Lime and zinc application influence soil zinc availability, dry matter yield and zinc uptake by maize grown on Alfisols

Sanjib K. Behera*, Arvind K. Shukla, Brahma S. Dwivedi, Brij L. Lakaria

ICAR-Indian Institute of Oil Palm Research, Pedavegi, West Godavari District, Andhra Pradesh 534450, India
ICAR-Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal, Madhya Pradesh 462038, India
ICAR-Indian Agricultural Research Institute, Pusa, New Delhi, 110012, India

*Corresponding author: sanjibkumarbehera123@gmail.com (S. K. Behera), ICAR-Indian Institute of Oil Palm Research, Pedavegi, West Godavari District, Andhra Pradesh 534450, India

ABSTRACT
Zinc (Zn) deficiency is widespread in all types of soils of world including acid soils affecting crop production and nutritional quality of edible plant parts. There is, however, limited information available regarding effects of lime and farmyard manure (FYM) addition on soil properties, phyto-available Zn by different extractants, dry matter yield, Zn concentration and uptake by maize (Zea mays L.). Green house pot experiments were carried out in two acid soils to study the effect of five levels of lime (0, 1/10 lime requirement (LR), 1/3 LR, 2/3 LR and LR), three levels of Zn concentration (0, 2.5 and 5.0 mg Zn kg⁻¹ soil) and two levels of FYM (0 and 10 t ha⁻¹) addition on soil pH, EC and OC content, phyto-available Zn in soil and dry matter yield, Zn concentration and uptake by maize plant grown up to 60 days.

Application of lime and FYM improved soil pH. Increased level of lime application reduced Zn extracted by DTPA, Mehlich 1, Mehlich 3, 0.1 N HCl and ABDTPA extractants. However, application of FYM along with lime improved Zn extraction. The amount of Zn extracted by different extractants followed the order DTPA-Zn < ABDTPA-Zn < Mehlich-1 Zn < 0.1 M HCl. Lime rate of 1/3rd LR was found to be optimum as dry matter yield of maize increased significantly with lime application up to 1/3rd LR in soils of both the series and decreased subsequently. Addition of FYM with and without lime increased dry matter yield.
Application of Zn up to 5.0 mg kg\(^{-1}\) to soil increased dry matter yield with and without FYM application in soils of Hariharapur series. Addition of higher doses of lime significantly reduced Zn concentration in maize crop grown in soils of both the series. Mean Zn uptake values were at par for no lime, 1/10\(^{th}\) LR and 1/3\(^{rd}\) LR with and without FYM application and it was significantly higher than Zn uptake by 2/3\(^{rd}\) LR and LR treatments. However, FYM application improved Zn uptake by maize crop. Zn extracted by different extractants like DTPA, ABDTPA, Mehlich 1, Mehlich 3 and 0.1 M HCl was positively and significantly correlated amongst themselves and with dry matter yield, Zn concentration and Zn uptake by maize.

Keywords: Alfisols, Lime, Farmyard manure, Zinc, Maize

1. Introduction

Globally, zinc (Zn) deficiency is the most widespread micronutrient deficiency problem resulting in reduced crop production and nutritional quality of edible plant parts (Cakmak, 2002). It is more prevalent in cereal growing areas and nearly 50% of world’s cereal growing areas are having soils with low plant-available Zn. It has also been reported in almost all countries (Alloway, 2008) including India in different soil types (Takkar, 1996; Shukla et al., 2014). It is commonly prevalent in high pH calcareous soils (Katyal and Vlek, 1985), and leached, heavily weathered and sandy acid soils with low organic matter content (Rautaray et al., 2003; Behera et al., 2011).

Soil acidity is a serious problem affecting crop production across the world including India which is having 34.5% of arable land with acid soils (Maji et al., 2012). Ameliorating acid soils with suitable amendments and proper nutrient especially Zn management in acid soils are areas of concern for obtaining higher crop yield. Amelioration of acidic soils is beneficial to plant growth because it improves soil pH and replenishes nutrients (Moon et al.,
Application of liming material is an effective method for amelioration of acid soils (Ponnette et al., 1991; Quoggio et al., 1995). Lime is normally oxides, carbonates and hydroxides of calcium or magnesium. There are about four types of lime viz., quicklime (CaO), slaked lime (Ca(OH)₂), limestone (CaCO₃) and dolomite. Application of CaCO₃ to acid soils reduced soil acidity, improved basic cations status and significantly increased the yields of crops grown on Ultisol (Cifu et al., 2004). However, adoption of standard recommendation of lime requirement (LR) for different groups of acid soils is difficult for farmers, which is uneconomical and unsustainable. Therefore, lower doses of LR like 1/10th, 1/3rd and 2/3rd of LR are applied by the farmers. There is dearth of information regarding the application of different doses of lime on Zn availability in acid soils.

Soil pH and organic matter content are the most important soil factors affecting phyto-availability of Zn in soil (Suman, 1986; Lindsay, 1992). Increased soil pH due to addition of lime can influence availability of Zn in soil by altering its equilibrium (Verma and Minhas, 1987). Higher level of soil pH results in reduced extractable Zn content due to increased adsorptive capacity, formation of hydrolyzed forms of zinc, chemisorption on calcium carbonate and co-precipitation in iron oxides (Cox and Kamprath, 1972). Available organic materials such as farmyard manure (FYM) are generally used by the farmers along with chemical fertilizers because it improves soil physical, chemical and biological properties (Nambiar, 1994). Addition of organic matter to soil results in enhanced microbiological activity which adds complexing agents as well as influences the redox status of soil. According to Moody et al. (1997) higher levels of organic matters enhance Zn availability by increasing exchangeable and organic fractions of Zn and reducing oxide fractions of Zn. The effect of addition of organic matter on Zn availability in soils has also been reported by different workers (Murthy, 1982; Ghanem and Mikkelsen, 1987). But the information
regarding influence of addition of lime with and without FYM to acid soils on Zn availability in soil and Zn concentration and Zn uptake by crops is limited.

Appropriate soil tests for plant available metal are not yet available for all types of agricultural soils around the world. However, extractants like diethylene triamine pentaacetic acid (DTPA), ethylene diamine tetra acetic acid (EDTA), hydrochloric acid, ammonium bicarbonate-DTPA (ABDTPA), Mehlich 1 and Mehlich 3 are used for extraction of plant available Zn from soils (Alloway, 2008). But DTPA extractant is the most widely used. The DTPA soil test was originally developed to categorize near-neutral and calcareous soils with insufficient plant available Zn to support maximum yield of crops (Lindsay and Norvell, 1978). But the same has been used for acid soils also for extraction of plant available Zn. According to O’Connor (1988), whenever one strays from the original design of the test, one should be aware of the possible consequences and pass that awareness on to others. Based on correlation among the extracted Zn by different extractants and with soil properties, Behera et al. (2011) reported the usefulness of DTPA, Mehlich 1, Mehlich 3, 0.1 N HCl and ABDTPA extractant for extraction of plant available Zn in acid soils of India. But there is scanty information available regarding the relationship of extracted Zn by different extractants with Zn concentration and uptake by crop plants. Therefore, the present study was carried out to evaluate the influence of lime and FYM addition on soil pH, EC and OC content, extracted Zn as extracted by different extractants and dry matter yield, Zn concentration and uptake by maize (Zea mays L.) and to analyze the relationship amongst them.

2. Materials and methods

2.1 Soil characteristics and methods of soil analysis
The bulk surface (0-15 cm depth) soils collected from Hariharpur series (Oxic Haplustalfs) (Bhubaneswar, India) and Debatoli series (Udic Rhodostalfs) (Ranchi, India) were used in the study. These soils were representative typical soils found in India. Selected characteristics of these soils are given in Table 1. The collected soil samples were air dried and stone and debris were removed and then ground to pass a 2 mm sieve. The samples were then stored for subsequent analysis. Soil properties like pH and EC were determined done on 1:2.5 soil water ratio (w/v) suspension using pH meter and EC meter following half an hour equilibrium (Jackson, 1973). Soil organic carbon (OC) content was estimated by chromic acid digestion-back titration method (Walkley and Black, 1934). The clay, silt and sand percent of soils were determined by hydrometer method (Bouyoucos, 1962). Calcium carbonate (CaCO$_3$) content was determined by rapid titration method (Puri, 1930) and cation exchange capacity (CEC) by neutral normal ammonium acetate method (Richards, 1954). Lime requirement (LR) of the soil was estimated by extractant buffer method (Shoemaker et al., 1961). The plant available Zn in soils was extracted by DTPA method (Lindsay and Norvell, 1978). After drying of FYM at 70 °C for 24 h followed by grinding to pass through 20 mesh sieve, one gram of ground FYM was dry-ashed at 450 °C for 2h. Ashed samples were extracted using 0.5 N HCl. Zn concentration was determined in filtered extracts. The OC, N, P and K concentrations in FYM were estimated by appropriate methods (Jackson, 1973). The OC, N, P, K and Zn content in FYM (on dry weight basis) were 0.12%, 0.48%, 0.10%, 0.55% and 12 mg kg$^{-1}$ respectively.

