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

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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.,

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2014). 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 ($CaCO_3$) and dolomite. Application $CaCO_3$ 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 penta acetic 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 per cent 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 ^{o}C for 24 h followed by grinding to pass through 20 mesh sieve, one gram of ground FYM was dry-ashed at 450 ^{o}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

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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-P_2O_5-K_2O @ 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 $CaCO_3$ and $ZnSO_4$ respectively. All nutrients were mixed in soil thoroughly before sowing of seeds. The soil in each plot 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 ^{o}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 HNO_3 and $HClO_4$ (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.

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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 ≤ .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. 1 a). With addition of graded doses of limes viz. from no lime, 1/10th LR, 1/3rd LR, 2/3rd 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. 1 b). 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. 2 a, 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 1/3rd LR (Table 4, Fig. 3 a) in soils of both the series. This indicated that lime application @ 1/3rd of LR was optimum for these soils. Application of higher doses of lime (2/3rd LR and LR) did not result in increased DMY. The mean DMY in 1/3rd 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 1/3rd LR. Application of graded doses of Zn upto 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, 1/10th LR and 1/3rd LR with and without FYM application and it was significantly higher than Zn uptake by 2/3rd 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 to50, 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 ($CEC<10$meq/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

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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 > NH_4OAc > $CaCl_2$ in polluted soils of rice in south-eastern China. The amount Zn extracted in polluted soils of central Iran followed the order Mehlich 3 > ABDTPA > DTPA > Mehlich 2 > $CaCl_2$ > 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 ABDTPA extractants in Hariharpur series and Zn extracted by Mehlich 1, 0.1 M HCl and ABDTPA 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), Mylavarapu 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 concentarion 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.

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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

T able 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	4.57	4.61	4.58	5.16	5.10	5.34	5.20	4.89
$1/10^{th}$ LR	4.80	5.01	4.83	4.88	5.46	5.42	5.44	5.44	5.16
$1/3^{rd}$ LR	5.69	6.14	5.57	5.80	5.93	6.49	5.97	6.13	5.97
$2/3^{rd}$ LR	6.45	6.53	6.62	6.53	6.92	7.08	6.57	6.86	6.70
LR	7.23	7.25	6.99	7.16	7.37	7.17	7.38	7.31	7.23
Mean	5.75	5.90	5.72	-	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								
					EC (dS m^{-1})				
No lime	0.14	0.11	0.13	0.13	0.13	0.15	0.14	0.14	0.13
$1/10^{th}$ LR	0.14	0.10	0.10	0.12	0.15	0.11	0.12	0.13	0.12
$1/3^{rd}$ LR	0.13	0.13	0.11	0.12	0.12	0.10	0.14	0.12	0.12
$2/3^{rd}$ LR	0.12	0.13	0.11	0.12	0.12	0.15	0.10	0.12	0.12
LR	0.13	0.14	0.12	0.13	0.15	0.14	0.15	0.15	0.14
Mean	0.13	0.12	0.11	-	0.13	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								
					OC (%)				
No lime	0.26	0.27	0.25	0.26	0.32	0.37	0.34	0.34	0.30
$1/10^{th}$ LR	0.27	0.24	0.27	0.26	0.33	0.34	0.39	0.35	0.31
$1/3^{rd}$ LR	0.25	0.24	0.27	0.25	0.31	0.36	0.37	0.35	0.30
$2/3^{rd}$ LR	0.27	0.25	0.23	0.25	0.30	0.34	0.32	0.32	0.29
LR	0.24	0.21	0.22	0.22	0.25	0.34	0.33	0.31	0.27
Mean	0.26	0.24	0.25	-	0.30	0.35	0.35	-	-
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								

