Original Research Article

An estimate of certain chelated, non-chelated zinc sources and levels on zinc use efficiency, availability and yield of rice grown in texturally different soils

Abstract

Innovations in fertilizer technologies (IFTs) pave a new path of producing different fertilizers. Fertilizers in different forms also play a significant role in rate of nutrient release and plant uptake inconsequence pulls up the crop productivity. The objective of this study was to estimate the performance of three zinc fertilizers [Zn sulfate heptahydrate (non-chelated), Zn- EDTA and Zn-humate (chelated)] at four levels (0, 2.5, 5.0, and 7.5 mg kg^{-1}) on zinc use efficiency, availability and crop productivity with rice. The performance Zn sources and levels were evaluated in field experiments. The trials were conducted in clay loam and sandy clay loam textured soils in a factorial randomized block design (FRBD) with three replications. Data recorded on yield, Zn uptake, DTPA-Zn, Zn uptake efficiency (ZnUPE), Zn utilization efficiency (ZnUTE), Zn use efficiency (ZnUE), fertilizer Zn uptake efficiency (FZnUPE), fertilizer Zn utilization efficiency (FZnUTE) and fertilizer Zn use efficiency (FZnUE). Among sources, Zn- EDTA recorded the highest grain (5307, 5545 kg ha^{-1}) and straw (6691, 6913 kg ha^{-1}) yield, Zn uptake and DTPA-Zn in both soils, respectively. When considering the levels, invariably of zinc sources the highest grain (5556, 5771 kg ha^{-1}) and straw (7029, 7120 kg ha^{-1}) yield obtained with 5 mg kg^{-1} Zn, while 7.5 mg kg^{-1} Zn registered the highest zinc uptake and DTPA- Zn both in clay loam and sandy clay loam soil, respectively. Our results identified that increased Zn levels increased ZnUPE, ZnUTE, and ZnUE. Addition of 2.5 mg kg^{-1} Zn recorded the highest FZnUPE and FZnUE, while 5.0 mg kg^{-1} Zn recorded the highest FZnUTE invariably of soil textures. Amongst the sources, Zn humate recorded higher ZnUE and its components compared to other two sources. Finally, we concluded that chelated zinc sources perform well than non-chelated (Zn sulphate heptahydrate), and among the chelated sources Zn EDTA was more effective than Zn humate both in clay loam and sandy clay loam soils.

Key words: Clay loam, DTPA-Zn, Rice yield, Sandy clay loam, Zn humate, Zn uptake, Zn use efficiency

1. Introduction

Rice (*Oryza sativa*) is a principal food grain (Hori and Sun, 2022), with almost half of the global population relying on it as a “stable diet” (Rathinapriya et al.,2019), predominantly in fast-growing and heavily inhabited parts of the world (Sen et al.,2020). Further it is the most important cereal crop in India and stable food for 50 percent of the world population that resides in Asia where 90 percent of the world’s rice is grown and consumed (Senthilvalavan, 2018). It provides 35–60% of the dietary calories consumed by nearly more than three billion people (Fageria and Baligar, 2003) and this number will increase to 4.6 billion people by 2050.

Continuous and imbalanced use of selected fertilizer nutrients have resulted in deterioration of soil health and as a consequences, deficiencies of zinc and other micronutrients are increasing (Singh and Singh 2017). Nearly 50% of the cultivated soils in India are low in plant available zinc and these soils are under intensive cultivation with no or little application of zinc fertilizers. Zn deficiency is a chronic problem among human populations under cereal-based (e.g., rice-wheat) system (Cakmak and Kutman, 2017); these two crops feeds world population is an unspoken truth. Zinc deficiency in crop plants results in not only yield reduction (Kamini Kumara, 2017) but also Zn malnutrition in humans, where a high proportion of rice is consumed as a staple food (Yao *et al.,* 2012). The total number of people estimated to be placed at a new risk of zinc deficiency by 2050 is 138 million. Zinc deficiency in rice has been widely reported in many rice-growing regions of the world (Tiong*et al*., 2014).

Application of Zn along with NPK fertilizer increases the grain yield dramatically in most cases (Fageria *et al.,* 2011; Singh *et al*., 2011). As zinc (Zn) is an essential element for plant nutrition, and its deficiency emerges as the most ubiquitous micronutrient deficiency. It is estimated that almost half of the soils in the world are deficient in zinc. Since cereal grains have inherently low concentrations, growing them on these potentially zinc-deficient soils further decreases grain zinc concentration. The Food and Agriculture Organization of the United Nations (FAO) estimates that 50% of world’s soils growing cereal grains are zinc deficient. It further estimates that agricultural production must increase by 70% by 2050 to feed over 9 billion people worldwide. India is no exception.

Survey and analytical reports of soils of India showed that about 50% of the soils were deficient in zinc (Singh,2000;Veeranagappa et al.,2010; Kumar et al.,2019), and in fact this is the most common micronutrient problem affecting crop yields in India. The reasons for the increase of incidences of zinc deficiency include large zinc removals due to high crop yields and intensive cropping systems, less application of organic manures, use of high analysis fertilizers, and increased use of phosphate fertilizers resulting in phosphorus induced zinc deficiency and the use of poor quality irrigation water. The soil conditions that commonly lead to zinc deficiency in crops are low total zinc concentrations, such as sandy soils; highly weathered parent materials with low total zinc contents, such as tropical soils. However crops are not equally susceptible to Zn deficiency and at the same soil some crops may suffer from zinc deficiency while others are not affected but rice.