Replicated soil samples were collected after harvesting of maize plants. Collected soil samples were processed and analyzed for pH, EC, OC content and DTPA-Zn concentration by the methodologies described above. The plant available Zn in soils was also extracted by Mehlich 1 (Perkins, 1970), 0.1 M HCl (Sorensen et al., 1971) and ABDTPA (Soltanpour and Schwab, 1977) extractants by following the respective prescribed methods. Estimation of
Zn concentration was done on the clear extract by atomic absorption spectrophotometer (AAS).

### 2.2 Green house study

Pot experiments were carried out in two Hariharapur and Debatoli series soils. The experiments were carried out in plastic pots having 4 kg of soil with five levels of LR (0, 1/10 LR, 1/3 LR, 2/3 LR and LR), three levels of Zn concentration (0, 2.5 and 5.0 mg Zn kg⁻¹ soil) and two levels of fresh FYM (35% moisture) (0 and 10 t ha⁻¹). All the pots received basal treatments of N-P₂O₅-K₂O @ 150-60-40 kg ha⁻¹. Fertilizer N, P and K were applied through analytical grade urea, calcium dihydrogen orthophosphate and muriate of potash, respectively. Lime and Zn were added to soil through laboratory grade CaCO₃ and ZnSO₄ respectively. All nutrients were mixed in soil thoroughly before sowing of seeds. The soil in each pot was then irrigated to field capacity with deionized water and kept for incubation for one week. Each treatment combination was replicated thrice in a factorial completely randomized design. Four seeds of cv. KH 101 of maize were sown in each pot. Two seedlings of maize per each pot were maintained after emergence. Pots were irrigated with water daily as per requirement of water on weight basis to maintain the field capacity. Above-ground biomass of plants from each pot was harvested at the end of 60 days of growth.

### 2.3 Plant analysis

Harvested above-ground biomass of each pot was washed in deionized water, and then dried in oven at 70 °C for 48 h. After drying, dry matter yield (DMY) of each pot was recorded. Dried plant material was then ground in a stainless steel Wiley mill, and digested in a di-acid mixture of HNO₃ and HClO₄ (Jackson, 1973). Zn concentration was then determined in aqueous extracts of the digested plant material by atomic absorption spectrophotometer (AAS). Zn uptake was calculated as DMY multiplied by the Zn concentration.
2.4 Statistical analysis

The data regarding soil properties, DMY, Zn concentration, Zn uptake and extracted Zn by different extractants subjected to analysis of variance method (Gomez and Gomez 1984). Least square difference (LSD) at $P \leq 0.01$ was used to compare among the treatment means. Pearson’s correlation coefficient values were estimated to establish relationship among soil properties, DMY, Zn concentration, Zn uptake and extracted Zn by different extractants.

3. Results

3.1 Soil properties

Application of lime at different rates significantly increased pH in soils of both Hariharapur and Debatoli series (Table 2, Fig. 1a). With addition of graded doses of limes viz. from no lime, $1/10^{th}$ LR, $1/3^{rd}$ LR, $2/3^{rd}$ LR and LR, soil pH increased from 4.58 to 7.16 (without FYM addition) and from 4.89 to 7.23 (with FYM addition) in Hariharapur series and from 5.83 to 6.95 (without FYM addition) and from 6.04 to 7.02 (with FYM addition) in Debatoli series. Application of FYM without lime increased soil pH in both the soils (Table 2). Combined application of lime and FYM also enhanced soil pH significantly. Addition of Zn did not have any effect on soil pH. Application of lime, FYM and Zn did not influence soil EC levels in soils of both the series (Table 2, Fig. 1b). However application of FYM increased soil OC content in soils of both series (Table 2, Fig. 1c). Addition of lime and Zn did not influence soil OC.

3.2 Extractable zinc in post-harvest soil

Data regarding amount Zn extracted by DTPA, Mehlich 1, 0.1 M HCl and ABDTPA extractants in post harvest soil are given in Table 3. The amount of extracted Zn by DTPA, Mehlich 1, and ABDTPA extractants decreased with increased level of lime application in soils of both the series (Fig. 2a, b, d). But addition of FYM (@ 10 t ha$^{-1}$) in combination of
different levels of lime led to marked enhancement of extracted Zn by different extractants in both the soils compared to only application of different lime levels (Table 3). Application Zn at different levels viz. 2.5 and 5.0 mg kg\(^{-1}\) with and without FYM increased the concentration of extracted Zn by the different extractants. The amount of Zn extracted by different extractants varied widely and it followed the order DTPA-Zn < ABDTPA-Zn < Mehlich-1 Zn < 0.1 M HCl.

3.3 Dry matter yield

DMY of maize increased significantly with lime application up to 1/3\(^{rd}\) LR (Table 4, Fig. 183 a) in soils of both the series. This indicated that lime application @ 1/3\(^{rd}\) of LR was optimum for these soils. Application of higher doses of lime (2/3\(^{rd}\) LR and LR) did not result in increased DMY. The mean DMY in 1/3\(^{rd}\) LR treatment without FYM and with FYM was 139% and 149% of control respectively in Harihpur series soils. Similarly in Debatoli series soil, the mean DMY was 84% and 120% of control without and with FYM application respectively in combination with 1/3\(^{rd}\) LR. Application of graded doses of Zn up to 5.0 mg kg\(^{-1}\) to soil increased DMY with and without FYM application in Hariharapur series. Whereas in Debatoli series, application of graded doses of Zn up to 5 mg kg\(^{-1}\) without FYM and application of Zn @ 2.5 mg kg\(^{-1}\) with FYM enhanced DMY.

3.4 Zinc concentration and uptake by maize

Addition of higher doses of lime significantly reduced Zn concentration in maize crop grown in soils of both the series (Table 4, Fig. 3 b). In contrast, application of Zn (@ 2.5 and 5.0 mg kg\(^{-1}\)) and FYM (@ 10 t ha\(^{-1}\)) increased Zn concentration in maize crop significantly in soils of both the series (Table 4). In soils of Hariharapur series, application Zn @ 2.5 and 5 mg kg\(^{-1}\) without and with FYM augmented Zn concentration in maize by 67.5 and 93.5 to 109 % respectively as compared to control (No Zn). Similarly, increased Zn concentrations of 22
to 35 and 58 to 73% were recorded with application of Zn @ 2.5 and 5 mg kg\(^{-1}\) without and with FYM respectively in comparison to no Zn control in soils of Debatoli series. Mean Zn uptake values were at par for no lime, 1/10\(^{th}\) LR and 1/3\(^{rd}\) LR with and without FYM application and it was significantly higher than Zn uptake by 2/3\(^{rd}\) LR and LR treatments in soils of both the series (Table 4, Fig. 3 c). However, Zn and FYM application improved Zn uptake by maize crop in soils of both series. Addition of Zn @ 2.5 and 5 mg kg\(^{-1}\) enhanced Zn uptake by 67 to 100 and 122 to 150% respectively as compared to no Zn control in soils of Hariharapur series. Whereas, the enhancements in Zn uptake were 36 to 50, 73 to 117% due to application of Zn @ 2.5 and 5 mg kg\(^{-1}\) respectively as compared to no Zn control in soils of Debatoli series.

4. Discussion

Lime is a basic chemical and its application neutralizes soil acidity (H\(^{+}\) and Al\(^{3+}\) ions) and makes soil more basic. In this study, application of increased rate of lime also enhanced soil pH. Anikwe et al. (2016) also reported increase in soil pH due to lime addition in an Ultisol of Nigeria. Application of lime along with FYM also enhanced soil pH. This is in line with the findings of Saha et al. (2012). Normally, addition of organic matter lowers soil pH by releasing H\(^{+}\) ions associated with organic anions or by nitrification in an open system (Porter et al., 1980). But in contrary, it may cause pH increases either by mineralization of organic anions to CO\(_2\) and water (thereby removing H\(^{+}\) ions) or because of the 'alkaline' nature of the organic material (Helyar, 1976). Increase in soil pH due to addition FYM in our study may be due to operation of the second mechanism.

