Manganese oxide bound zinc, AFeOX=Amorphous iron oxide bound zinc, CFeOX=Crystalline iron oxide bound zinc, CARB=Carbonate bound zinc, RES=Residual zinc.

Table 6. Correlation coefficient (r) between zinc fractions in soil after harvest of wheat (60 DAS)

Zinc Fractions	WSEX	OC	MnOX	AFeOX	CFeOX	CARB	RES	DTPA-Available
WSEX	1.000	0.862**	0.752**	0.819**	0.821**	0.936**	0.791**	0.943**
OC		1.000	0.906**	0.996**	0.958**	0.883**	0.926**	0.850**
MnOX			1.000	0.909**	0.918**	0.890**	0.930**	0.659*
AFeOX				1.000	0.956**	0.851**	0.921**	0.815**
CFeOX					1.000	0.851**	0.954**	0.795**
CARB						1.000	0.890**	0.810**
RES							1.000	0.688*
DTPA-Available								1.000

* and ** significant at P = 0.05 and P = 0.01, respectively; where, DAS=Days After Sowing, WSEX=Water soluble + exchangeable zinc, OC=Organically complexed zinc, MnOX=Manganese oxide bound zinc, AFeOX=Amorphous iron oxide bound zinc, CFeOX=Crystalline iron oxide bound zinc, CARB=Carbonate bound zinc, RES=Residual zinc.

Table 7. Correlation coefficient (r) between different fractions of zinc in soil after harvest of maize (60 DAS)

	WSEX	OC	MnOX	AFeOX	CFeOX	CARB	RES	DTPA-Available
WSEX	1.000	0.839**	0.406	0.441	0.048	0.799**	0.785**	0.915**
OC		1.000	0.816**	0.709**	0.326	0.911**	0.978**	0.895**
MnOX			1.000	0.772**	0.532	0.801**	0.872**	0.549
AFeOX				1.000	0.894**	0.796**	0.747**	0.343
CFeOX					1.000	0.484	0.385**	-0.101
CARB						1.000	0.935**	0.754**
RES							1.000	0.836**
DTPA-Available								1.000

* and ** significant at P = 0.05 and P = 0.01, respectively; where, DAS=Days After Sowing, WSEX=Water soluble + exchangeable zinc, OC=Organically complexed zinc, MnOX=Manganese oxide bound zinc, AFeOX=Amorphous iron oxide bound zinc, CFeOX=Crystalline iron oxide bound zinc, CARB=Carbonate bound zinc, RES=Residual zinc.

Table 8. Correlation coefficient (r) between fractions of zinc in soil and plant (60 DAS)

	Zn fractions in soil after harvest of crop							
	WSEX	OC	MnOX	AFeOX	CFeOX	CARB	RES	DTPA-Available
Zn in wheat plant	0.935**	0.752**	0.526	0.703**	0.676*	0.773**	0.591*	0.973**
Zn in maize plant	0.913**	0.825**	0.442	0.224	-0.221	0.693*	0.761**	0.989**

* and ** significant at P = 0.05 and P = 0.01, respectively; where, DAS=Days After Sowing, WSEX=Water soluble + exchangeable zinc, OC=Organically complexed zinc, MnOX=Manganese oxide bound zinc, AFeOX=Amorphous iron oxide bound zinc, CFeOX=Crystalline iron oxide bound zinc, CARB=Carbonate bound zinc, RES=Residual zinc.