The availability (bio) and fate of zinc in soils is affected by both properties of soil (soil pH, clay colloids, competitive cations, and anions) and source (water soluble, insoluble, chelated, non-chelated, granular, powder and nano,etc) (Alloway,2004;Gohil et al, 2022); and other factors that affect availability of zinc in soil to plants. Therefore, selection of Zn fertilizer to make sure of higher percentage Zn bio-availability in different soils and which should enhances the crop productivity (Milani et al., 2012; Santos et al.,2019). Water soluble Zn fertilizers like white vitriol i.e. Zn sulphate make more available Zn to plant and also losses; whereas chelated Zn sources like Zn-EDTA and Zn humate promoting slow and longer Zn availability for plants than water soluble (Mattiello et al.,2017).Therefore, it is essential choose correct source to improve the fertilizer use efficiency especially in soils where zinc availability is deficient and crop requirement is vital. In addition, several micronutrient fertilizers trials conducted in India reported that 63 percent of the trials responded well to micronutrient fertilization especially Fe and Zn (Singh,2007;Gohil et al.,2022).

Several studies have reported that use efficiency of various Zn fertilizers on cereal productivity. However, there is little information on proper doses/ levels and zinc source application for different soils (zinc deficient) especially to food crops wherever blanket recommendation followed. The study area of the present work is also falls under zinc deficient soils (Singh, 2000; Singh,2009) in coastal belt of cauvery deltaic area of Tamilnadu (Fig.1). Coastal soils of cauvery deltaic area are well known rice growing zone (rice bowl) of Tamilnadu cloaked with zinc deficiency, having major area covered with soil textures of clay loam and sandy clay loam the CDZ coastal belt. Hence, it is highly imperative to evaluate the response of Zn nutrition on rice productivity to cope up the targeted yield and also to avoid farmers' income by yield loss due to zinc deficiency. Therefore, zinc management needs greater attention in crop production to combat with wide spread zinc deficiency in many rice growing areas throughout the world. There are many study reports available on zinc fertilizers usage, application methods and use efficiency, yield maximization of rice grown in normal soils but information on these aspects in zinc deficient soils are scanty. With this background, present study was undertaken in two different textured soils (zinc deficient clay loam and sandy clay loam) to zinc fertilization using chelated and non-chelated zinc fertilizers with different levels to determine the suitable source and level of zinc fertilizer based on yield of rice, Zn uptake, soil availablezinc and use efficiency.

2. Materials and Methods

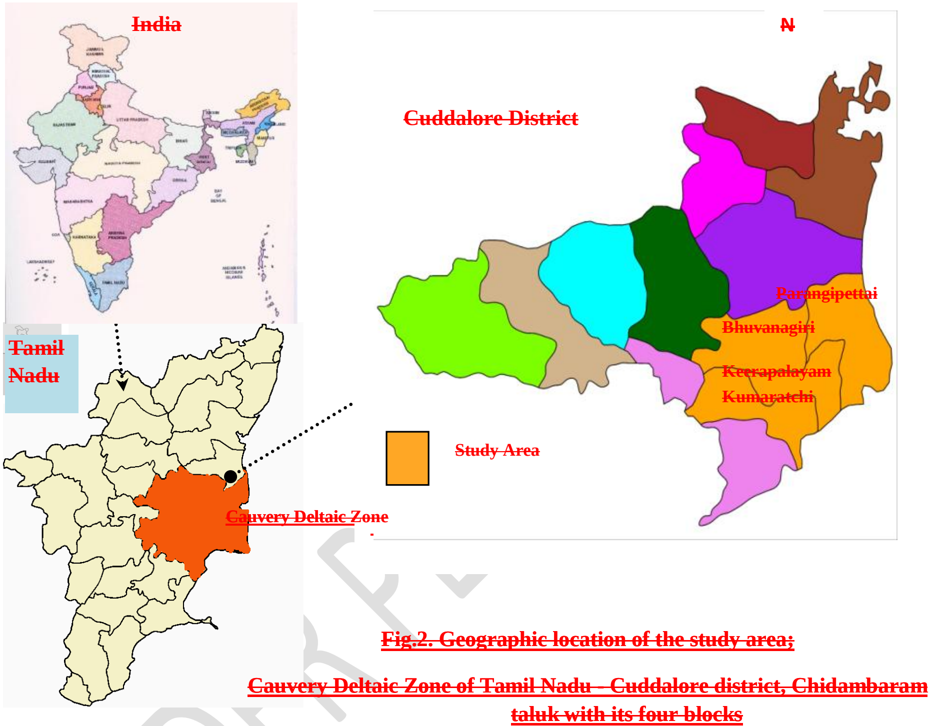
2.1. Experimental soils

Field experiments were conducted in farmers holding in Kharif; soils deficient in zinc belonging two soil series viz., Kondal series (*Typic Haplusterts*) and Paduagi series (*Typic Ustifluvent*) in 2018.The experimental soil (Kondal series) is clay loam in texture with pH- 8.50, EC- 0.92 dSm^{-1}, CEC- 43.1Cmol(p^{+}) kg^{-1}, organic carbon- 5.41g kg^{-1}, $KMnO_4$-N- 302.0 kg ha^{-1}(medium), Olsen-P- 19.0 kg ha^{-1}(medium), NH_4OAc-K- 306.0 kg ha^{-1}(high) and DTPA-Zn- 0.56 mg kg^{-1}(deficient) , Similarly , in Paduagi series, experimental soil is sandy clay loam with pH-7.8, EC- 0.89 dSm^{-1}, CEC- 24.2 Cmol(p^{+}) kg^{-1}, organic carbon- 6.3g kg^{-1}, $KMnO_4$-N- 276.0 kg ha^{-1}(medium), Olsen-P- 18.0 kg ha^{-1}(medium), NH_4OAc-K- 293.0 kg ha^{-1}(high) and DTPA-Zn- 0.52 mg kg^{-1}(deficient).Initial soil analysis were carried out by following standard procedures (table 1).