Application of lime reduced the concentrations of extractable Zn extracted by DTPA, Mehlich 1 and ABDTPA extractants. Reduced availability of Zn in soil due to liming has also been reported by Tlustos et al. (2006) and Vondrackova et al. (2013). It is because of
conversion of plant available fractions of Zn to plant unavailable fractions resulting in effective immobilisation (Davis-Carter and Shuman, 1993). But application of FYM improved the concentrations of extracted Zn. Addition of organic matter led to formation of organic acids by microbial decomposition, which mobilize soil bound Zn and restrict the fixation of soluble Zn by chelating it (Shukla, 1971; Sarkar and Deb, 1982; Tagwira et al., 1992). It has also been reported by Saha et al. (1999) that application of organic matter to cultivated acid soils was essential to counteract the adverse effect of lime application on Zn availability. Application Zn with and without FYM enhanced the concentrations of extracted Zn significantly. Rupa et al. (2003) also reported increased concentration of exchangeable plus water soluble, inorganically, organically and oxide bound Zn in two Alfisols due to addition of increased Zn rates.

Among the extractants used in this study, DTPA extracted lowest amount of Zn. This is in agreement with the findings of Behera et al. (2011) who reported lowest amount of Zn extracted by DTPA compared other extractants like Mehlich 1, Mehlich 3, 0.1 M HCl and ABDTPA, by analysing four hundred soil samples collected from cultivated acid soils of India. This may be ascribed to lower extracting power of DTPA in these soils owing to reduced active sites of DTPA at lower pH values. Higher extractability of ABDTPA compared to DTPA in these soils because of ABDTPA solution pH of 7.6 which allowed DTPA to chelate and extract more Zn from soil. Mehlich 1 extractant which was originally developed for prediction of plant available P in acidic coastal plain soil (pH<6.5) with low cation exchange capacity (CEC<10meq/100g) and low organic matter (<5%), extracted more amount of Zn compared to DTPA and ABDTPA extractants. Higher extractability of Zn by 0.1 M HCl has also been reported by Naik and Das (2010) as compared to DTPA and 0.05 M HCl extracted Zn in low land rice soils. This is because 0.1 M HCl extracts Zn from freshly adsorbed iron and manganese oxides, carbonates, or decomposing organic matter and Zn.
bound with the octahedral-OH in layer silicates (Hodgson, 1963). Dilute mineral acids of pH 1-2 showed the greatest extracting power for extraction of Zn, followed by buffered solutions of pH 7-9 containing chelating agents and buffers or very dilute acids of pH 4-5 (Misra et al., 1989). Zhang et al. (2010) reported Zn extraction capacity of different extractants in the order of EDTA > Mehlich 3 > Mehlich 1 > DTPA > NH₄OAc > CaCl₂ in polluted soils of rice in south-eastern China. The amount Zn extracted in polluted soils of central Iran followed the order Mehlich 3 > DTPA > Mehlich 2 > CaCl₂ > HCl (Hosseiwwnpur and Motaghian, 2015).

Significant increase in DMY was recorded with application of lime up to 1/3rd LR. Increase in DMY with lime application up to 1/3rd LR may be ascribed to increase in soil pH and positive influence on nutrient availability in soil (Tisdale, 2005). Increased DMY due to FYM addition may be due to positive influence of on nutrient availability and uptake. Increased DMY due to Zn addition in soils of Hariharapur series revealed that Zn is a limiting nutrient in this soil. It was evident from low initial DTPA-Zn status (0.47 mg kg⁻¹) of this soil. Grain and vegetative tissue (stover) yield of maize increased significantly with successive application of Zn up to 1 kg ha⁻¹ in a Zn-deficient (DTPA-Zn 0.38 mg kg⁻¹) Vertisol of India (Behera et al., 2015). Zn addition to a soil with 0.18 mg kg⁻¹ Zn enhanced wheat grain yield (Cakmak et al., 2010a; Cakmak et al., 2010b). However in Debatoli series, DMY response to Zn application was obtained in spite of high initial DTPA-Zn status (1.45 mg kg⁻¹) which needs further investigation. In contrast to our findings, Zhang et al. (2012) and Wang et al. (2012) reported that zinc fertilizer application did not improve the biomass and grain yields of wheat and maize in rain-fed and low Zn calcareous soils of China. This may be attributed to Zn availability in soil influenced by several factors (Alloway, 2009) and efficiency of the crops/genotypes to utilize available Zn in soils (Cakmak et al., 1998).
Addition of lime significantly reduced Zn concentration. This may be due to reduced availability Zn in soil due to increased soil pH. Soil pH significantly influences Zn distribution among different fractions and availability in soil (Sims, 1986; Smith, 1994) and the plant uptake is primarily related with different Zn fractions (Behera et al., 2008). However, FYM and Zn application improved Zn concentration in maize. Application of 5 and 10 mg Zn kg\(^{-1}\) enhanced Zn concentration of navy bean shoot from 19.93 mg kg\(^{-1}\) to 38.12 and 54.8 mg kg\(^{-1}\) respectively (Gonzalez et al., 2008). Significant increase in Zn concentration in ear leaves of spring maize, shoots of wheat and in maize and wheat grains was also reported by Wang et al. (2012). Payne et al. (1988) also reported increased Zn concentration in maize grain under highest ZnSO\(_4\) application from a long-term experiment.

Soil pH was negatively and significantly correlated with Zn concentration \((r = -0.509^{**}, r = -0.343^{**})\) and Zn uptake by maize \((r = -0.397^{**}, r = -0.326^{**})\) in both the soil series (Table 5). This revealed that increased soil pH resulted in decreased Zn concentration and Zn uptake in maize and vice versa. Wang et al. (2006) also recorded increased Zn concentration in *Thlaspi caerulescens* with decreased soil pH. Soil OC content was positively and significantly correlated with DMY \((r = 0.221^{*})\), Zn concentration \((r = 0.232^{*})\) and Zn uptake \((r = 0.294^{**})\) in Hariharpur series only. It was also positively and significantly correlated with DTPA, Mehlich 1 and 0.1 M HCl extracted Zn in soils of both the series. This is in line with the findings of Katyal and Sharma (1991) and Shidhu and Sharma (2010). DMY was positively and significantly correlated with Zn uptake \((r = 0.605^{**}, 0.727^{**})\) in soils of both the series. It was also positively and significantly correlated with Zn extracted by DTPA, Mehlich 1, 0.1 M HCl and ABTDTPA extractants in Hariharpur series and Zn extracted by Mehlich 1, 0.1 M HCl and ABTDTPA extractants in Debatoli series. Zn concentration in maize was positively and significantly correlated with Zn uptake by maize and extracted Zn by different extractants in soils of both the series. Positive and significant correlation
Coefficient values were also obtained for Zn uptake vs Zn extracted by different extractants in soils of both the series. Zn extracted by different extractants in soils of both series were positively and significantly correlated with each other. The values of correlation coefficients ranged from $r = 0.811^{**}$ to $r = 0.937^{**}$. This indicated that the trend of extraction of Zn from both the soils, by different extractants used in the study is similar. It corroborates the findings of Gartley et al. (2002), Mylavaranu et al. (2002), Nascimento et al. (2007) and Behera et al. (2011) who have reported the suitability of extractants like DTPA, ABDTPA, Mehlich 1, Mehlich 3 and 0.1 M HCl for extraction of phyto-available Zn in acids of different parts of the world. Since Zn extracted by different extractants like DTPA, ABDTPA, Mehlich 1, Mehlich 3 and 0.1 M HCl was positively and significantly correlated amongst themselves and with DMY, Zn concentration and Zn uptake by maize, all these extractants can be used for extraction of Zn from acid soils.

5. Conclusion

From the study, it is concluded that application of lime with and without FYM influenced phyto-available Zn extracted by different extractants like DTPA, ABDTPA, Mehlich 1, Mehlich 3 and 0.1 M HCl in two acid soils of India. Increased level of lime application led to enhancement of soil pH and reduction in extractable Zn in soils of both the series and Zn concentration in maize. Lime application of 1/3LR was found to be optimum for amelioration in these soils. Application of FYM along with lime improved the concentration of extractable Zn in soil. Soil OC content was positively and significantly correlated with Zn extracted by different extractants. Since DTPA, ABDTPA, Mehlich 1, Mehlich 3 and 0.1 M HCl extractable Zn in soils of both the series were positively and significantly correlated with dry matter yield, Zn concentration and Zn uptake, these extractants could be used for extraction of Zn in acid soils.
Acknowledgements

The study was supported by the grant from Indian Council of Agricultural Research, New Delhi. We thank the Director of ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India for providing necessary facilities for conducting the research work. We acknowledge the help rendered by Ms. P. Singh, Mr. R. Singh and Mr. D. K. Verma during the execution of the work.