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Debatoli series									
				pH					
No lime	5.88	5.85	5.77	5.83	6.14	6.17	6.45	6.25	6.04
1/10th LR	5.93	5.88	5.94	5.92	6.28	6.42	6.56	6.42	6.17
1/3rd LR	6.38	6.21	6.21	6.27	6.44	6.57	6.58	6.53	6.40
2/3rd LR	6.64	6.67	6.6	6.64	6.76	6.75	6.64	6.72	6.68
LR	6.96	6.99	6.9	6.95	7.27	6.87	7.14	7.09	7.02
Mean	6.36	6.32	6.28	-	6.58	6.56	6.67	-	-
LSD (0.01)	Lime = 0.17, Zn level = ns, FYM level = 0.20, Lime x Zn level = ns, Lime x FYM level = 0.47, Zn level x FYM level = ns								
				EC (dS m^{-1})					
No lime	0.23	0.22	0.27	0.24	0.21	0.26	0.23	0.23	0.24
1/10th LR	0.27	0.27	0.23	0.25	0.21	0.23	0.20	0.21	0.24
1/3rd LR	0.23	0.23	0.24	0.23	0.17	0.29	0.25	0.24	0.24
2/3rd LR	0.23	0.21	0.21	0.21	0.23	0.19	0.24	0.22	0.22
LR	0.24	0.17	0.29	0.23	0.19	0.30	0.26	0.25	0.24
Mean	0.24	0.22	0.25	-	0.20	0.25	0.24	-	-
LSD (0.01)	Lime = ns, Zn level = ns, FYM level = 0.04, Lime x Zn level = ns, Lime x FYM level = ns, Zn level x FYM level = ns								
				OC (%)					
No lime	0.21	0.28	0.22	0.24	0.22	0.29	0.30	0.27	0.25
1/10th LR	0.22	0.22	0.21	0.22	0.28	0.28	0.28	0.28	0.25
1/3rd LR	0.21	0.25	0.24	0.23	0.28	0.26	0.29	0.28	0.26
2/3rd LR	0.18	0.22	0.25	0.21	0.31	0.25	0.28	0.28	0.25
LR	0.21	0.25	0.26	0.24	0.28	0.30	0.28	0.28	0.26
Mean	0.21	0.24	0.24	-	0.27	0.27	0.29	-	-
LSD (0.01)	Lime = ns, Zn level = ns, FYM level = 0.04, Lime x Zn level = ns, Lime x FYM level = ns, Zn level x FYM level = ns								

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T able 3 Effect of FYM, lime and Zn application on extractable Zn in soils.

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									
	DTPA-Zn (mg kg^{-1})								
No lime	0.40	1.44	2.95	1.60	0.88	1.68	3.21	1.92	1.76
1/10th LR	0.40	1.24	2.30	1.31	0.66	1.67	3.20	1.84	1.58
1/3rd LR	0.38	1.06	1.64	1.03	0.61	1.62	2.68	1.64	1.33
2/3rd LR	0.37	0.86	1.45	0.89	0.44	1.59	2.55	1.53	1.21
LR	0.34	0.77	1.25	0.79	0.44	1.27	2.53	1.41	1.10
Mean	0.38	1.08	1.92	-	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								
	Mehlich 1-Zn (mg kg^{-1})								
No lime	0.78	1.68	3.85	2.10	1.23	3.70	5.08	3.34	2.72
1/10th LR	0.77	1.66	3.74	2.06	1.17	3.20	4.88	3.08	2.57
1/3rd LR	0.74	1.50	3.27	1.84	1.05	2.64	4.79	2.83	2.33
2/3rd LR	0.66	1.48	2.26	1.47	1.03	2.54	4.49	2.69	2.08
LR	0.51	1.24	1.92	1.22	0.94	2.54	4.25	2.58	1.90
Mean	0.69	1.51	3.01	-	1.09	2.92	4.70	-	-
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								
	0.1 M HCl-Zn (mg kg^{-1})								
No lime	0.90	2.50	4.62	2.67	1.50	3.81	6.24	3.85	3.26
1/10th LR	0.89	2.31	4.61	2.60	1.34	3.72	6.20	3.75	3.18
1/3rd LR	0.84	2.25	4.28	2.46	1.33	3.39	5.68	3.47	2.96
2/3rd LR	0.84	2.18	3.94	2.32	1.22	3.05	5.62	3.30	2.81
LR	0.84	1.93	3.91	2.23	1.06	3.03	5.43	3.17	2.70