2.2. Experimental design, treatments and analysis

Field experiments were conducted in factorial randomized block design (FRBD) with three replications with cultivation of rice (variety ADT 43). The treatment consists of four levels of zinc viz., 0, 2.5, 5.0 and 7.5 mg kg^{-1} applied through three sources zinc sulphate heptahydrate (non-chelated), Zn-EDTA and Zn-humate (cheated). Treatments were replicated thrice. All the plots (plot size of 5mx4m) received uniform dose 120:40:40 kg N, P_2O_5 and K_2O kg ha^{-1} applied through urea, Di-ammonium phosphate (DAP) and muriate of potash. The grain and straw yield was recorded at harvest; samples were collected from tagged plants, dried at 105^{o}C for 16 -18 hours (until constant weight), weighed, and ground for further analysis. The grain and straw samples were analysed for zinc concentration was quantified in atomic absorption spectrophotometer with microwave digester (AAS-MD - Thermo Fisher/ICE

3000) and zinc uptake was computed by multiplying zinc content with grain/straw. Soil samples were collected from respective treatments, processed and DTPA Zn was analysed in AAS-MD. Based on yield and zinc uptake, following zinc use efficiency parameters were worked out using formula suggested by Fageria *et al*.(2009).



~~Fig.2. Geographic location of the study area;~~

~~Cauvery Deltaic Zone of Tamil Nadu - Cuddalore district, Chidambaram taluk with its four blocks~~

Study locations 11°10´ and 78°20 (Thergumangudi) & 11°35´ and 79°50 (Vadampur) villages

$$\textbf{Zinc uptake efficiency (ZnUPE)} = \frac{\text{Zn in plant (g ha}^{-1}\text{)}}{\text{Zn in soil (mg kg}^{-1}\text{)}}$$

$$\textbf{Zinc utilization efficiency (ZnUTE)} = \frac{\text{Yield (kg ha}^{-1}\text{)}}{\text{Zn in plant (g ha}^{-1}\text{)}}$$

$$\textbf{Zinc use efficiency (ZnUE)} = \frac{\text{Yield (kg ha}^{-1}\text{)}}{\text{Zn in soil (mg kg}^{-1}\text{)}}$$

$$\textbf{Fertilizer Zn uptake efficiency (FZnUPE)} = \frac{\text{Zn in fertilized plant (g ha}^{-1}\text{)} - \text{Zn in control plant (g ha}^{-1}\text{)}}{\text{Zn applied (mg kg}^{-1}\text{)}}$$

$$\textbf{Fertilizer Zn utilization efficiency (FZnUTE)} = \frac{\text{Yield in fertilized plots (kg)} - \text{yield in control plot (kg)}}{\text{Zn in fertilized plant (mg kg}^{-1}) - \text{Zn in control plants (mg kg}^{-1})}$$

$$\textbf{Fertilizer Zn use efficiency (FZnUE)} = \frac{\text{Fertilized plot yield (kg)} - \text{control plot yield (kg)}}{\text{Zn applied (mg kg}^{-1})}$$

2.3. Statistical analysis

The data were subjected to factorial analysis using **SPSS** version 28.0.0.0 (190) and wherever the treatment differences were found significant (F test), critical differences were worked out at five per cent (p=0.05) probability level and the values are furnished. Treatment differences which were not significant are denoted as "NS".

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3. Results

3.1. Rice yield

The close examination of the data in table 1 revealed significant influence of zinc applied at different rates through different sources on rice yield over control in Vertisol (clay loam) and Entisol(sandy clay loam). A linear increase in grain yield was noticed up to 5 mg kg^{-1} (5556, 5771 kg ha^{-1}) and straw yield (7029, 7120 kg ha^{-1}) in Vertisol and Entisol, respectively and declined at 7.5 mg kg^{-1} Zn. The percent increase in grain yield ranged from (15.7 to 25.9) and (13.8 to 21.8%) and straw yield ranged from (12.5 to 23.8%) and (11.2 to 17.2%) in Vertisol and Entisol, respectively. Zinc optimization was worked out through quadratic polynomial function ($y=-30.64x^2+355.64x+4726.1$, $R^2 = 0.9963$**, Entisol and $y=-33.48x^2 + 389.06x +4394.2$, $R^2= 0.9918$**, Vertisol) to achieve maximum rice yield and it showed 5.81 mg kg^{-1} for both soils (Fig.3). With respect to zinc sources, addition of zinc (chelated source) as Zn-EDTA recorded the highest grain yield (5307 and 5546 kg ha^{-1}) and straw yield (6693 and 6913 kg ha^{-1}) in Vertisol and Entisol, respectively and significantly superior to zinc sulphate and Zn-humate. The interaction between zinc sources and rates was significant with respect to rice yield (table 2). Irrespective of zinc sources, grain and straw yield of rice increased up to 5 mg kg^{-1} and declined thereafter. Similarly, at all zinc levels, the maximum rice yield was noticed Zn-EDTA. The percent 15.8 increase under different combinations in grain yield (15.8 to 29.9%) and (13.6 to 25.5%) and straw yield ranged from (12.1 to 27.4%) and (11.6 to 20.2%) in Vertisol and Entisol, respectively. The maximum grain yield (5732, 5946 kg ha^{-1}) and straw yield (7234, 7302 kg ha^{-1}) was noticed with application of 5 mg kg^{-1} Zn through zinc sulphate in Vertisol and Entisol, respectively.