References

Alloway BJ (2008) Zinc in soils and crop nutrition. International Zinc Association, Brussels, Belgium. pp. 1-135.

Alloway BJ (2009) Soil factors associated with zinc deficiency in crops and humans. Environ Geochem Health 31: 537–548.

Anikwe MAN, Eze JC, Ibudialo AN, (2016) Influence of lime and gypsum application on soil properties and yield of cassava (Manihot esculenta Crantz.) in a degraded Ultisol in Agbani, Enugu Southeastern Nigeria. Soil Till Res 158: 32-38.

Behera SK, Shukla AK, Singh MV, Wanjari RH, Singh P (2015) Yield and zinc, copper, manganese and iron concentration in maize (Zea mays L.) grown on Vertisol as influenced by zinc application from various zinc fertilizers. J Plant Nutri 38(10): 1544-1557.

Behera SK, Singh D, Dwivedi BS, Singh S, Kumar K, Rana DS (2008) Distribution of fractions of zinc and their contribution towards availability and plant uptake of zinc under long-term maize (Zea mays L.)-wheat (Triticum aestivum L.) cropping on an Inceptisol. Aust J Soil Res 46 (1): 83-89.

Behera SK, Singh MV, Singh KN, Todwal S (2011) Distribution variability of total and extractable zinc in cultivated acid soils of India and their relationship with some selected soil properties. Geoderma 162 (3-4): 242-250.
Bouyoucos GJ (1962) Hydrometer method improved for making particle size analysis of soils. Agron J 54: 464.

Cakmak I, Torun B, Erenoglu B, Ozturk L, Marschner H, Kalayci M, Ekiz H, Yilmaz A (1998) Morphological and physiological differences in the response of cereals to zinc deficiency. Euphytica 100: 349–357.

Cakmak I (2002) Plant nutrition research priorities to meet human needs for food in sustainable ways. Pl Soil 247: 3–24.

Cakmak I, Kalayci M, Kaya Y, Torun AA, Aydin N, Wang Y, Arisoy Z, Erdem H, Yazici A, Gokmen OLO, Horst, WJ (2010a) Biofortification and localization of zinc in wheat grain. J Agric Food Chem 58: 9092–9102.

Cakmak I, Pfeiffer WH, McClafferty B (2010b) Biofortification of durum wheat with zinc and iron. Cereal Chem 87: 10–20.

Cifu M, Xiaonan L, Zhihong C, Zhengyi H, Wanzhu M (2004) Long-term effects of lime application on soil acidity and crop yields on a red soil in Central Zhejiang. Pl Soil 265: 101-109.

Cox FR, Kamprath EJ (1972) Micronutrients soil tests. In: Mortvedt JJ, Giordano PM, Lindsay WL (Eds.), Micronutrients in Agriculture. Soil Science Society of America, Madison, WI.

Davis-Carter, JG, Shuman LM (1993) Influence of texture and pH of kaolinitic soils on zinc fractions and zinc uptake by peanuts. Soil Sci 155: 376–384.

Gartley KL, Sims JT, Olsen CT, Chu P (2002) Comparison of soil test extractants used in mid-Atlantic United States. Commun Soil Sci Plant Anal 33(5&6): 873-895.

Ghanem SA, Mikkelsen PS (1987) Effect of organic matter changes in soil zinc fractions found in wet land soils. Commun Soil Sci Plant Anal 18: 1217–1234.
Gomez KA, Gomez AA (1984) Statistical Procedures for Agricultural Research, 2nd ed. John Wiley & Sons, New York, NY.

Gonzalez D, Obrador A, Lopez-Valdivia LM, Alvarez JM (2008) Effect of zinc source applied to soils on its availability to navy bean. Soil Sci Soc Am J 72: 641–649.

Helyar KR (1976) Nitrogen cycling and soil acidification. J Aust Inst Agric Sci 42: 217-21.

Hodgson JF (1963) Chemistry of micronutrient elements in soils. Adv Agron 15: 119-150.

Hosseiwnpur AR, Motaghian H (2015) Evaluating of many chemical extractants for assessment of Zn and Pb uptake by bean in polluted soils. J Soil Sci Pl Nutri 15 (1): 24-34.

Jackson ML (1973) Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd, New Delhi.

Katyal JC, Sharma BD (1991) DTPA-extractable and total Zn, Cu, Mn and Fe in Indian soils and their association with some soil properties. Geoderma 49: 165-179.

Katyal JC, Vlek PLG (1985) Micronutrient problems in tropical Asia. Fert Res 7: 131-150.

Lindsay WL (1972) Zinc in soils and plant nutrition. Adv Agron 24: 147-186.

Lindsay WL, Norvell WA (1978) Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci Soc Am J 42: 421-448.

Maji AK, Obi Reddy GP, Sarkar D (2012) Acid soils of India – Their extent and spatial distribution. NBSS&LUP Bull. 145, NBSS&LUP, Nagpur, India. 138 pp.

Misra AK, Nayar PK, Patnaik S (1989) Effect of flooding on extractable zinc, copper, boron, and molybdenum in soils and their relation with yield and uptake of these nutrients by rice (Oryza sativa). Indian J Agril Sci 59: 415-421.

Moody PW, Yo SA, Aitken RL (1997) Soil organic carbon, permanganate fractions, and the chemical properties of acid soils. Aust J Soil Res 35: 1301-1308.
Moon DH, Chang YY, Ok YS, Cheong KH, Koutsospyros A, Park JH, (2014) Amelioration of acidic soil using various renewable waste resources. Environ Sci Poll Res 21: 774-780.

Murthy ASP (1982) Zinc fractions in wetland rice soils and their availability to rice. Soil Sci 133: 150–154.

Mylavarapu RS, Sanchez JF, Nguyen JH, Bartos JM (2002) Evaluation of Mehlich-1 and Mehlich-3 extraction procedures for plant nutrients in acid mineral soils of Florida. Commun Soil Sci Plant Anal 33(5&6): 807-820.

Naik SS, Das DK (2010) Evaluation of various zinc extractants in lowland rice soils under the influence of zinc sulphate and chelated zinc. Commun Soil Sci Plant Anal 41: 122-134.

Nambiar KKM (1994) Soil fertility and crop productivity under long-term fertilizer use in India. Indian Council of Agricultural Research, New Delhi.

Nascimento CWA, Melo EEC, Nascimento RSMP, Leite PVV (2007) Effect of liming on the plant availability and distribution of zinc and copper among soil fractions. Commun Soil Sci Plant Anal 38: 545-560.

O’Connor GA (1988) Use and Misuse of the DTPA soil test. J Environ Qual 17: 715-718.

Payne GG, Martens DC, Winarko C, Perera NF (1988) Form and availability of copper and zinc following long-term copper sulfate and zinc sulfate applications. J Environ Qual 17: 707-711.

Perkins HF (1970) A rapid method of evaluating the zinc status of coastal plain soils. Commun Soil Sci Plant Anal 1: 35-42.

Ponnette Q, Frankart R, Poma Rojas W, Petit C (1991) Effects of mineral amendments on the physico-chemical properties of a brown acid soil in a beech stand in the Belgian Ardennes. Pedologie 41: 89–100.
Porter WM, Cox WJ, Wilson I (1980). Soil acidity ... is it a problem in Western Australia? West Aust J Agric 21: 126-33.

Puri AN (1930) A new method for estimating total carbonates in soil. Imp Agric Res Pusa Bull 206, pp. 7.

Quoggio JA, Gallo PB, Mascarenhas HA (1995) Agronomic efficiency of limestone with different acid-neutralizing capacity under field condition. Plant-Soil Interactions at Low pH: Principle and Management, pp: 491–496.

Rautaray SK, Ghosh BC, Mitra BN (2003) Effect of fly ash, organic wastes, and chemical fertilizers on yield, nutrient uptake, heavy metal content and residual fertility in a rice-mustard cropping sequence under acid lateritic soil. Biorec Techn 90: 275-283.

Richards LA (1954) Diagnosis and Improvement of Saline and Alkali soils. USDA Agricultural Handbook No. 60. US Government Printing Office, Washington, DC.

Rupa TR, Rao CS, Rao AS, Singh M (2003) Effect of farmyard manure and phosphorous on zinc transformations and phyto-availability in two alfisols of India. Biorec Tech 87: 279-288.