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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								
	ABDTPA-Zn (mg kg^{-1})								
No lime	0.71	2.03	4.06	2.27	1.16	2.54	3.98	2.56	2.42
1/10th LR	0.68	1.98	3.19	1.95	1.11	2.43	3.92	2.49	2.22
1/3rd LR	0.59	1.70	2.62	1.64	1.00	2.43	3.84	2.42	2.03
2/3rd 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	-	-
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								
Debatoli series									
	DTPA-Zn (mg kg^{-1})								
No lime	1.45	2.62	3.29	2.45	1.63	2.80	4.33	2.92	2.69
1/10th LR	1.30	2.32	2.93	2.18	1.37	2.54	4.01	2.64	2.41
1/3rd LR	1.08	1.94	2.91	1.98	1.32	2.37	3.79	2.49	2.24
2/3rd LR	0.99	1.78	2.80	1.86	1.08	2.25	2.95	2.09	1.98
LR	0.77	1.72	2.73	1.74	0.99	2.21	2.48	1.89	1.82
Mean	1.12	2.08	2.93	-	1.28	2.43	3.51	-	-
LSD (0.01)	Lime = 0.21, Zn level = 0.50, FYM level = 0.35, Lime x Zn level =0. 75, Lime x FYM level = 0.78, Zn level x FYM level = 0.98								
	Mehlich 1-Zn (mg kg^{-1})								
No lime	1.73	3.61	6.78	4.04	2.64	4.78	6.78	4.73	4.39
1/10th LR	1.63	3.60	6.59	3.94	2.44	4.20	6.28	4.31	4.12
1/3rd LR	1.51	3.44	6.12	3.69	2.42	4.10	6.21	4.24	3.97
2/3rd LR	1.49	3.33	4.13	2.98	2.40	4.06	5.69	4.05	3.52
LR	1.26	3.15	4.06	2.82	2.37	3.74	5.46	3.86	3.34
Mean	1.53	3.43	5.54	-	2.45	4.18	6.08	-	-
LSD (0.01)	Lime = 0.09, Zn level = 0.50, FYM level = 0.28, Lime x Zn level =0. 45, Lime x FYM level = 0.42, Zn level x FYM level = 0.85								

	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
1/10th LR	2.32	4.42	5.34	4.03	2.75	4.70	6.93	4.79	4.41
1/3rd LR	2.22	4.40	6.07	4.23	2.86	5.25	7.61	5.24	4.74
2/3rd 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
1/10th LR	1.82	3.46	4.19	3.16	1.98	3.37	5.89	3.75	3.46
1/3rd LR	1.61	2.77	4.60	2.99	1.93	3.46	5.17	3.52	3.26
2/3rd 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								

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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
$1/10^{th}$ LR	2.43	2.37	2.16	2.32	2.21	2.74	2.66	2.53	2.43
$1/3^{rd}$ LR	2.88	2.87	2.96	2.83	2.57	2.89	3.66	2.98	2.91
$2/3^{rd}$ 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								
	Zn concentration (mg kg^{-1})								
No lime	54.0	84.0	112	83.3	57.4	104	119	93.2	88.4
$1/10^{th}$ LR	53.3	87.4	113	84.6	59.2	99.5	119	92.7	88.6
$1/3^{rd}$ LR	38.5	63.5	75.0	59.0	46.3	72.8	80.0	66.4	62.7
$2/3^{rd}$ 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								
	Zn uptake (mg pot^{-1})								
No lime	0.11	0.14	0.23	0.16	0.12	0.27	0.26	0.22	0.19
$1/10^{th}$ LR	0.13	0.21	0.24	0.19	0.13	0.27	0.32	0.24	0.22
$1/3^{rd}$ LR	0.10	0.18	0.22	0.17	0.11	0.21	0.29	0.20	0.19
$2/3^{rd}$ LR	0.08	0.13	0.16	0.12	0.09	0.14	0.20	0.15	0.13

