Int.J.Curr.Microbiol.App.Sci (2017) *6*(9): 2883-2895

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 6 Number 9 (2017) pp. 2883-2895**
Journal homepage: http://www.ijcmas.com

Original Research Article https://doi.org/10.20546/ijcmas.2017.609.355

Impact of Long-Term Green Manuring on Zinc Transformations in Calcareous Soil under Rice-Wheat System

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Keywords

Green manure, FYM, Zinc fractions, Rice, Wheat and Calcareous soil.

Article Info

Accepted:
26 August 2017
Available Online:
10 September 2017

A B S T R A C T

A long-term field experiment was carried out with green manuring to see the impact on Zinc transformations in calcareous soil under rice-wheat cropping system. After completion of 5th cycle, Soil samples were collected from each plot and Zinc transformation process was executed. The distribution of native and applied Zn into different fractions indicated that most of the total-Zn remains in residual form and the quantity in plant usable forms like water soluble + exchangeable, complexed and organic form were very low which were about 0.34 to 0.91, 1.00 to 1.46 and 1.17 to 1.91 per cent, respectively of the total Zn. The order of dominancy of different fractions in soil was : residual Zn > crystalline sesquioxide Zn > organically complexed Zn > inorganically complexed Zn > amorphous sesquioxide Zn > water soluble + exchangeable Zn. Mutual transformation of water soluble + exchangeable Zn, organically Zn, crystalline sesquioxide Zn and residual Zn, seem to be dominant for maintaining Zn- equilibria in soil. The correlation and multiple regression were very well explained the importance of water soluble + exchangeable, organically complexed Zn and crystalline sesquioxide bound Zn in providing sustainable crop production by maintaining Zn-nutrition to crops under rice-wheat system. The existence of dynamic equilibria among different Zn-fractions as evident from significant correlation among themselves indicated that there is mutual transformation of Zn fractions to maintain Zn equilibria in soil. In conclusions, Dhaincha as well as Green gram plus FYM enhances WSE and ORG-Zn, which are most important for Zn nutrition to Rice-wheat.

Introduction

Zinc, an essential element in plant growth and metabolism, exists in soil in different forms such as primary and secondary minerals, insoluble inorganic and organic precipitates, soluble organic complexes and exchangeable and adsorbed forms and as soil solution zinc. These forms are in a state of dynamic equilibrium. The amount and rate of transformation of these forms of zinc solution determine the size of the labile Zn pool.

There are many reports on study of different micronutrient fractions of soils (Viets, 1962; Smith and Shoukry, 1968; Iyengar and Deb, 1977; Raja and Iyenger, 1986; Meki and Olusegun, 2012), but only few studies have been carried out with the application of organic and inorganic fertilizers under rice-wheat cropping system in calcareous soils (Prasad *et al.*, 2010; Kamali *et al.*, 2010, 2011; Pandey, 2012). The calcareous soil of

Bihar occupying a sizeable area is deficient of zinc to the extent of 80-90% of the tested soil samples and symptoms of zinc deficiency are frequently observed on many crops (Sakal *et al.,* 1996). Widespread occurrence of zinc deficiency in soil suggests that both native and applied forms of Zn react with the inorganic and organic phase in soil and thereby affect its availability. Zinc diffusion, which is one of the most limiting steps in calcareous soil, is affected by the application of organic materials. Availability of Zn to plants is influenced by amount of Zn present in different chemical pools which could be affected by organic matter incorporation. Zinc is known to exist in soil in different chemical pools and its solubility and availability to plant is a function of physical and chemical properties of the soil. Organic amendments such as Green manure, FYM, compost, crop residue, etc. have marked effect on the solubility and availability of different forms of Zn because of their bio-degradation in soil (Singh *et al.,* 2003; Mishra *et al.,* 2009; Dhaliwal *et al.,* 2010, 2012; Kumar and Kumar, 2012; Kumari and Singh, 2012). The wide scale adoption of rice-wheat system has ushered in an increase in agricultural production, but this intensive system over a period of time and nature of the crops has set declining yield trends as well as deterioration in soil productivity even with optimum use of fertilizers. Hence, for restoration of soil productivity, there is an urgent need to look forward to other options of supplying plant nutrient like Green Manure, FYM, crop residues incorporation. The adverse effect of incorporation of rice and wheat straw can be counteracted by integrating organic amendments with crop residues (Singh *et al.,* 2004). The continuous recycling of crop residue restores the organic matter content and also increases microbial population in the soil (Prasad, 2005). Therefore, for sustained agricultural productivity on a long term basis, proper appraisal of different forms of zinc and their relationships with soil characteristics and Zn uptake by crops is essential. Hence, the present investigation was carried out to study the effect of green manuring on zinc fractions of calcareous soil and their influences on zinc nutrition.