Saha JK, Adhikari T, Mandal B (1999) Effect of lime and organic matter on distribution of zinc, copper, iron, and manganese in acid soils. Commun Soil Sci Plant Anal 30 (13-14): 1819-1829.

Sarkar AK, Deb DL (1982) Zinc fractions in rice soils and their contribution to plant uptake. J Indian Soc Soil Sci 30: 63–69.

Shaha SC, Kashem MA, Khan TO (2012) Effect of Lime and Farmyard Manure on the Concentration of Cadmium in Water Spinach (Ipomoea aquatica). ISRN Agron. DOI:10.5402/2012/719432

Shukla UC (1971) Organic matter and zinc availability in soil. Pl Soil 6(4): 309-314.
Shukla AK, Tiwari PK, Chandra Prakash (2014) Micronutrient deficiencies vis-à-vis food and nutritional security of India. Indian J Fert 10(12): 94-112.

Shuman LM (1986) Effect of liming on the distribution of manganese, copper, iron and zinc among the soil fractions. Soil Sci Soc Am J 50: 1236-1240.

Sidhu GS, Sharma BD (2010) Diethylenetriaminepentaacetic acid-extractable micronutrients status in soil under a rice-wheat system and their relationship with soil properties in different agroclimatic zones of Indo-Gangetic Plains of India. Commun Soil Sci Plant Anal 41: 29-51.

Sims JT (1986) Soil pH effects on the distribution and plant availability of manganese, copper and zinc. Soil Sci Soc Am J 50: 367–373.

Smith SR (1994) Effect of soil pH on availability to crops of metals in sewage sludge treated soils. I. Nickel, copper and zinc uptake and toxicity to ryegrass. Environ Pollut 85: 321–327.

Soltanpour PN, Schwab AP (1977) Anew soil test for simultaneous extraction of macro and micronutrients in alkaline soils. Commn Soil Sci Pl Anal 8: 195-207.

Sorensen RC, Oelsligle DD, Knuden D (1971) Extraction of Zn, Fe and Mn from soils with 0.1 M hydrochloric acid as affected by soil properties, solution, soil ratio; and length of extraction period. Soil Sci 11: 352-359.

Tagwira F, Piha M, Mugwira L (1992) Effect of pH, and phosphorus and organic matter contents on zinc availability and distribution in two Zimbabwean soils. Commun Soil Sci Plant Anal 23: 1485-1500.

Tisdale SL, Havlin A, Nelson WL, Beton JD (2005) Soil Fertility and Fertilizers. New Delhi: Pearson Education, Inc.

Tlustoš P, Száková J, Kořínek K, Pavliková D, Hanč A, Balík J (2006) The effect of liming on cadmium, lead, and zinc uptake reduction by spring wheat grown in contaminated soil. Plant Soil Environ 52 (1): 16–24.
Verma TS, Minhas RS (1987) Zinc and phosphorus interaction in a wheat-maize cropping system. Fert Res 13: 77-86.

Vondráčková S, Hejcman M, Tlustoš P, Száková J (2013) Effect of quick lime and dolomite application on mobility of elements (Cd, Zn, Pb, As, Fe, and Mn) in contaminated soils. Pol J Environ Stud 22(2): 577-589.

Walkley AJ, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37: 29-38.

Wang J, Mao H, Zhao H, Huang D, Wang Z (2012) Different increases in maize and wheat grain zinc concentrations caused by soil and foliar applications of zinc in Loess Plateau, China. Field Crops Res 135: 89–96.

Wang AS, Angle JS, Chaney RL, Delorme TA, Reeves RD (2006) Soil pH effects on uptake of Cd and Zn by Thlaspi caerulescens. Pl Soil 281: 325–337.

Zhang M, Liu Z, Wang H (2010) Use of single extraction methods to predict bioavailability of heavy metals in polluted soils of rice. Commun Soil Sci Plant Anal 41: 820-831.

Zhang YQ, Sun YX, Ye YL, Rezaul Karim M, Xue YF, Yan P, Meng QF, Cui ZL, Cakmak I, Zhang FS, Zou CQ (2012) Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crop Res 125: 1–7.
Table 1 Some selected characteristics of the experimental soils.

| Soil characteristics       | Hariharapur series | Debatoli series |
|----------------------------|--------------------|-----------------|
| Taxonomic classification   | Oxic Haplustalfs   | Udic Rhodustalfs|
| pH (1:2.5)                 | 4.50               | 5.80            |
| EC (dS m\(^{-1}\))        | 0.14               | 0.23            |
| Organic carbon (%)         | 0.31               | 0.22            |
| Clay (%)                   | 12.1               | 14.2            |
| Silt (%)                   | 15.0               | 11.6            |
| Sand (%)                   | 73.2               | 75.1            |
| CaCO\(_3\) (%)             | 20.0               | 32.0            |
| CEC (cmol(p\(^+\)) kg\(^{-1}\)) | 3.90     | 5.10            |
| Lime requirement (g kg\(^{-1}\)) | 3.34     | 1.51            |
| DTAP-Zn (mg kg\(^{-1}\))  | 0.47               | 1.45            |
Table 2 Soil pH, EC and OC content as influence by FYM, lime and Zn application.

| Treatments | No FYM | FYM (10 t ha⁻¹) | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | Overall mean |
|------------|--------|-----------------|--------|----------------|----------------|------|--------|----------------|----------------|------|--------------|
| Hariharapur series | | | pH | | | | | | | | | |
| No lime | 4.56 | 5.16 | 5.10 | 5.34 | 5.20 | 4.89 |
| 1/10 LR | 4.80 | 5.46 | 5.42 | 5.44 | 5.44 | 5.16 |
| 1/3 LR | 5.69 | 5.93 | 6.49 | 5.97 | 6.13 | 5.97 |
| 2/3 LR | 6.45 | 6.92 | 7.08 | 6.57 | 6.86 | 6.70 |
| LR | 7.23 | 7.37 | 7.17 | 7.38 | 7.31 | 7.23 |
| Mean | 5.75 | 6.17 | 6.25 | 6.14 | - | - |

LSD (0.01) Lime = 0.19, Zn level = ns, FYM level = 0.25, Lime x Zn level = ns, Lime x FYM level = 0.51, Zn level x FYM level = ns

| Treatments | No FYM | FYM (10 t ha⁻¹) | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | Overall mean |
|------------|--------|-----------------|--------|----------------|----------------|------|--------|----------------|----------------|------|--------------|
| Hariharapur series | | | EC (dS m⁻¹) | | | | | | | | | |
| No lime | 0.14 | 0.13 | 0.15 | 0.14 | 0.14 | 0.13 |
| 1/10 LR | 0.14 | 0.12 | 0.11 | 0.12 | 0.12 | 0.12 |
| 1/3 LR | 0.13 | 0.12 | 0.10 | 0.10 | 0.10 | 0.10 |
| 2/3 LR | 0.12 | 0.11 | 0.12 | 0.12 | 0.10 | 0.10 |
| LR | 0.13 | 0.12 | 0.13 | 0.15 | 0.15 | 0.14 |
| Mean | 0.13 | 0.12 | 0.11 | 0.13 | 0.13 | 0.13 |

LSD (0.01) Lime = ns, Zn level = ns, FYM level = ns, Lime x Zn level = ns, Lime x FYM level = ns, Zn level x FYM level = ns

| Treatments | No FYM | FYM (10 t ha⁻¹) | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | Overall mean |
|------------|--------|-----------------|--------|----------------|----------------|------|--------|----------------|----------------|------|--------------|
| Hariharapur series | | | OC (%) | | | | | | | | | |
| No lime | 0.26 | 0.32 | 0.37 | 0.34 | 0.34 | 0.30 |
| 1/10 LR | 0.27 | 0.33 | 0.34 | 0.39 | 0.39 | 0.31 |
| 1/3 LR | 0.25 | 0.31 | 0.36 | 0.37 | 0.35 | 0.30 |
| 2/3 LR | 0.27 | 0.30 | 0.34 | 0.32 | 0.32 | 0.29 |
| LR | 0.24 | 0.25 | 0.22 | 0.25 | 0.25 | 0.33 |
| Mean | 0.26 | 0.30 | 0.35 | 0.35 | 0.35 | 0.31 |