3.2. Zinc uptake

Zinc applied at different rates through various zinc sources caused significant improvement in zinc uptake in grain and straw at 5% level in Vertisol and Entisol over control (table 1). Zinc uptake in grain and straw increased with zinc rates and maximum value in grain (137.7, 157.7 g ha^{-1}) and straw (387.5, 408.3 g ha^{-1}) was noticed with 7.5 mg kg^{-1} in Vertisol and Entisol, respectively. However, comparable value of zinc uptake was noticed with 5 mg kg^{-1}. The percent improvement in zinc uptake in grain ranged from (56.8 to 86.3, 51.8 to 79.5) and straw ranged from (27.5 to 45.7, 25.5 to 41.3) in Vertisol and Entisol, respectively. Among zinc sources, the maximum zinc uptake in grain (128.4 and 145.3 g ha^{-1}) and straw (366.2, 396.8 g ha^{-1}) was realized with application of zinc through Zn-EDTA and it was significantly superior to other two sources.

3.3. DTPA-Zinc

DTPA-Zn in Vertisol and Entisol was significantly influenced by application of zinc at different rates through zinc sources over control (table 1). The DTPA-Zn was higher in Vertisol than in Entisol. Available zinc increased linearly with zinc levels and maximum value was noticed with 7.5 mg kg $^{-1}$ and was on par with 5 mg kg^{-1} Zn. With regards to sources, zinc as Zn-EDTA outperformed zinc sulphate and Zn-humate in elevating the DTPA-Zn status. Available zinc improved to the tune of (58 to 81.4 %) and (64.9 to 97.3%) in Vertisol and Entisol, respectively due to zinc rates.

3.4. Zinc Use Efficiency

Addition of zinc at different rates through various sources influenced zinc use efficiency and its parameters (table 3). Zinc uptake efficiency (ZnUPE), Zinc utilization efficiency (ZnUTE), Zinc use efficiency (ZnUE), Fertilizer Zn uptake efficiency (FZnUPE), fertilizer Zn utilization efficiency (ZnUTE) and fertilizer Zn use efficiency (FZnUE) was maximum with Zn- humate followed by Zn-EDTA and zinc sulphate. Zinc uptake efficiency (ZnUPE), Zinc utilization efficiency (ZnUTE), Zinc use efficiency (ZnUE) decreased with zinc levels and maximum value was noticed in control. While Fertilizer Zn uptake efficiency (FZnUPE) and fertilizer Zn use efficiency (FZnUE) was maximum with 2.5 mg kg^{-1} and fertilizer Zn utilization efficiency (FZnUTE) was maximum with 5.0 mg kg^{-1}.