Materials and Methods

A long-term field experiment was started in Kharif 2000 in light textured highly calcareous soil at RAU Research farm, Pusa. The experimental soil had pH 8.40, EC 0.32 dSm $^{-1}$, OC 3.80 g kg^{-1}, CEC 8.2 [cmol (p+) kg^{-1}], Free $CaCO_3$ 34.40% and available Zn 0.73 mg kg^{-1}. The experiment was laid out in a RBD with following treatment details as T_1-control, T_2-Sunhemp every year, T_3-sunhemp alternate year, T_4-Dhaincha every year, T_5-Dhaincha alternate year, T_6- Green gram every year, T_7- Green gram + 2.5 t FYM ha^{-1} every year, T_8-Green gram + 5.0 t FYM ha^{-1} every year, T_9-10 t FYM ha^{-1} every year and T_{10}-10 kg Zn ha^{-1} alternate year. These were mixed thoroughly though out the respective experimental plot one week prior to transplanting of rice. After completion of 5th crop cycle (in 2005), soil samples were collected, processed and fractionation of soil Zinc was done using the method proposed by Iyengar and Deb (1977), modified by Raja and Iyengar (1986). The flow sheet showing the sequential extraction procedure is given in figure 1.

Total zinc

A portion of 0.5 g air dried soil was weighed into a platinum crucible and treated with 5 ml HNO_3 + 5 ml HF and left to stand overnight. Then 2.5 ml $HClO_4$ and 2 drops of H_2SO_4 were added. The content was digested and fumed to just moist dryness. After cooling, 5 ml HCl was used to dissolve and wash the crucible. After 1 hour, the residue was transferred to 50 ml volumetric flask and volume was made-up with distilled water up-to the mark. The readings were recorded with the help of Perkin Elemer Atomic Absorption Spectrophotometer. The residual Zn was determined by subtracting all forms of Zn extracted from the total Zn content.

Statistical analysis and presentation of data

Statistical analysis was done according to the methods outlined by Panse and Sukhatme (1967). The critical difference (CD) at 5 per cent level of probability was worked out for comparing the significant treatment effects. The correlation and multiple regressions were also carried out with the help of computers. The Standard Regression Coefficient (SRC) was worked out as below:

Where,

$$SRC = bi \sqrt{\frac{\Sigma x_i^2}{\Sigma y_i^2}}$$

bi = estimated regression coefficient

$$\Sigma x_i^2 = \Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}$$

$$\Sigma y_i^2 = \Sigma y_i^2 - \frac{(\Sigma y_i)^2}{n}$$

Results and Discussion

Distribution of zinc into different fractions

The data on soil zinc fractions like water soluble plus exchangeable, inorganically complexed, organically bound, amorphous sesquioxide bound, crystalline sesquioxide bound, residual and total zinc as reported in table 1, revealed that content of these fraction in different treatments varied from 0.53 to 1.55, 1.55 to 2.65, 1.82 to 3.42, 1.52 to 2.17, 2.20 to 5.13, 147.38 to 176.06 and 155.00 to 188.00 mg kg^{-1}, respectively. It is also clear from the data in table 1 that most of the total Zn was present in residual form and only small fraction was present in easily available form. It was observed that green manure and FYM application increased all the fractions of Zn except amorphous fraction. It is also clear from the data that most of the Zn recycled through green manuring as well as application of FYM alone or in conjunction with green manure got accumulated in residual as well as organic fraction. It was conspicuous from the data in table 2 that more than 95 per cent of the total native zinc existed in residual fraction. However, an application of Zn either through inorganic fertilizer or recycled with organic sources, there was reduction in the quantity of this fraction. The reduction was more pronounced when Zn was applied through FYM. Green manuring and FYM application increase the organic fraction of Zn from 1.17 to 1.91 per cent while this change in water soluble plus exchangeable fraction was from 0.34 to 0.70 per cent. The distribution of other Zn fractions in native or applied Zn varied from 1.00 to 1.46 per cent (complexed form), 0.53 to 1.27 per cent (amorphous form) and 1.42 to 3.00 per cent in crystalline form. The distribution of native and applied Zn into the form held by water soluble plus exchangeable Zn was much less than that held by crystalline Fe and Al oxide. Although, the per cent of total Zn in organically complexed form was found next to crystalline Fe and Al oxide bound form but the transformation of applied Zn was meagre. The distribution of total Zn into residual fraction was also reported to be more than 90 per cent (Mandal and Mandal, 1986). However, other worker like Singh *et al.*, (1987) and Spalbar *et al.*, (2017) reported 75 - 90 per cent of total Zn in the form of residual fraction. Mandal and Mandal (1986) also reported that a small fraction viz., 0.26, 0.74, 1.58 and 0.71 per cent of the total Zn occured as water soluble + exchangeable, organic complexed, amorphous sesquioxide and crystalline sesquioxide bound forms. High content of Zn as organic fraction in the present investigation might be due high organic carbon build up in soil due to green manuring and FYM additions. The order of dominance of different Zn fractions in soil was Residual Zn > crystalline sesquioxide bound- Zn > Organically bound-Zn > Inroganic complexed Zn > Amorphous sesquioxide bound Zn > water soluble + exchangeable Zn.

Relationship among different zinc fractions

The data on correlation coefficient value among different Zn fractions (Table 3) revealed that dynamic equilibrium of zinc existed between water soluble plus exchangeable, inorganic complexed, organically complexed, crystalline sesquioxide bound and residual forms as positive and highly significant correlation coefficient values were noted among these fractions. Zinc in amorphous sesquioxide bound failed to produce significant correlation with any fraction of Zn except organically complexed Zn (r = -0.711*). Existence of dynamic equilibrium among all these fracttions have been reported by many workers like Hazra *et al.,* (1987), Chowdhary *et al.,* (1997), Sharad and Verma (2001), Begum *et al.,* (2016) and Okoli *et al.,* (2016). This suggested that mutual transformation of water soluble plus exchangeable Zn, inorganically complexed Zn, organically complexed Zn, crystalline sesquioxide bound Zn and residual Zn seems to be dominant for maintaining Zn equilibria in soil during absorption of Zn by crops. The mutual significant correlation among different fractions also helps in maintaining quick equilibria and replenishing the available fractions in soil to meet the crop requirement.

Relationship of Zn fractions with plant and soil parameters

The correlation studies were carried out for plant parameters like grain yield of rice and wheat, total Zn uptake by rice and wheat and available Zn and organic carbon in soil with different Zn fractions and the correlation coefficient value (r) are presented in table 4. It was noticed that all the Zn fractions except amorphous sesquioxide boun-Zn, were significantly and positively correlated with all the plant parameters tested except grain yield of wheat which produce significant and positive correlation only with organic Zn (r = 0.714**). It is also conspicuous from the data that organically complexed fraction of Zn was significantly and positively correlated with all the plant parameters. Among different fractions, water soluble plus exchangeable fraction produced highest correlation coefficient values with all the plant and soil parameters tested showing its highest importance in maintaining Zn nutrition to rice-wheat system. The importance of exchangeable and organically bound Zn with respect to Zn nutrition of rice and wheat has also been demonstrated by Sharad and Verma (2001), Umesh *et al.,* (2013) and Kumari *et al.,*.(2015) Contribution of these two fractions in DTPA extractable Zn has been shown by above workers. In the present study significant correlation of available Zn with water soluble + exchangeable, inorganically complexed and crystalline sesquioxide bound form demonstrated that DTPA-Zn was able to extract Zn from these fractions. Highest correlation coefficient value of organic bound-Zn was noted with organic carbon showing the importance of green manuring in Zn nutrition of crops.