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LR	0.05	0.09	0.14	0.09	0.06	0.10	0.16	0.11	0.10
Mean	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								
Debatoli series									
	Dry matter (g pot^{-1})								
No lime	2.84	3.55	4.19	3.53	3.45	3.72	3.44	3.57	3.55
1/10th LR	3.37	3.94	4.52	3.94	3.56	4.06	4.21	3.91	3.93
1/3rd LR	3.71	4.32	4.54	4.19	3.80	4.84	4.46	4.37	4.28
2/3rd LR	3.55	3.67	4.43	3.88	3.53	3.74	3.76	3.68	3.78
LR	3.27	3.54	3.46	3.42	3.46	3.59	3.55	3.54	3.48
Mean	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								
	Zn concentration (mg kg^{-1})								
No lime	62.2	85.0	119	88.7	71.0	86.2	126	94.4	91.6
1/10th LR	60.4	78.4	105	81.3	70.7	84.3	116	90.3	85.8
1/3rd LR	55.3	68.9	94.8	73.0	71.6	77.3	97.9	82.3	77.6
2/3rd LR	47.8	66.5	75.2	63.2	52.4	69.5	80.2	67.4	65.3
LR	39.7	60.6	64.8	55.0	44.8	62.6	70.6	59.4	57.2
Mean	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								
	Zn uptake (mg pot^{-1})								
No lime	0.18	0.30	0.50	0.33	0.25	0.32	0.44	0.34	0.33
1/10th LR	0.20	0.31	0.47	0.33	0.24	0.34	0.49	0.36	0.34
1/3rd LR	0.21	0.30	0.43	0.31	0.27	0.37	0.44	0.36	0.34
2/3rd LR	0.17	0.24	0.33	0.25	0.19	0.26	0.30	0.25	0.25
LR	0.13	0.21	0.23	0.19	0.15	0.23	0.25	0.21	0.20
Mean	0.18	0.27	0.39	-	0.22	0.30	0.38	-	-
LSD (0.01)	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								

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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									
EC	0.058	1								
OC	-0.089	-0.084	1							
Dry matter yield	0.059	0.093	0.221*	1						
Zn conc.	-0.590**	-0.029	0.232*	0.047	1					
Zn uptake	-0.397**	0.036	0.294**	0.605**	0.792**	1				
DTPA-Zn	0.010	-0.073	0.211*	0.391**	0.610**	0.523**	1			
Mehlich 1-Zn	0.130	-0.045	0.272**	0.281**	0.510**	0.545**	0.897**	1		
0.1 M HCl-Zn	0.046	-0.076	0.242*	0.260*	0.633**	0.626**	0.871**	0.929**	1	
ABDTPA-Zn	-0.011	-0.013	0.136	0.285**	0.656**	0.673**	0.887**	0.922**	0.923**	1
Debatoli series										
pH	1									
EC	0.032	1								
OC	0.113	-0.098	1							
Dr matter yield	-0.154	0.096	0.011	1						
Zn conc.	-0.343**	0.042	0.158	0.384**	1					
Zn uptake	-0.326**	0.086	0.110	0.727**	0.905**	1				
DTPA-Zn	-0.087	0.061	0.290**	0.133	0.741**	0.715**	1			
Mehlich 1-Zn	0.168	0.091	0.317**	0.330**	0.589**	0.568**	0.811**	1		
0.1 M HCl-Zn	0.188	0.130	0.294**	0.333**	0.562**	0.545**	0.822**	0.937**	1	
ABDTPA-Zn	-0.074	0.108	0.193	0.419**	0.772**	0.748**	0.889**	0.890**	0.887**	1

*$p \leq 0.05$; **$p \leq 0.01$.

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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.