4. Discussion

Micronutrients are essential for increasing crop production and enhancing animal and human health. Within the broad category of mineral-linked stresses, zinc (Zn) deficiency is one of the most widespread limiting factors to crop production, affecting more than 30 % of the world's soils, including many agricultural lands of different countries like South Asia. In the present study, rice responded significantly to application of zinc at different rates through different sources in both Vertisol and Entisol. From the polynomial regression equation, it was noticed that in both soils, to achieve maximum yield, addition of 5.81 mg kg^{-1} Zn is needed. Application of 5.81 mg kg^{-1} Zn caused 25.1 and 21 percent increase in grain yield over control in Vertisol and Entisol. Evidence of Rahman *et al*. (2011) proved that addition of 10 kg Zn ha^{-1} recorded maximum grain yield in soils of Bangladesh and Jena *et al*. (2006) and Rahmatullah *et al*. (2007) also reported 25 and 45 percent increase in grain yield on addition of 10 kg Zn ha^{-1} in soils of Odisha and Pakistan. Higher grain yield due to zinc application stems from the fact that experimental soil was deficient in zinc and further it is attributed to involvement in many metallic enzyme systems, regulating functions and auxin production (Chauhan et *al.*, 2017) and enhanced carbohydrate synthesis and its transport to site of grain production (Pedda Babu et al., 2007 and Khan *et al*., 2009). Significant increase in grain yield is also associated with improved DTPA-Zn levels in soils and zinc uptake (Talib *et al.*, 2016). This was confirmed by significant and positive linear relationship between grain yield and DTPA–Zn (Fig.4). Linear regression analysis indicated that DTPA-Zn accounted for 96 and 98% variation in rice yield in Vertisol and Entisol. Alvarez *et al*. (2001) reported that significant portion of fertilizer zinc remain in soil as exchangeable and organic complexed Zn. Positive impact of zinc fertilization on grain yield was further confirmed by significant positive linear relationship noticed between grain yield and zinc uptake (Fig.5) and linear regression analysis indicated that zinc uptake accounted for 98% variation in grain yield. Grain yield reduced in the absence of zinc addition is due to impairment in anther and pollen grain development in zinc deficiency plant as a result of low level of IAA and protein. In present study, grain yield declined at 7.5 mg kg^{-1} Zn. Higher level of zinc is likely to destroy metabolic balance in plants to result in disorder of other mineral nutrient status which has reduced rice grain yield (Mahmoud Asadi *et al*., 2012). Khan *et al*. (2012) reported reduction in grain yield at 12 and 15 kg Zn ha^{-1} in soils of Pakistan. Selection of appropriate zinc source as soil application can be alternative strategy to improve plant available zinc in lowland rice soil, thereby improving zinc uptake and finally grain yield. In the present study, addition of 5 mg Zn kg^{-1} through Zn –EDTA recorded the highest grain yield (5732 and 5946 kg ha^{-1}) in Vertisol and Entisol, respectively. The percent increase due to Zn-EDTA over control was 30 and 24.4 in Vertisol and Entisol, respectively. At the same level of zinc applied (5 mg kg^{-1}), zinc sulphate and Zn-humate caused 25 and 21% and 22 and 18% increase over control in Vertisol and Entisol, respectively. This might be due to greater efficiency of Zn-EDTA in maintaining zinc in soil solution for a longer period for higher plant zinc uptake and finally higher yield (Naik and Das, 2007). Karak *et al*. (2006) reported chelated zinc is 5 times more effective than inorganic salts. Zinc chelation differs in physical state, chemical reactivity, costs, bioavailability and susceptibility to leaching. Zinc form stronger chelates with inorganic one compared to naturally occurring organic ligands (Mortvedt and Gilken, 1993). Thus higher grain yield was noticed with Zn-EDTA than Zn-humate. Higher straw yield with zinc application over control and the maximum value with 5 mg Zn kg^{-1} through Zn-EDTA is associated with favourable effect of zinc on proliferation of roots and thereby increased uptake of nutrients from soil and supplying to aerial parts of the plant and ultimately higher vegetative growth (Naik and Das, 2008). Rice yield was higher in Entisol than Vertisol. But grain yield response and percent increase over control was higher with Vertisol than Entisol. Soil under Vertisol had higher oil pH, slightly calcareous and low zinc content. Rice response to zinc fertilization rate varied with soil pH, texture, available zinc status (Muhammad Arif *et al*., 2012)

Graded dose of zinc increased zinc uptake in grain and straw and the maximum value was noticed with 7.5 mg Zn kg^{-1} in both soils. Zinc uptake is controlled by many factors i.e. amount of DTPA-Zn, transfer of zinc to root surfaces and interaction of Zn with other nutrients in soil or within plant (Robson, 1993). Increase in zinc uptake in grain and straw on application of zinc was reported by Srivastava *et al*. (2016).Further, increased quantity of zinc in soil solution by the application of chelated zinc could have facilitated greater absorption of zinc compared to zinc sulphate. The greater influence of Zn-EDTA over other sources of zinc might be due to less retention, greater transport and movement of chelated zinc to plant roots (Naik and Das, 2008).

The availability of zinc in soil or applied as fertilizer is governed by the net effect of physical, chemical and biological reactions in soil (Kumar and Qureshi, 2012). In the present study, the highest DTPA-Zn was associated with 7.5 mg Zn kg^{-1}. Significant increase in available zinc at higher level of zinc applied reported by Keram *et al*. (2012). Relatively higher DTPA-Zn with Zn-EDTA might be associated with very little or no interaction between soil components preventing various harmful reactions occurring in soil as compared to soil treated with zinc sulphate which enhances greater fixation and adsorption (Karak et *al*., 2005). Kumar and Qureshi (2012) also reported similar results that higher DTPA-Zn with Zn-EDTA than Zn-humate application paddy soils.

Nutrient use deficiency is used as a measure of the capacity of the plant to acquire and utilize nutrients for biological yield. Zinc uptake efficiency (ZnUPE), Zinc utilization efficiency (ZnUTE), Zinc use efficiency (ZnUE) decreased with zinc levels. The decrease in zinc use efficiency parameters with zinc levels is the result of progressive decrease in grain yield with increasing zinc rates in zinc deficient soil. For example higher zinc use efficiency at lower levels of zinc was reported in rice by (Fageria, 2001). In our study, chelated zinc recorded higher zinc use efficiency compared to zinc sulphate. This denotes that water solubility and mobility of zinc fertilizer in soil is the major determinants of its use efficiency especially in paddy soils. Due to lesser reaction of chelated zinc with soil components, thereby maintaining higher concentration of zinc in soil solution (Das *et al.*, 2002) and greater stability in soil compared to zinc sulphate (Rahman *et al*., 2012). Alvarez *et al*. (2001) reported that when zinc was added as Zn-EDTA, the amount of most labile pool (WS-Zn, Exch-Zn, Com-Zn) increased throughout soil profile. Linear regression equation confirmed the significant positive role of DTPA-Zn and zinc uptake on zinc use efficiency and zinc utilization efficiency (Fig.6) and it accounted for 97 to 98% variation in zinc use efficiency.

5. Conclusions

The application of Zn-EDTA at 5 mg Zn kg^{-1} resulted in maximum rice yield in zinc deficient soils of Vertisol and Entisol. Zn-humate recorded maximum zinc use efficiency. The study results proved that bio-fortification of Zn in rice could ease by Zn-humate application Vertisol and Entisol. Further, field experiments should be conducted for various rice varieties in different agro climatic zones for effective Zn management in Zn deficient soils; Zn fertilization can provide an efficient answer to capacitate rice productivity with resilient ways to face adversities in malnutrition.