LSD (0.01) Lime = ns, Zn level = ns, FYM level = 0.03, Lime x Zn level = ns, Lime x FYM level = ns, Zn level x FYM level = ns
| Treatment          | pH Mean | LSD (0.01) | Lime | Zn level | FYM level | Lime x Zn level | Lime x FYM level | Zn level x FYM level |
|--------------------|---------|------------|------|----------|-----------|-----------------|------------------|---------------------|
| No lime            | 5.85    | 0.24       |      |          |           |                 |                  |                     |
| 1/10th LR          | 5.88    | 0.24       |      |          |           |                 |                  |                     |
| 1/3rd LR           | 5.92    | 0.24       |      |          |           |                 |                  |                     |
| 2/3rd LR           | 6.27    | 0.24       |      |          |           |                 |                  |                     |
| LR                 | 6.11    | 0.24       |      |          |           |                 |                  |                     |

**EC (dS m⁻¹)**

| Treatment          | Mean | LSD (0.01) | Lime | Zn level | FYM level | Lime x Zn level | Lime x FYM level | Zn level x FYM level |
|--------------------|------|------------|------|----------|-----------|-----------------|------------------|---------------------|
| No lime            | 0.22 | 0.24       |      |          |           |                 |                  |                     |
| 1/10th LR          | 0.22 | 0.24       |      |          |           |                 |                  |                     |
| 1/3rd LR           | 0.23 | 0.24       |      |          |           |                 |                  |                     |
| 2/3rd LR           | 0.24 | 0.24       |      |          |           |                 |                  |                     |
| LR                 | 0.24 | 0.24       |      |          |           |                 |                  |                     |

**OC (%)**

| Treatment          | Mean | LSD (0.01) | Lime | Zn level | FYM level | Lime x Zn level | Lime x FYM level | Zn level x FYM level |
|--------------------|------|------------|------|----------|-----------|-----------------|------------------|---------------------|
| No lime            | 0.24 | 0.24       |      |          |           |                 |                  |                     |
| 1/10th LR          | 0.24 | 0.24       |      |          |           |                 |                  |                     |
| 1/3rd LR           | 0.24 | 0.24       |      |          |           |                 |                  |                     |
| 2/3rd LR           | 0.24 | 0.24       |      |          |           |                 |                  |                     |
| LR                 | 0.24 | 0.24       |      |          |           |                 |                  |                     |

**EC (dS m⁻¹)**

| Treatment          | Mean | LSD (0.01) | Lime | Zn level | FYM level | Lime x Zn level | Lime x FYM level | Zn level x FYM level |
|--------------------|------|------------|------|----------|-----------|-----------------|------------------|---------------------|
| No lime            | 6.36 | 0.24       |      |          |           |                 |                  |                     |
| 1/10th LR          | 6.84 | 0.24       |      |          |           |                 |                  |                     |
| 1/3rd LR           | 6.44 | 0.24       |      |          |           |                 |                  |                     |
| 2/3rd LR           | 6.42 | 0.24       |      |          |           |                 |                  |                     |
| LR                 | 6.44 | 0.24       |      |          |           |                 |                  |                     |
| Treatments | No FYM | FYM (10 t ha\(^{-1}\)) |
|------------|--------|-----------------------|
|            | No Zn  | 2.5 mg Zn kg\(^{-1}\) | 5.0 mg Zn kg\(^{-1}\) | Mean | No Zn  | 2.5 mg Zn kg\(^{-1}\) | 5.0 mg Zn kg\(^{-1}\) | Mean |
| Hariharapur series | DTPA-Zn (mg kg\(^{-1}\)) | Overall mean |
| No lime | 0.40 | 1.60 | 0.88 | 1.68 | 3.21 | 1.92 | 1.76 |
| 1/10 \(\text{th}\) LR | 0.40 | 1.31 | 0.66 | 1.67 | 3.20 | 1.84 | 1.58 |
| 1/3 \(\text{rd}\) LR | 0.38 | 1.03 | 0.61 | 1.62 | 2.68 | 1.64 | 1.33 |
| 2/3 \(\text{rd}\) LR | 0.37 | 0.89 | 0.44 | 1.59 | 2.55 | 1.53 | 1.21 |
| LR | 0.34 | 0.79 | 0.44 | 1.27 | 2.53 | 1.41 | 1.10 |
| Mean | 0.38 | 1.08 | 0.61 | 1.57 | 2.83 | - | - |
| LSD (0.01) | Lime = 0.02, Zn level = 0.25, FYM level = 0.20, Lime x Zn level = 0.35, Lime x FYM level = 0.28, Zn level x FYM level = 0.47 |

| Treatments | No lime | 1/10 \(\text{th}\) LR | 1/3 \(\text{rd}\) LR | 2/3 \(\text{rd}\) LR | LR |
|------------|---------|----------------------|----------------------|----------------------|-----|
| MeHlich 1-Zn (mg kg\(^{-1}\)) | 0.78 | 0.77 | 0.74 | 0.66 | 0.51 |
| Mean | 0.69 | 1.08 | 1.24 | 1.48 | 1.84 |
| LSD (0.01) | Lime = 0.10, Zn level = 0.42, FYM level = 0.25, Lime x Zn level = 0.55, Lime x FYM level = 0.37, Zn level x FYM level = 0.70 |

| Treatments | No lime | 1/10 \(\text{th}\) LR | 1/3 \(\text{rd}\) LR | 2/3 \(\text{rd}\) LR | LR |
|------------|---------|----------------------|----------------------|----------------------|-----|
| 0.1 M HCl-Zn (mg kg\(^{-1}\)) | 0.90 | 0.89 | 0.84 | 0.84 | 0.84 |
| Mean | 0.89 | 2.31 | 2.18 | 2.18 | 1.93 |
| LSD (0.01) | Lime = 0.10, Zn level = 0.42, FYM level = 0.25, Lime x Zn level = 0.55, Lime x FYM level = 0.37, Zn level x FYM level = 0.70 |
|                | ABDTPA-Zn (mg kg\(^{-1}\)) | DTPA-Zn (mg kg\(^{-1}\)) | Mehlich 1-Zn (mg kg\(^{-1}\)) |
|----------------|-----------------------------|---------------------------|--------------------------------|
| Mean           | 0.86 2.23 4.27 - 1.29 3.40 5.83 - - |                   |                                |
| LSD (0.01)     | Lime = 0.02, Zn level = 0.30, FYM level = 0.27, Lime x Zn level = 0.37, Lime x FYM level = 0.30, Zn level x FYM level = 0.60 |                   |                                |
| No lime        | 0.71 2.03 4.06 2.27 1.16 2.54 3.98 2.56 2.42 | 1.45 2.62 3.29 2.45 1.63 2.80 4.33 2.92 2.69 | 1.73 3.61 6.78 4.04 2.64 4.78 6.78 4.73 4.39 |
| 1/10 LR        | 0.68 1.98 3.19 1.95 1.11 2.43 3.92 2.49 2.22 | 1.30 2.32 2.93 2.18 1.37 2.54 4.01 2.64 2.41 | 1.63 3.60 6.59 3.94 2.44 4.20 6.28 4.31 4.12 |
| 1/3 LR         | 0.59 1.70 2.62 1.64 1.00 2.43 3.84 2.42 2.03 | 1.08 1.94 2.91 1.98 1.32 2.37 3.79 2.49 2.24 | 1.51 3.44 6.12 3.69 2.42 4.10 6.21 4.24 3.97 |
| 2/3 LR         | 0.52 1.52 2.29 1.44 0.95 2.37 3.61 2.31 1.88 | 0.99 1.78 2.80 1.86 1.08 2.25 2.95 2.09 1.98 | 1.49 3.33 4.13 2.98 2.40 4.06 5.69 4.05 3.52 |
| LR             | 0.49 1.25 2.12 1.29 0.93 2.21 3.31 2.15 1.72 | 0.60 1.70 2.85 - 1.03 2.40 3.73 - - | 1.26 3.15 4.06 2.82 2.37 3.74 5.46 3.86 3.34 |
| Mean           | 0.60 1.70 2.85 - 1.03 2.40 3.73 - - |                   |                                |
| LSD (0.01)     | Lime = 0.05, Zn level = 0.28, FYM level = 0.32, Lime x Zn level = 0.32, Lime x FYM level = 0.41, Zn level x FYM level = 0.62 |                   |                                |
| No lime        | 0.71 2.03 4.27 2.27 1.16 2.54 3.98 2.56 2.42 |                   |                                |
| 1/10 LR        | 0.68 1.98 3.19 1.95 1.11 2.43 3.92 2.49 2.22 |                   |                                |
| 1/3 LR         | 0.59 1.70 2.62 1.64 1.00 2.43 3.84 2.42 2.03 |                   |                                |
| 2/3 LR         | 0.52 1.52 2.29 1.44 0.95 2.37 3.61 2.31 1.88 |                   |                                |
| LR             | 0.49 1.25 2.12 1.29 0.93 2.21 3.31 2.15 1.72 |                   |                                |
| Mean           | 0.60 1.70 2.85 - 1.03 2.40 3.73 - - |                   |                                |
|          | 0.1 M HCl-Zn (mg kg\(^{-1}\)) |          |          |          |          |          |          |
|----------|-------------------------------|----------|----------|----------|----------|----------|----------|
| No lime  | 2.35  4.26  4.66  3.76  2.80  4.54  6.69  4.68  4.22 |
| 1/10 LR  | 2.32  4.42  5.34  4.03  2.75  4.70  6.93  4.79  4.41 |
| 1/3 LR   | 2.22  4.40  6.07  4.23  2.86  5.25  7.61  5.24  4.74 |
| 2/3 LR   | 2.23  3.87  7.46  4.52  2.91  5.14  7.01  5.02  4.77 |
| LR       | 2.22  4.53  6.96  4.57  2.85  6.06  7.79  5.57  5.07 |
| Mean     | 2.27  4.30  6.10  -    2.83  5.14  7.21  -    -    |
| LSD (0.01) | Lime = 0.06, Zn level = 0.35, FYM level = 0.37, Lime x Zn level = 0.45, Lime x FYM level = 0.45, Zn level x FYM level = 0.79 |