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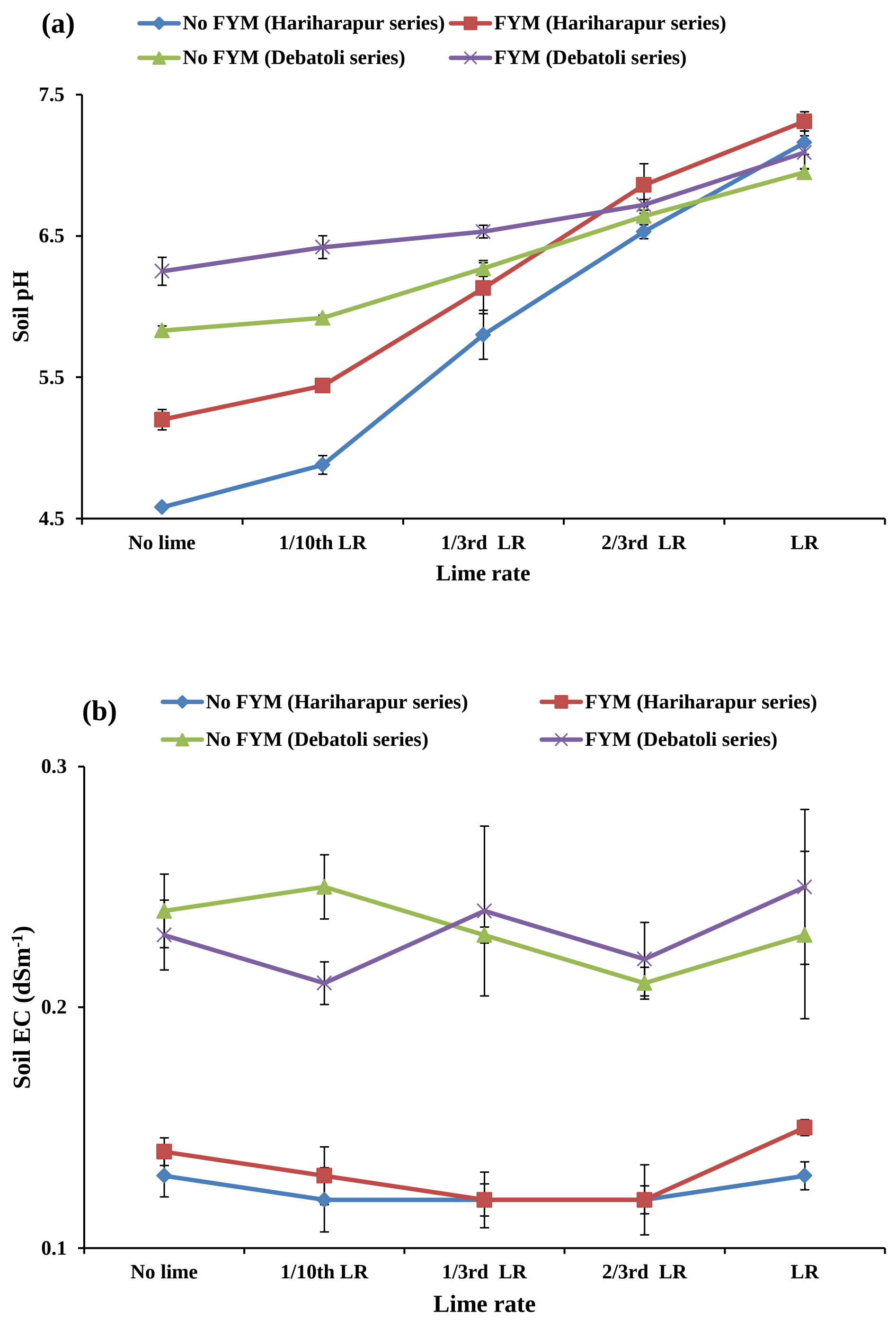