Novelty statement

Large area of this region (CDZ) has been reported to be zinc deficient and rice is grown in three fourth of the total area. The experiment was initiated to provide suitable source and levels for clay loam and sandy clay loam textured soils to get maximum yield and enhancing ZnUE. The outcome of the experiment clearly revealed that Zn-EDTA could be the most suitable source with 5 mg kg^{-1} of Zn to get maximum rice yield and Zn-humate recorded the maximum ZnUE.

Data availability Statement

The data that support this work are available within the article itself.

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Table 1. Effect of sources and levels of zinc on rice yield, zinc uptake and DTPA –Zn

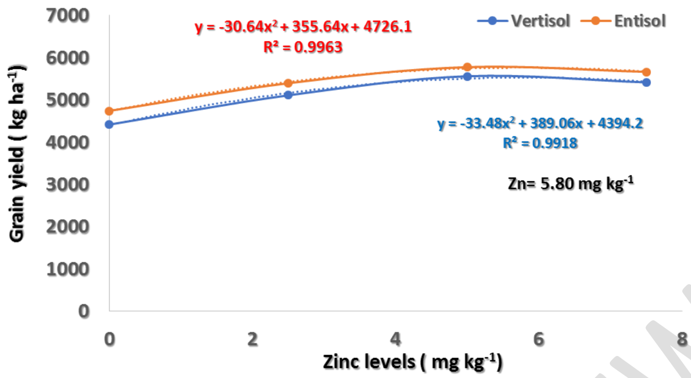
Treatments	Vertisol					Entisol				
	Rice yield (kg ha^{-1})		Zinc uptake (g ha^{-1})		DTPA Zn (ppm)	Rice yield (kg ha^{-1})		Zinc uptake (g ha^{-1})		DTPA Zn (ppm)
	Grain	Straw	Grain	Straw		Grain	Straw	Grain	Straw	
Sources										
$ZnSO_4$	5118	6454	119.5	340.5	0.72	5383	6756	135.4	370.5	0.64
Zn-EDTA	5307	6691	128.4	366.2	0.73	5546	6913	145.3	396.8	0.65
Zn- humate	4937	6300	99.9	322.1	0.57	5238	6519	116.3	330.4	0.48
CD@5%	72	56	5.0	9.5	0.02	79	69	5.3	10.3	0.02
Zn Levels (mg kg^{-1})										
0	4412	5677	73.9	265.9	0.43	4737	6074	87.3	289.1	0.37
25	5104	6386	115.9	339.0	0.68	5391	6744	131.9	362.9	0.61
5.0	5556	7029	136.2	383.3	0.78	5771	7120	153.5	403.3	0.73
7.5	5411	6834	137.7	387.5	0.81	5659	6979	156.7	408.3	0.75
CD@5%	90	65	4.9	9.5	0.03	91	79	5.6	12.1	0.03

Table 2. Interaction effect of zinc levels (mg kg^{-1}) and sources on rice yield (kg ha^{-1})

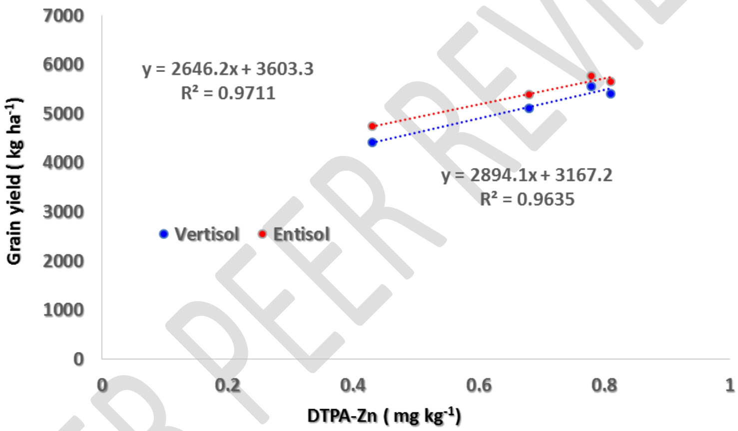
Levels Sources	Vertisol					Entisol				
	0	2.5	5.0	7.5	Mean	0	2.5	5.0	7.5	Mean
Grain yield										
$ZnSO_4$	4409	5107	5550	5405	5118	4781	5379	5748	5623	5383
Zn-EDTA	4606	5284	5732	5607	5307	4845	5559	5946	5833	5546
Zn- humate	4221	4921	5385	5221	4937	4580	5234	5618	5520	5238
Mean	4412	5104	5556	5411		4737	5391	5771	5659	
	S	L	S x L			S	L	S x L		
CD at 5%	72	90	155			79	91	158		
Straw yield										
$ZnSO_4$	5711	6365	6976	6763	6454	6066	6776	7155	7027	6756
Zn-EDTA	5831	6620	7234	7078	6691	6272	6915	7302	7162	6913
Zn- humate	5489	6173	6876	6662	6300	5883	6541	6904	6748	6519
Mean	5677	6386	7029	6834		6074	6744	7120	6979	
	S	L	S x L			S	L	S x L		
CD at 5%	56	65	112			69	79	138		

Table 3. Effect of zinc levels and source on zinc use efficiency and its components in rice