The relative contribution of soil Zn fractions towards plant parameters as well as available Zn was tried to be studied through multiple regression analysis.

Fig.1 Flow sheet showing the scheme adopted for sequential fractionation of soil Zinc

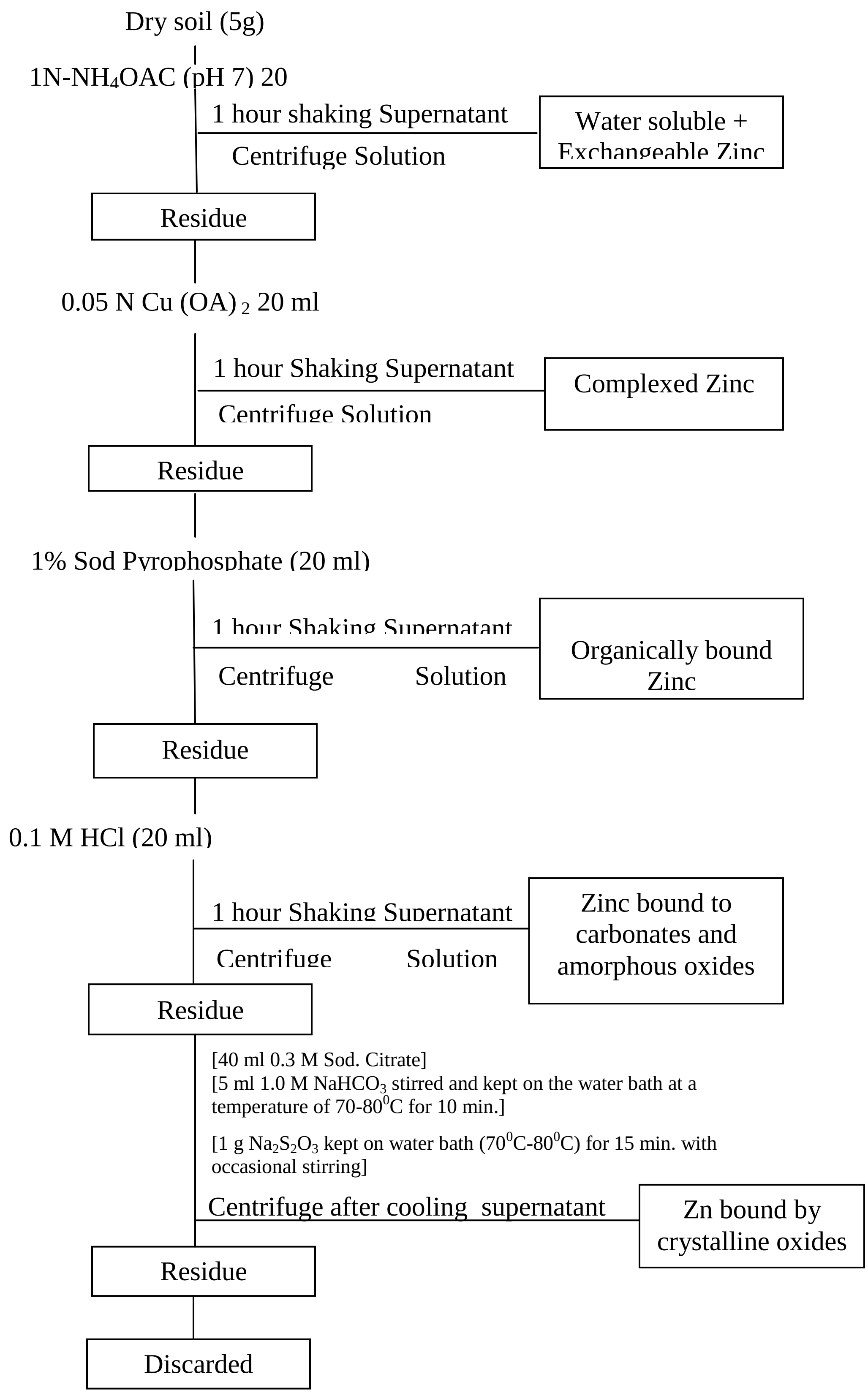

Table.1 Distribution of Zn in different fractions (mg kg^{-1}) in post-harvest soil of wheat (10^{th} crop) as Influenced by green manuring under rice-wheat system