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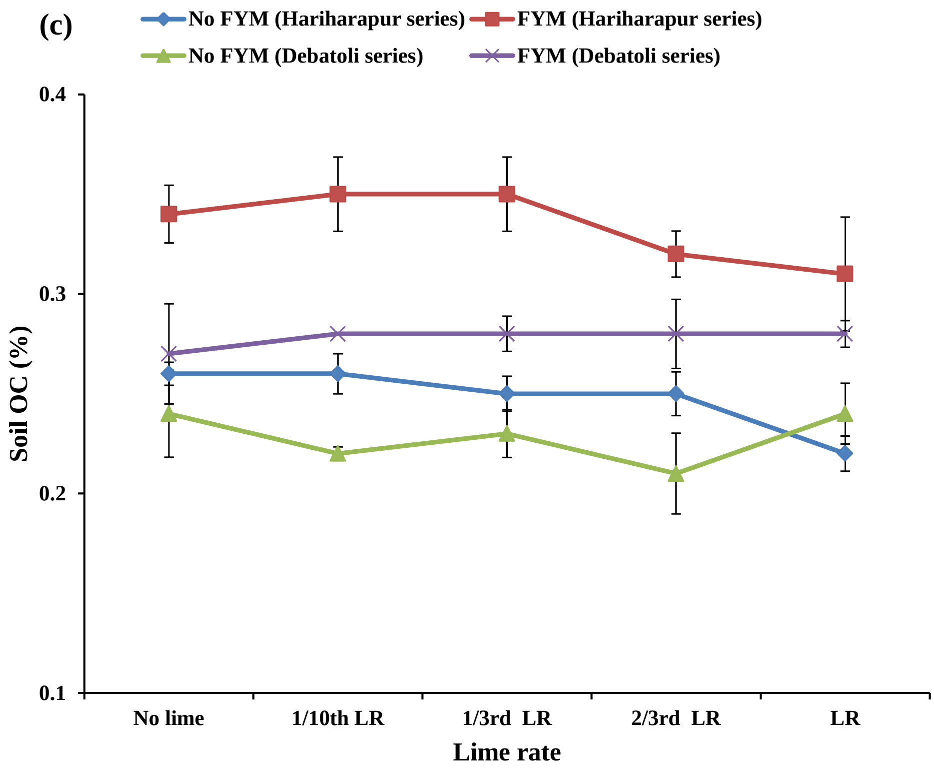

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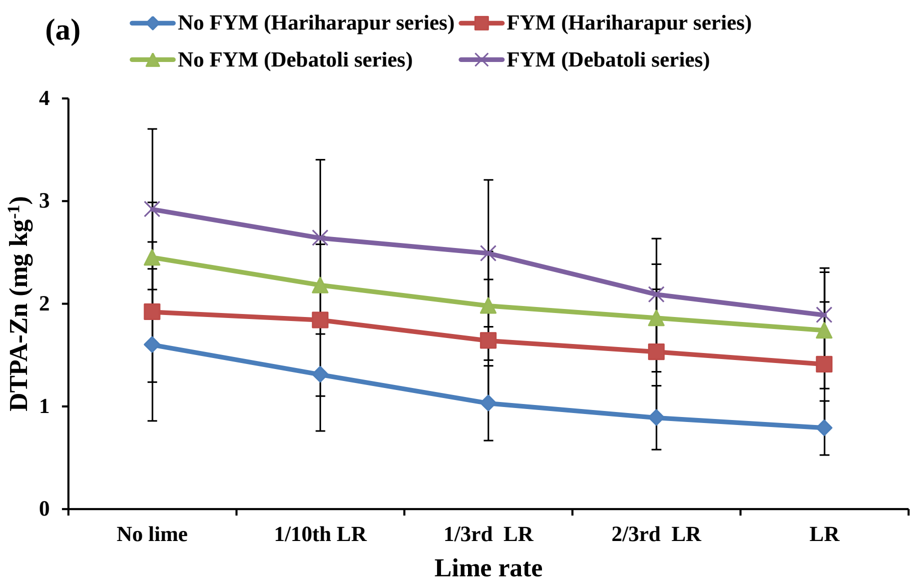