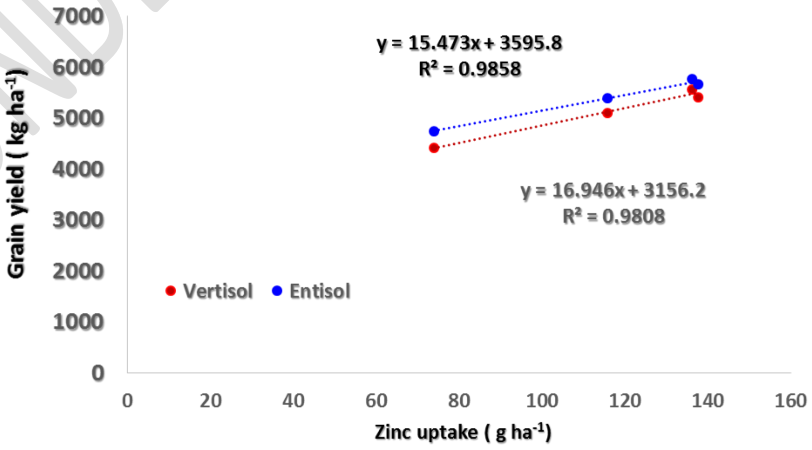
Treatments	Zinc uptake efficiency (ZnUPE) (g kg^{-1})		Zinc utilization efficiency (ZnUTE) (kg mg^{-1})		Zinc use efficiency (ZnUE) (kg mg^{-1})		Fertilizer Zn uptake efficiency (FZnUPE) (g kg^{-1})		Fertilizer Zn utilization efficiency (FZnUTE)		Fertilizer Zn use efficiency (FZnUE) (kg kg^{-1})	
Soil	Vertisol	Entisol	Vertisol	Entisol	Vertisol	Entisol	Vertisol	Entisol	Vertisol	Entisol	Vertisol	Entisol
Zinc sources												
$ZnSO_4$	83	106	428.3	397.6	3554	4205	2.0	6.0	164.7	140.5	106.7	90.8
Zn-EDTA	88	112	413.0	381.7	3635	4266	6.0	7.0	165.0	158.1	104.9	106.3
Zn- humate	87	121	494.2	450.4	4331	5456	6.0	6.0	184.7	184.1	107.7	97.8
Zinc levels (mg kg^{-1})												
0	86	118	597.0	542.6	5130	6401	-	-	-	-	-	-
2.5	85	108	440.4	408.1	3753	4419	8.0	9.0	165.2	143.7	138.4	130.8
5.0	87	105	407.9	375.9	3562	3953	6.0	7.0	179.6	156.2	114.4	103.4
7.5	85	104	392.9	361.1	3340	3773	4.0	5.0	159.3	132.9	66.6	61.5



~~Fig.3~~ **Optimization of zinc rates to achieve maximum grain yield**



~~Fig.4~~ **Linear relationship between DTPA-Zn and grain yield**



~~Fig.5~~ **Linear relationship between zinc uptake and grain yield**

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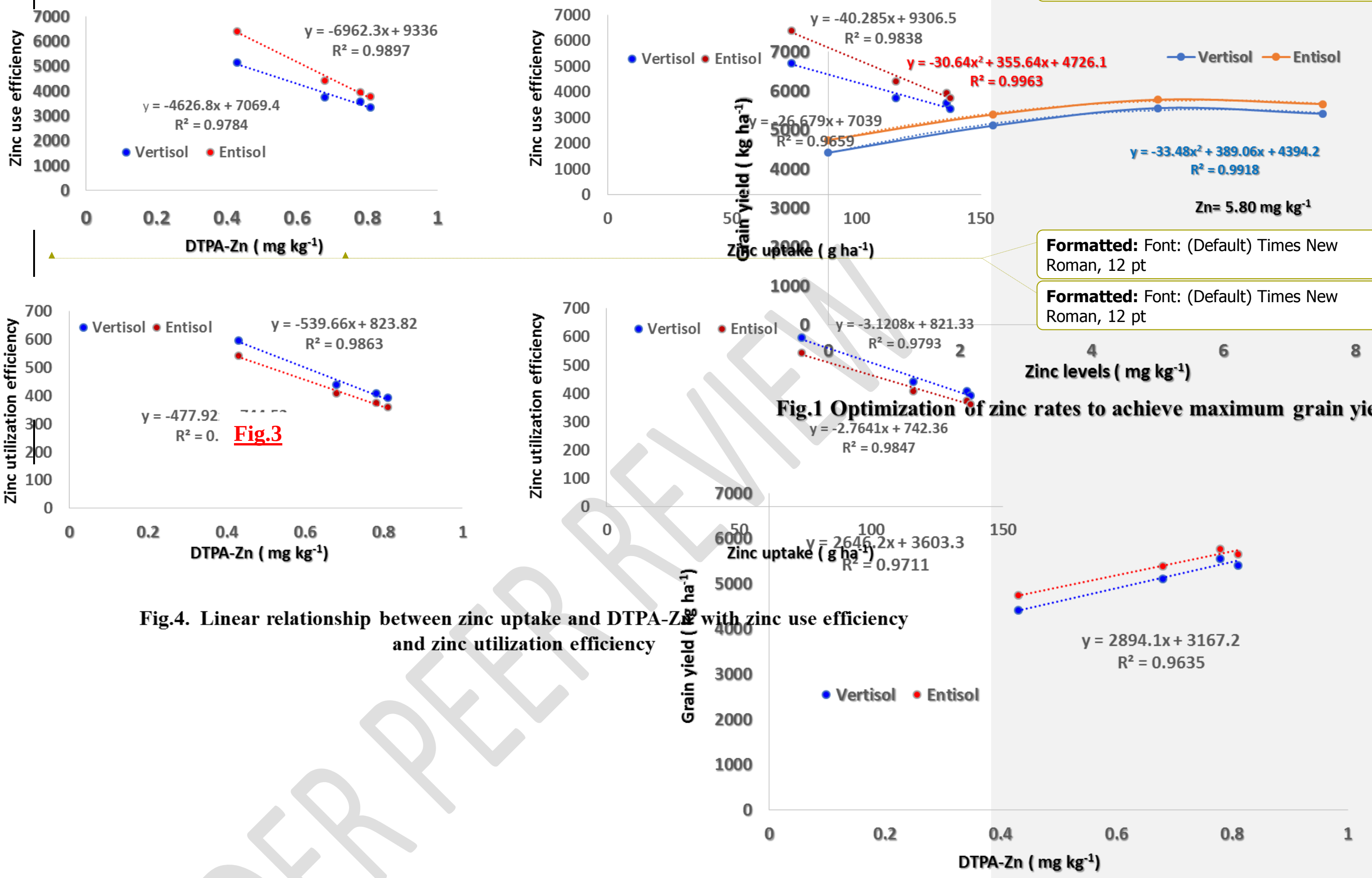