|          | ABDTPA-Zn (mg kg\(^{-1}\)) |          |          |          |          |          |          |
|----------|-------------------------------|----------|----------|----------|----------|----------|----------|
| No lime  | 2.10  3.19  4.23  3.18  2.12  3.34  5.17  3.54  3.36 |
| 1/10 LR  | 1.82  3.46  4.19  3.16  1.98  3.37  5.89  3.75  3.46 |
| 1/3 LR   | 1.61  2.77  4.60  2.99  1.93  3.46  5.17  3.52  3.26 |
| 2/3 LR   | 1.36  2.05  5.12  2.84  1.75  3.02  4.26  3.01  2.93 |
| LR       | 1.22  2.17  4.22  2.54  1.53  3.36  4.42  3.10  2.82 |
| Mean     | 1.62  2.73  4.47  -    1.86  3.31  4.98  -    -    |
| LSD (0.01) | Lime = 0.10, Zn level = 0.35, FYM level = 0.20, Lime x Zn level = 0.47, Lime x FYM level = 0.40, Zn level x FYM level = 0.70 |
Table 4  Effect of FYM, lime and Zn application on dry matter yield, Zn concentration and Zn uptake by maize.

| Treatments | No FYM | FYM (10 t ha⁻¹) | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | No Zn | 2.5 mg Zn kg⁻¹ | 5.0 mg Zn kg⁻¹ | Mean | Overall mean |
|------------|--------|----------------|-------|----------------|----------------|------|-------|----------------|----------------|------|--------------|
| Hariharapur series | | | Dry matter (g pot⁻¹) | | | | | | | | |
| No lime | 1.64 | 2.02 | 2.04 | 1.90 | 2.06 | 2.60 | 2.23 | 2.30 | 2.10 | |
| 1/10 LR | 2.43 | 2.37 | 2.16 | 2.32 | 2.21 | 2.74 | 2.66 | 2.53 | 2.43 | |
| 1/3 LR | 2.88 | 2.87 | 2.96 | 2.83 | 2.57 | 2.89 | 3.66 | 2.98 | 2.91 | |
| 2/3 LR | 2.65 | 2.37 | 2.66 | 2.64 | 2.40 | 2.40 | 3.01 | 2.66 | 2.65 | |
| LR | 1.77 | 2.06 | 2.52 | 2.12 | 1.94 | 2.05 | 2.71 | 2.23 | 2.18 | |
| Mean | 2.27 | 2.34 | 2.47 | - | 2.23 | 2.53 | 2.85 | - | - | |
| LSD (0.01) Lime = 0.30, Zn level = 0.11, FYM level = 0.25, Lime x Zn level =0. 50, Lime x FYM level = 0.61, Zn level x FYM level = 0.42 |
| No lime | 54.0 | 84.0 | 112 | 83.3 | 57.4 | 104 | 119 | 93.2 | 88.4 | |
| 1/10 LR | 53.3 | 87.4 | 113 | 84.6 | 59.2 | 99.5 | 119 | 92.7 | 88.6 | |
| 1/3 LR | 38.5 | 63.5 | 75.0 | 59.0 | 46.3 | 72.8 | 80.0 | 66.4 | 62.7 | |
| 2/3 LR | 27.4 | 52.7 | 60.8 | 47.0 | 35.4 | 59.8 | 67.6 | 54.2 | 50.6 | |
| LR | 25.2 | 44.8 | 54.2 | 41.4 | 31.2 | 48.9 | 58.1 | 46.1 | 43.7 | |
| Mean | 39.7 | 66.5 | 83.0 | - | 45.9 | 76.9 | 88.8 | - | - | |
| LSD (0.01) Lime = 3.50, Zn level = 0.11, FYM level = 2.00, Lime x Zn level =3.21, Lime x FYM level = 5.70, Zn level x FYM level = 3.15 |
| No lime | 0.11 | 0.14 | 0.23 | 0.16 | 0.12 | 0.27 | 0.26 | 0.22 | 0.19 | |
| 1/10 LR | 0.13 | 0.21 | 0.24 | 0.19 | 0.13 | 0.27 | 0.32 | 0.24 | 0.22 | |
| 1/3 LR | 0.10 | 0.18 | 0.22 | 0.17 | 0.11 | 0.21 | 0.29 | 0.20 | 0.19 | |
| 2/3 LR | 0.08 | 0.13 | 0.16 | 0.12 | 0.09 | 0.14 | 0.20 | 0.15 | 0.13 | |
### Debatoli series