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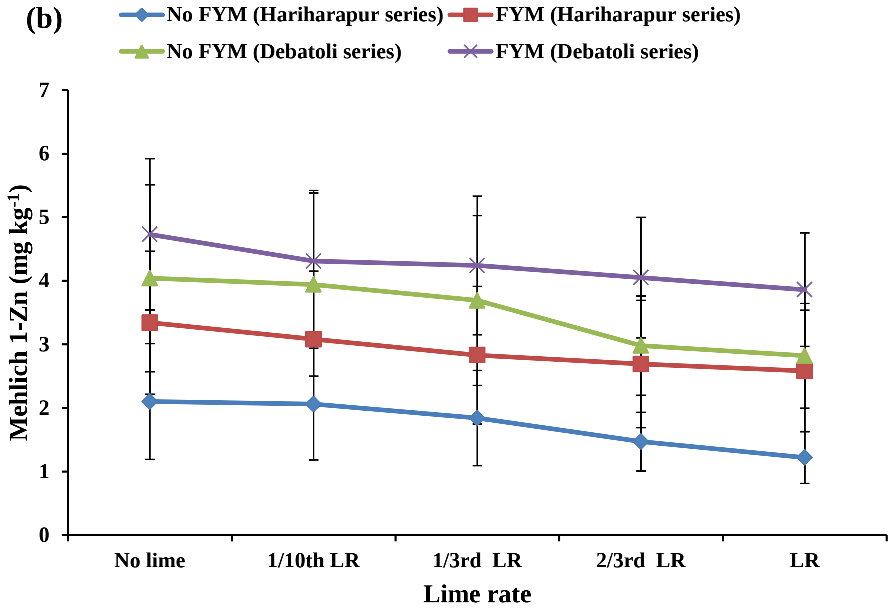

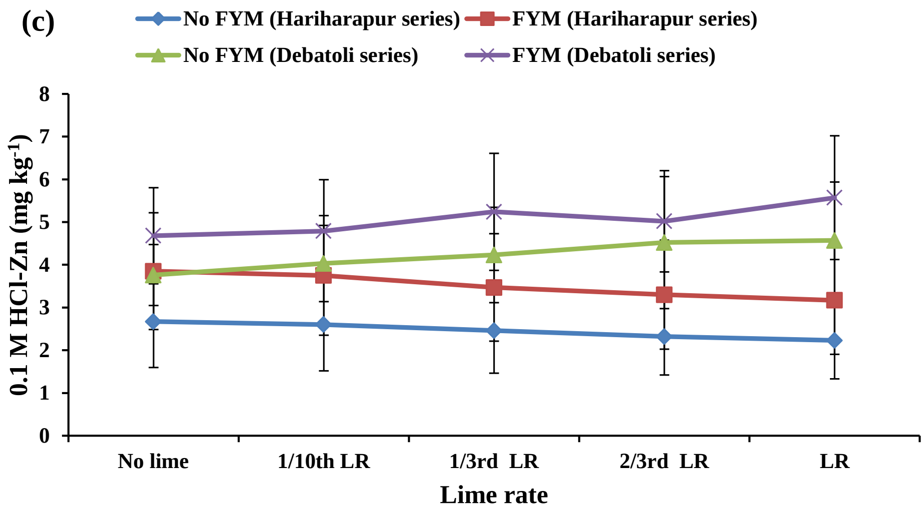

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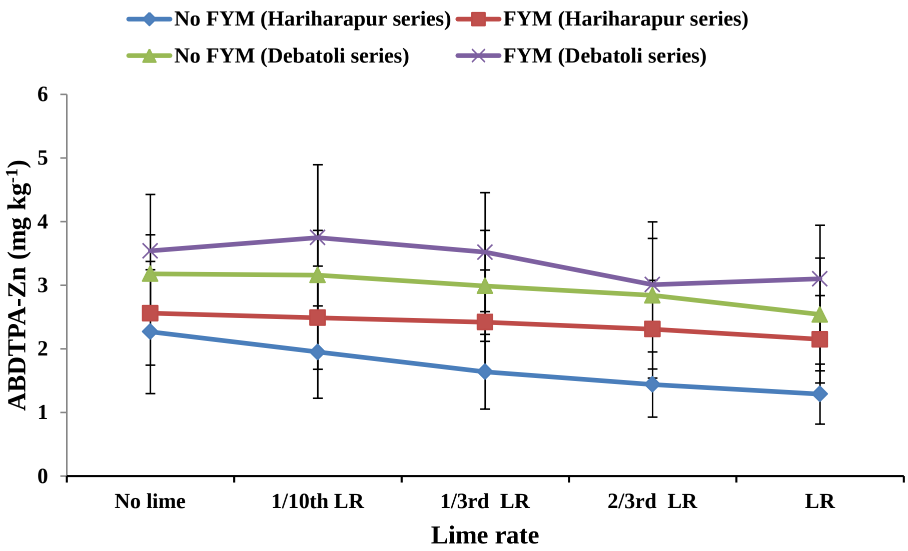