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Fig.1 Optimization of zinc rates to achieve maximum grain yiel

Fig.3

Fig.4. Linear relationship between zinc uptake and DTPA-Zn with zinc use efficiency and zinc utilization efficiency

Fig.2. Linear relationship between DTPA-Zn and grain yield

Fig.4

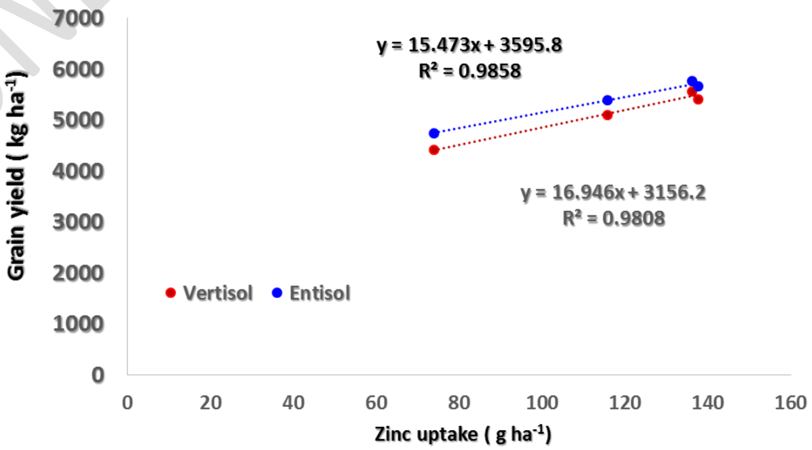

Fig.3 Linear relationship between zinc uptake and grain yield

Fig.5

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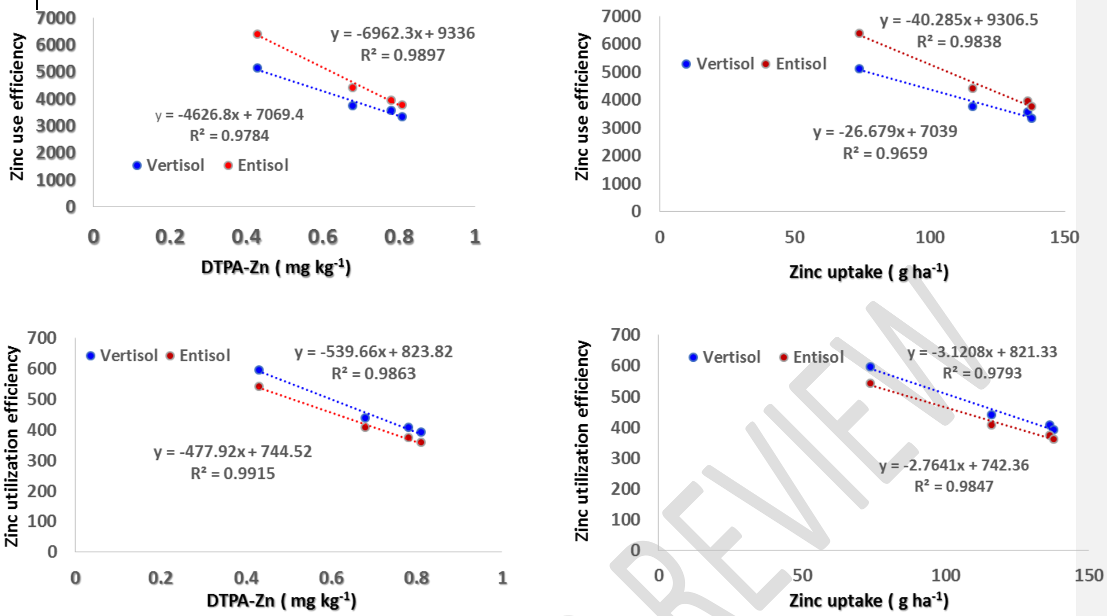

Fig.6 **Linear relationship between zinc uptake and DTPA-Zn with zinc use efficiency and zinc utilization efficiency**