|                | Dry matter (g pot\(^{-1}\)) | Zn concentration (mg kg\(^{-1}\)) | Zn uptake (mg pot\(^{-1}\)) |
|----------------|-----------------------------|-----------------------------------|-----------------------------|
| **LR**         |                             |                                   |                             |
| 0.05           | 0.05 0.09 0.14 0.09 0.06 0.10 0.16 0.11 0.10 | 0.05 0.09 0.20 0.10 0.20 0.25 0.25 0.11 0.10 | 0.05 0.09 0.20 0.10 0.20 0.25 0.25 0.11 0.10 |
| *Mean*         | 0.09 0.15 0.20 - 0.10 0.20 0.25 - - | 0.09 0.15 0.20 - 0.10 0.20 0.25 - - | 0.09 0.15 0.20 - 0.10 0.20 0.25 - - |
| **LSD (0.01)** | Lime = 0.002, Zn level = 0.005, FYM level = 0.004, Lime x Zn level = 0.008, Lime x FYM level = 0.007, Zn level x FYM level = 0.012 | Lime = 0.002, Zn level = 0.005, FYM level = 0.004, Lime x Zn level = 0.008, Lime x FYM level = 0.007, Zn level x FYM level = 0.012 | Lime = 0.002, Zn level = 0.005, FYM level = 0.004, Lime x Zn level = 0.008, Lime x FYM level = 0.007, Zn level x FYM level = 0.012 |
| No lime        | 2.84 3.55 4.19 3.53 3.45 3.72 3.44 3.57 3.55 | 62.2 85.0 119 88.7 71.0 86.2 126 94.4 91.6 | 0.18 0.30 0.50 0.33 0.25 0.32 0.44 0.34 0.33 |
| 1/10 th LR     | 3.37 3.94 4.52 3.94 3.56 4.06 4.21 3.91 3.93 | 55.3 68.9 94.8 73.0 71.6 77.3 97.9 82.3 77.6 | 0.20 0.31 0.47 0.33 0.24 0.34 0.49 0.36 0.34 |
| 1/3 rd LR      | 3.71 4.32 4.54 4.19 3.80 4.84 4.46 4.37 4.28 | 47.8 66.5 75.2 63.2 52.4 69.5 80.2 67.4 65.3 | 0.21 0.30 0.43 0.31 0.27 0.37 0.44 0.36 0.34 |
| 2/3 rd LR      | 3.55 3.67 4.43 3.88 3.53 3.74 3.76 3.68 3.78 | 39.7 60.6 64.8 55.0 44.8 62.6 70.6 59.4 57.2 | 0.17 0.24 0.33 0.25 0.19 0.26 0.30 0.25 0.25 |
| LR             | 3.27 3.54 3.46 3.42 3.46 3.59 3.55 3.54 3.48 | 3.35 3.80 4.23 - 3.56 3.99 3.88 - - | 0.13 0.21 0.23 0.19 0.15 0.23 0.25 0.21 0.20 |
| *Mean*         | 3.35 3.80 4.23 - 3.56 3.99 3.88 - - | 3.35 3.80 4.23 - 3.56 3.99 3.88 - - | 3.35 3.80 4.23 - 3.56 3.99 3.88 - - |
| **LSD (0.01)** | Lime = 0.32, Zn level = 0.22, FYM level = ns, Lime x Zn level = 0.58, Lime x FYM level = ns, Zn level x FYM level = ns | Lime = 1.80, Zn level = 0.20, FYM level = 1.50, Lime x Zn level = 2.10, Lime x FYM level = 3.80, Zn level x FYM level = 2.10 | Lime = 0.32, Zn level = 0.22, FYM level = ns, Lime x Zn level = 0.58, Lime x FYM level = ns, Zn level x FYM level = ns |
| No lime        | 62.2 85.0 119 88.7 71.0 86.2 126 94.4 91.6 | 53.1 71.9 91.8 - 62.1 76.0 98.1 - - | 0.18 0.30 0.50 0.33 0.25 0.32 0.44 0.34 0.33 |
| 1/10 th LR     | 60.4 78.4 105 81.3 70.7 84.3 116 90.3 85.8 | 55.3 68.9 94.8 73.0 71.6 77.3 97.9 82.3 77.6 | 0.20 0.31 0.47 0.33 0.24 0.34 0.49 0.36 0.34 |
| 1/3 rd LR      | 55.3 68.9 94.8 73.0 71.6 77.3 97.9 82.3 77.6 | 47.8 66.5 75.2 63.2 52.4 69.5 80.2 67.4 65.3 | 0.21 0.30 0.43 0.31 0.27 0.37 0.44 0.36 0.34 |
| 2/3 rd LR      | 47.8 66.5 75.2 63.2 52.4 69.5 80.2 67.4 65.3 | 39.7 60.6 64.8 55.0 44.8 62.6 70.6 59.4 57.2 | 0.17 0.24 0.33 0.25 0.19 0.26 0.30 0.25 0.25 |
| LR             | 39.7 60.6 64.8 55.0 44.8 62.6 70.6 59.4 57.2 | 53.1 71.9 91.8 - 62.1 76.0 98.1 - - | 0.13 0.21 0.23 0.19 0.15 0.23 0.25 0.21 0.20 |
| *Mean*         | 53.1 71.9 91.8 - 62.1 76.0 98.1 - - | 53.1 71.9 91.8 - 62.1 76.0 98.1 - - | 53.1 71.9 91.8 - 62.1 76.0 98.1 - - |
| **LSD (0.01)** | Lime = 1.80, Zn level = 0.20, FYM level = 1.50, Lime x Zn level = 2.10, Lime x FYM level = 3.80, Zn level x FYM level = 2.10 | Lime = 1.80, Zn level = 0.20, FYM level = 1.50, Lime x Zn level = 2.10, Lime x FYM level = 3.80, Zn level x FYM level = 2.10 | Lime = 1.80, Zn level = 0.20, FYM level = 1.50, Lime x Zn level = 2.10, Lime x FYM level = 3.80, Zn level x FYM level = 2.10 |
| No lime        | 0.18 0.30 0.50 0.33 0.25 0.32 0.44 0.34 0.33 | 0.18 0.27 0.39 - 0.22 0.30 0.38 - - | 0.18 0.27 0.39 - 0.22 0.30 0.38 - - | Lime = 0.03, Zn level = 0.11, FYM level = 0.02, Lime x Zn level = ns, Lime x FYM level = 0.08, Zn level x FYM level = ns | Lumbricillus sp.
Table 5  Pearson's correlation coefficient values revealing relationship among soil properties, dry matter yield, Zn concentration, Zn uptake and extracted Zn in soils (n = 90).

|          | pH  | EC  | OC  | Dry matter yield | Zn conc. | Zn uptake | DTPA-Zn | Mehlich 1-Zn | 0.1 M HCl-Zn | ABDTPA-Zn |
|----------|-----|-----|-----|------------------|----------|-----------|---------|--------------|--------------|-----------|
| Hariharapur series |     |     |     |                  |          |           |         |              |              |           |
| pH       | 1   | -0.084 | 1   |                  |          |           |         |              |              |           |
| EC       | 0.058 | 1   |     | 0.093 | 0.221*   | 1         | 0.047   | 0.310**   | 0.605**     | 0.792**   |
| OC       | -0.089 | 0.093 | 1   | 0.029 | 0.232*   | 0.047    | 0.310** | 0.605**     | 0.792**     | 0.523**   |
| Dry matter yield | -0.059 | 0.093 | 1   | 0.029 | 0.232*   | 0.047    | 0.310** | 0.605**     | 0.792**     | 0.523**   |
| Zn conc.  | -0.397** | -0.036 | 0.294** | 0.301** | 0.633** | 0.669** | 0.285** | 0.673**     | 0.887**     | 0.923**   |
| Zn uptake | 0.010 | 0.073 | 0.211** | 0.301** | 0.633** | 0.669** | 0.285** | 0.673**     | 0.887**     | 0.923**   |
| DTPA-Zn | 0.010 | 0.073 | 0.211** | 0.301** | 0.633** | 0.669** | 0.285** | 0.673**     | 0.887**     | 0.923**   |
| Mehlich 1-Zn | 0.130 | -0.045 | 0.272** | 0.281** | 0.817** | 0.871** | 0.922** | 0.923**     | 1            |           |
| 0.1 M HCl-Zn | 0.046 | -0.007 | 0.242*  | 0.260*  | 0.633** | 0.669** | 0.285** | 0.673**     | 0.887**     | 0.923**   |
| ABDTPA-Zn | -0.011 | -0.001 | 0.135  | 0.285** | 0.633** | 0.669** | 0.285** | 0.673**     | 0.887**     | 0.923**   |

Debatoli series |     |     |     |                  |          |           |         |              |              |           |
| pH       | 1   | 0.032 | 1   |                  |          |           |         |              |              |           |
| EC       | 0.113 | -0.098 | 1   | 0.011 | 0.317** | 1         | 0.333** | 0.333**     | 0.333**     | 0.333**   |
| OC       | -0.154 | -0.096 | 0.158 | 0.186 | 0.290** | 0.333** | 0.333** | 0.333**     | 0.333**     | 0.333**   |
| Dry matter yield | -0.343** | -0.042 | 0.158 | 0.186 | 0.290** | 0.333** | 0.333** | 0.333**     | 0.333**     | 0.333**   |
| Zn conc.  | -0.326** | 0.086 | 0.110 | 0.133 | 0.727** | 0.727** | 0.727** | 0.727**     | 0.727**     | 0.727**   |
| Zn uptake | -0.087 | 0.061 | 0.133 | 0.133 | 0.727** | 0.727** | 0.727** | 0.727**     | 0.727**     | 0.727**   |
| DTPA-Zn | -0.087 | 0.061 | 0.133 | 0.133 | 0.727** | 0.727** | 0.727** | 0.727**     | 0.727**     | 0.727**   |
| Mehlich 1-Zn | 0.168 | 0.091 | 0.137 | 0.133 | 0.727** | 0.727** | 0.727** | 0.727**     | 0.727**     | 0.727**   |
| 0.1 M HCl-Zn | 0.188 | 0.130 | 0.204** | 0.333** | 0.333** | 0.333** | 0.333** | 0.333**     | 0.333**     | 0.333**   |
| ABDTPA-Zn | -0.074 | 0.108 | 0.193 | 0.419** | 0.419** | 0.419** | 0.419** | 0.419**     | 0.419**     | 0.419**   |

*p ≤ 0.05; **p ≤ 0.01.
Fig. 1. Soil pH, EC and OC as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.

Fig. 2. Extractable Zn by different extractants as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.

Fig. 3. Dry matter yield, Zn concentration and Zn uptake by maize as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.
(a) soil pH
(b) soil EC (dSm⁻¹)
Fig. 1. Soil pH, EC and OC as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.
DTPA-Zn (mg kg\(^{-1}\)) vs Lime rate

(a) No FYM (Hariharapur series) vs FYM (Hariharapur series)

No FYM (Debatoli series) vs FYM (Debatoli series)
Fig. 2. Extractable Zn by different extractants as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.
Fig. 3. Dry matter yield, Zn concentration and Zn uptake by maize as influenced by interaction of Zn application and lime rate in Hariharapur and Debatoli series. Error bars represent ± SE.