Treatments	Different fractions of Zinc						
	WSE	COM	ORG	AMO	CRY	RES-Zn	Total-Zn
T_1 – Control	0.53	1.55	1.62	1.52	2.20	147.38	155.00
T_2 – Sunhemp (every year)	0.76	1.99	2.50	1.12	3.15	157.48	167.00
T_3 – Sunhemp (alternate year)	0.67	1.69	2.18	1.74	2.76	152.97	162.00
T_4 – Dhaincha (every year)	1.03	2.04	3.30	1.08	3.57	161.98	173.00
T_5 – Dhaincha (alternate year)	0.67	1.86	2.32	1.28	2.70	156.17	165.00
T_6 – Green gram (every year)	0.64	2.08	2.08	2.00	3.06	152.14	162.00
T_7 – Green gram + 2.5t FYM ha^{-1} (every year)	0.83	2.12	2.38	1.62	3.07	155.98	166.00
T_8 – Green gram + 5t FYM ha^{-1} (every year)	1.27	2.65	3.34	1.04	4.20	168.51	181.00
T_9 – 10.0 t FYM ha^{-1} (every year)	1.21	2.51	3.42	1.00	3.80	176.06	188.00
T_{10} – 10 kg Zn ha^{-1} (alternate year)	1.55	2.41	2.21	2.17	5.13	157.54	171.00
Mean	0.92	2.09	2.54	1.46	3.34	158.67	169.00
S.Em. ±	0.032	0.051	0.104	0.061	0.158	7.466	4.496
CD(0.05)	0.094	0.152	0.308	0.179	0.468	NS	13.357

WSE: -Water soluble + Exchangeable, COM: - Inorganically complexed, ORG: - Organically complexed, AMO: - Amorphous sesquioxide, CRY: - crystalline sesquioxide, RES: - Residual zinc

Total.2 Effect of green manuring on per cent (%) contribution of different fractions towards total zinc in post-harvest soil

Treatments	Different fractions of Zinc					
	WSE	COM	ORG	AMO	CRY	RES
T_1 – Control	0.34	1.00	1.17	0.98	1.42	95.08
T_2 – Sunhemp (every year)	0.46	1.19	1.50	0.67	1.89	94.30
T_3 – Sunhemp (alternate year)	0.41	1.04	1.35	1.07	1.70	94.43
T_4 – Dhaincha (every year)	0.60	1.18	1.91	0.62	2.06	93.63
T_5 – Dhaincha (alternate year)	0.41	1.13	1.41	0.78	1.64	94.65
T_6 – Green gram (every year)	0.40	1.28	1.28	1.23	1.89	93.91
T_7 – Green gram + 2.5t FYM ha^{-1} (every year)	0.50	1.28	1.43	0.98	1.85	93.96
T_8 – Green gram + 5t FYM ha^{-1} (every year)	0.70	1.46	1.85	0.57	2.32	93.10
T_9 – 10.0 t FYM ha^{-1} (every year)	0.64	1.34	1.82	0.53	2.02	93.65
T_{10} – 10 kg Zn ha^{-1} (alternate year)	0.91	1.41	1.29	1.27	3.00	92.13
Mean	0.54	1.2	1.49	0.87	1.96	93.11

WSE:-Water soluble + Exchangeable, COM:- Inorganically complexed, ORG:- Organically complexed, AMO:- Amorphous sesquioxide, CRY:- crystalline sesquioxide, RES:- Residual zinc