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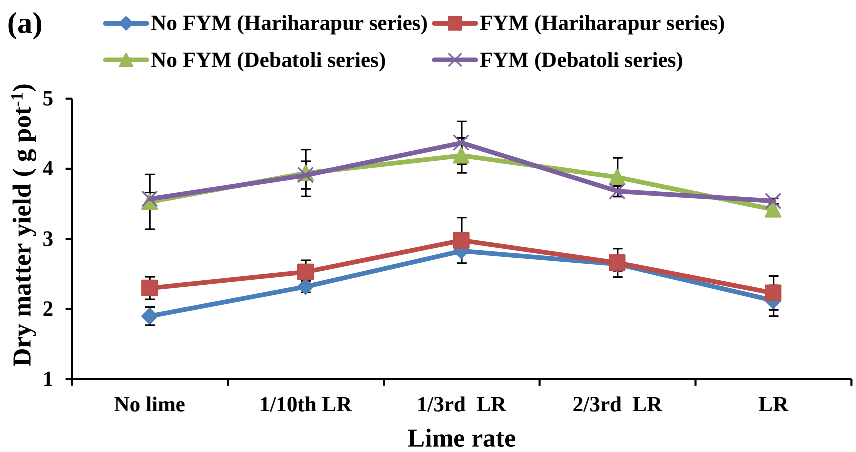

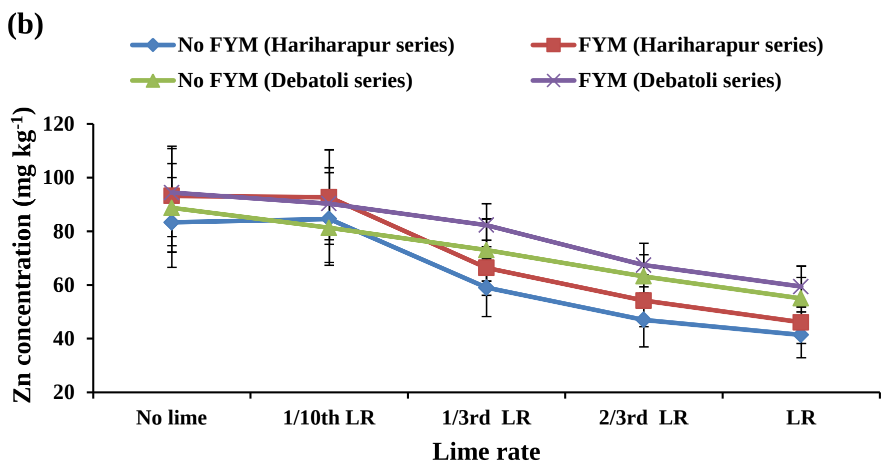

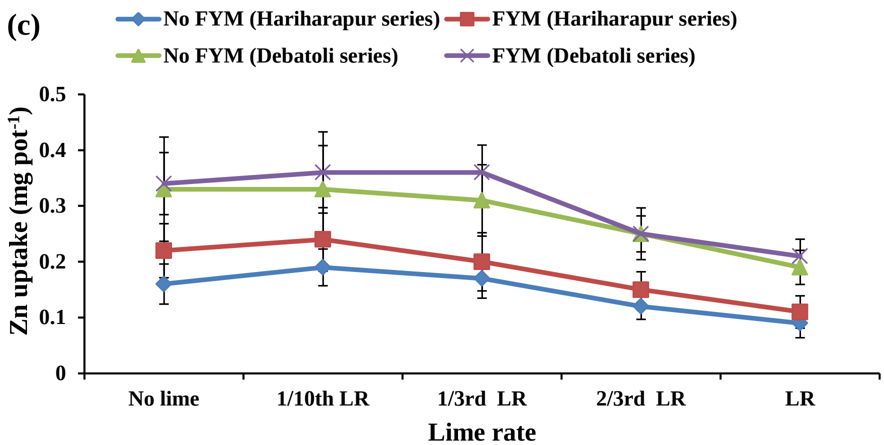

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