Table.3 Correlation coefficient among different soil Zinc fractions

	Inorganically complexed-Zn	Organically complexed-Zn	Amorphous sesquioxide-Zn	Crystalline sesquioxide-Zn	Residual- Zn
Water soluble + Exchangeable-Zn	0.850**	0.579	-0.027	0.963**	0.670*
Inorganically complexed-Zn		0.708*	-0.190	0.850**	0.805**
Organically complexed-Zn			-0.711*	0.510	0.923**
Amorphous sesquioxide-Zn				0.105	-0.624
Crystalline sesquioxide-Zn					0.574

*= significant at 0.05 level, **= significant at 0.01 level

Table.4 Correlation coefficient between plant and soil parameters Vs Zinc fractions in soil

Plant/soil parameters	**Different fractions of Zinc**					
	WSE	**COM**	**ORG**	**AMO**	**CRY**	**RES**
Grain yield of Rice	0.782**	0.860**	0.804**	-0.359	0.752*	0.784**
Grain yield of wheat	0.621	0.494	0.714*	-0.478	0.602	0.619
Zinc uptake by rice	0.943**	0.887**	0.679*	-0.137	0.924**	0.726*
Zinc uptake by wheat	0.930**	0.850**	0.704*	-0.204	0.900**	0.719*
Available Zinc	0.946**	0.770**	0.396	0.145	0.956**	0.497
Organic carbon	0.558	0.711*	0.970**	-0.778**	0.483	0.931**

*= significant at 0.05 level, **= significant at 0.01 level
WSE:-Water soluble + Exchangeable, COM:- Inorganically complexed, ORG:- Organically complexed, AMO:- Amorphous sesquioxide, CRY:- crystalline sesquioxide, RES:- Residual zinc

Table.5 Step down multiple regression showing influence of Zinc pools on plant parameters and available zinc of soil

S. No.	Y Factor		Regression analysis	R^2	R^2(adj)
1.	Grain yield of rice (Y_1)	a.	50.28 + 4.86 (0.54) WSE + 5.82 (0.67) COM + 3.93 (0.80) ORG – 0.07 (-0.01) AMO –0.86(-0.25) CRY - 0.22 (-0.72) Total Zn.	0.854	0.561
		b.	50.13 + 4.91 (0.54) WSE + 5.81 (0.67) COM + 3.97 (0.80) ORG – 0.89 (-0.26) CRY - 0.22 (-0.72) Total Zn.	0.854	0.671
		c.	44.85 + 2.72 (0.30) WSE + 4.97 (0.58) COM + 3.78 (0.76) ORG – 0.18 (-0.60) Total Zn.	0.851*	0.731
		d.	22.15 + 2.01 (0.22) WSE + 3.30 (0.38) COM + 2.00 (0.40) ORG	0.828*	0.742
		e.	20.59 + 5.00* (0.58)COM + 1.95 (0.39) ORG	0.814**	0.761
		f.	20.51 + 7.39** (0.86) COM	0.737**	0.704
2.	Grain yield of wheat (Y2)	a.	38.80 – 2.13 (-0.56) WSE – 3.47 (-0.96) COM + 0.49 (0.24) ORG – 2.03 (-0.67) AMO + 2.67(1.87) CRY + 0.01 (0.06) Total Zn.	0.829	0.487
		b.	39.81 – 1.99 (-0.53) WSE – 3.38 (-0.94) COM + 0.56 (0.27) ORG – 2.03 (-0.67) AMO + 2.62(1.84) CRY	0.829	0.615
		c.	40.99 – 2.17 (-0.57) WSE – 3.09 (-0.86) COM – 2.61* (-0.86) AMO + 2.82(1.97) CRY	0.820*	0.675
		d.	41.29 – 3.05 (-0.84) COM – 2.37 (-0.78) AMO + 2.00* (1.40) CRY	0.801*	0.702
3.	Zinc uptake by rice (Y3)	a.	178.73 + 96.00 (0.56) WSE + 38.10 (0.23) COM + 25.44 (0.27) ORG – 2.46 (-0.02) AMO + 12.86 (0.20) CRY – 1.24 (-0.21) Total Zn.	0.931	0.793
		b.	173.48 + 97.79 (0.57) WSE + 37.95 (0.23) COM + 27.05 (0.29) ORG + 11.52 (0.18) CRY – 1.24 (-0.21) Total Zn.	0.931*	0.845
		c.	241.63 + 125.96** (0.73) WSE + 48.87 (0.30) COM + 29.44 (0.30) ORG – 1.74 (-0.29) Total Zn.	0.930**	0.873
		d.	28.89 + 119.25* (0.69) WSE + 33.27 (0.20) COM + 12.70 (0.13) ORG	0.924**	0.886
		e.	61.46 + 142.41** (0.83) WSE + 18.92 (0.20) ORG	0.915**	0.891
		f.	91.06 + 162.45** (0.94) WSE	0.890**	0.875

Contd...

4.	Zinc uptake by wheat (Y_4)	a.	340.67 + 77.24 (0.74) WSE + 17.89 (0.18) COM + 23.16 (0.39) ORG – 12.32 (-0.14) AMO + 7.88 (0.20) CRY - 1.76 (-0.48) Total Zn.	0.924	0.771
		b.	368.40 + 94.44* (0.88) WSE + 23.34 (0.23) COM + 26.73 (0.46) ORG – 8.76 (-0.10) AMO – 2.01 (-0.54) Total Zn.	0.922*	0.825
		c.	321.90 + 89.35* (0.83) WSE + 18.38 (0.18) COM + 31.49 (0.54) ORG – 1.79 (-0.49) Total Zn.	0.920**	0.856
		d.	272.04 + 96.92** (0.90) WSE + 29.07 (0.50) ORG – 1.28 (-0.35) Total Zn.	0.915**	0.872
		e.	104.76 + 84.04** (0.78) WSE + 14.65 (0.25) ORG	0.905**	0.877
		f.	127.69 + 99.56** (0.9) WSE	0.863**	0.846
5.	Available Zinc (Y_5)	a.	0.44 + 0.19 (0.46) WSE – 0.03 (-0.07) COM – 0.08 (-0.34) ORG – 0.04 (-0.13) AMO + 0.11 (0.71) CRY + 0.001 (0.07) Total Zn.	0.950*	0.849
		b.	0.57 + 0.21 (0.50) WSE – 0.02 (-0.04) COM – 0.07 (-0.30) ORG – 0.04 (-0.13) AMO + 0.10 (0.67) CRY	0.950*	0.886
		c.	0.56 + 0.21 (0.50) WSE – 0.07 (-0.32) ORG – 0.04 (-0.13) AMO + 0.10 (0.65) CRY	0.949**	0.910
		d.	0.47 + 0.24 (0.58) WSE – 0.04 (-0.19) ORG + 0.08 (0.49) CRY	0.946**	0.919
		e.	0.56 + 0.44** (1.08) WSE – 0.05 (-0.23) ORG	0.29**	0.909

*= significant at 0.05 level, **= significant at 0.01 level
WSE:-Water soluble + Exchangeable, COM:- Inorganically complexed, ORG:- Organically complexed, AMO:- Amorphous sesquioxide, CRY:- crystalline sesquioxide, RES:- Residual zinc

Stepwise multiple regression equation of grain yield of rice (Y_1), grain yield of wheat (Y_2), total Zn uptake by rice (Y_3), total Zn uptake by wheat (Y_4) and available Zn in post-harvest soil (Y_5) as Y factors were worked out taking different fractions of Zn like water soluble + exchangeable (WSE) inorganically complexed (COM), organically complexed (ORG) amorphous sesquioxide bound (AMO), crystalline sesquioxide bound (CRY), residual Zn (RES) and total Zn as X factors and presented in table 5. Step-down multiple regression equation for grain yield of rice could significantly be explained through variations in COM and ORG Zn. The individual effect of inorganically complexed (COM) Zn was significant and positive. Inclusion of other fractions like, residual, water soluble + exchangeable, amorphous sesquioxide and total Zn explained additional 4.0 per cent variation in grain yield of rice. The standard regression coefficient as given in parentheses indicated that inorganically complexed (COM) Zn was most important Zn fractions, as compared to organically complexed (ORG) Zn and other Zn fractions.

The extent of variation in grain yield of wheat which could be explained through the variation in inorganically complexed (COM), amorphous sesquioxide bound (AMO) and crystalline sesquioxide bound Zn (equation'd' of Y_2) was found to be 80.1 per cent with significant effect of amorphous and crystalline sesquioxide bound Zn fractions. Addition of other Zn fractions like residual Zn, water soluble + exchangeable, organically complexed and total-Zn in the step-wise regression equation (equation d of Y_2) hardly explained up-to 2.8 per cent additional variation in grain yield of wheat. On comparing standard regression coefficient, the relative importance among Zn fractions was more for crystalline sesquioxide bound Zn followed by amorphous sesquiioxide bound Zn in explaining the variation in grain yield of wheat.

The importance of Zn fractions like water soluble + exchangeable and organically bound Zn has been shown through multiple regression equation ('e' of Y_3) where 91.5 per cent variations in total Zn uptake by rice crop was explained through variations in these fractions. Further inclusion of other fractions in the regression equation hardly explained 1.6 per cent additional variation in total Zn uptake by rice. From equation 'e' water soluble + exchangeable Zn emerged as the most important Zn fraction followed by organically bound Zn fraction as reflected by their standard regression coefficient values.

As high as 90.5 per cent variations in total Zn uptake by wheat could significantly be explained through the variation in water soluble + exchangeable and organically bound Zn as evident from equation (e of Y_4). Further inclusion of other four fractions hardly explained any discernible change in total Zn uptake by wheat. However, exclusion of organically bound fraction in the regression equation (f of Y_4), depleted the extent of variation to be explained was to the extent of 4.2 per cent. The individual effect of water soluble and exchangeable Zn fraction was highly significant and positive as well as also gave higher standard regression coefficient values denoting importance with respect to total Zn uptake by wheat.

With regards to available Zn content in post-harvest soil, as high as 94.6 per cent variation (equation 'd' of Y_5) could significantly be explained through the variations in water soluble + exchangeable Zn, organic complexed Zn and crystalline sesquioxide bound Zn. However, the individual effect of these three fractions was non-significant. Further, inclusion of other Zn fractions was able to explain only 0.4 per cent additional variations whereas deletion of crystalline bound and organically bound Zn fraction from the regression equation failed to explained about 1.7 and 5.1 per cent, additional variations, respectively. Comparing the standard regression coefficient in (equation 'd' of Y_5), it appears that water soluble + exchangeable Zn followed by crystalline sesquioxide Zn was more responsible for variation in available Zn content of soil.

From the foregoing multiple regression studies, it appears that water soluble Zn fraction followed by organically bound-Zn played key role in explaining the variations in yield and Zn-uptake by crops under rice-wheat system. The available Zn in post-harvest soil appears to be controlled by the above two fractions. However, the contribution of crystalline form of Zn cannot be ignored in maintaining Zn nutrition to crops under rice-wheat system. It may be inferred from the result that green manuring played a vital role in Zn nutrition by maintaining Zn equilibria in soil. The results regarding relationship between soil Zn fractions and plant parameters are in conformity with the findings of Chawdhary *et al.,* (1997), Sharad and Verma (2001) and Kumari *et al.,* (2015).

The different fractions of soil Zn are in dynamic equilibrium with each other and their availability to growing crop depends on their intensities and soil condition. This implies that depleted levels of readily available Zn in soil could be replenished by other pools of soil Zn. Among different Zn fractions, Zn bound to crystalline oxide, followed by Zn bound to carbonate and amorphous oxide played key role in explaining the variation in yield and Zn uptake by rice and wheat.

Acknowledgements

The authors are thankful to the sir Dr. A. P. Singh, former Professor, Department of Soil Scienc, RAU, Pusa for their guidance and suggestions during course of investigation and also RAU, Pusa for providing financial assistance. (This manuscript has BAU communication no.300/2017)

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How to cite this article:

Sunil Kumar. 2017. Impact of Long-Term Green Manuring on Zinc Transformations in Calcareous Soil under Rice-Wheat System. *Int.J.Curr.Microbiol.App.Sci.* 6(9): 2883-2895.
doi: https://doi.org/10.20546/ijcmas.2017.609.355