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Long-term Effect of Residual Zinc and Crop Residues Incorporation on Soil Health and Crop Productivity under Calcareous Soils of Rice-Wheat System in India

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A B S T R A C T

Rice-wheat (*Oryza sativa* L.-*Triticum aestivum* L.) rotation is the major production system in Asia, covering about 18 million ha. Continuous and conventional RWC system practice has witnessed a significant slowdown in the yield growth rate. The sustainability of this important cropping system is at risk due to second-generation problems (low fertility status, multiple nutrient deficiencies, and imbalanced use of fertilizers, ground water depletion at faster rate, soil salinization, and inadequate system diversity). Our results after super-imposition of treatments on an 18-year rice-wheat rotation trial in eastern Indo-Gangetic plains demonstrated significant effects of crop residues incorporation and Zn application on soil macro-nutrients, micro-nutrients, their availability, soil chemical productivities and crop productivity. Maximum rice and wheat yields were obtained at 100% crop residues incorporation along with 10 kg residual application of starter Zn ha^{-1}. The crop residue incorporation and Zn application increased its uptake by 60% and 57%, respectively. Incorporation of crop residues increased Fe uptake by rice and wheat by19% and 39%, respectively. There was an improvement on soil chemical properties (pH and OC) with crop residue incorporation. The macro- and micronutrients soil availability also increased with crop residues incorporation, whereas Zn application reduced Fe, Cu and Mn availability in calcareous soils. The crop residues incorporation can augment micronutrient availability in the calcareous soils. Our results highlight the research need to understand the mechanisms and availability of macro- and micronutrients under different crop residue incorporation levels and micronutrient application in rice-wheat cropping system, which is crucial for developing innovative nutrient application technologies and associated agronomy for higher yield potential.

Introduction

Rice-wheat cropping (RWC) system is fundamental to South Asia's food security as it plays a leading role in contributing food grains for the region. In India alone, RWC system occupies about 10.5 M ha and contributes about 40% of the country's total food grain basket (Saharawat *et al.,* 2010). With the adoption of high yielding varieties, higher application of inputs of plant nutrition, irrigation water and improved crop management practices, the productivity of RWC system in the region was remarkably increased and had ushered into Green Revolution primarily in North-Western India (Nawaz *et al.,* 2015). However, these gains were accompanied by widespread problems of soil health and resource degradation, which now pose a serious challenge to the continued ability of the region to meet the food demand of an ever-increasing population. Future food production will be limited on a global scale by the availability of land, water, and energy, it will need to successfully address the environmental problems created by current and past agricultural activities, and it must be both adapted to and mitigate against the impacts of climate change (Godfray *et al.,* 2010). In recent years, RWC system has witnessed a significant slowdown in the yield growth rate. The sustainability of this important cropping system is at risk due to second-generation problems (low fertility status, multiple nutrient deficiencies, imbalanced use of fertilizers, ground water depletion at faster rate, soil salinization, and inadequate system diversity). Decoupling future growth from the unsustainable use of fertilizers, nutrients, water, energy, chemicals, and land for increasing food production has become one of the cornerstones for a new sustainable development agenda (Rockstrom *et al.,* 2013; Dobermann *et al.,* 2013). The current approach of RWC production is now known to be ecologically intrusive and economically and environmentally unsustainable which is further aggravated with the fast changing climate in the region.The main reasons for low system productivity even in irrigated areas are the inadequate and imbalanced use of fertilizers in these nutrient exhaustive crops, which have consequently declined the organic carbon and soil health (Yadav *et al.,* 2005).

Hence, for restoration of soil health and productivity, there is an urgent need to look forward to other options like, crop residues incorporation for supplying plant nutrients. The adverse effect of incorporation of rice and wheat straw can be counteracted by integrating organic amendments with crop residues (Singh *et al.,* 2012). The continuous recycling of crop residues restores the organic matter content and also increases microbial population in the soil (Das *et al.,* 2015; Prasad *et al.,* 2010). The RWC system in the next few decades has to be an eco-efficient revolution, with at least 30% to 50% increases in the efficiency of scarce inputs as fertilizers and nutrients used while also ensuring the availability of nutritious and safe food for all and minimizing many negative environmental impacts associated with contemporary food systems. Integrated nutrient management is one of the most important components of the agricultural production system to sustain higher crop yields and maintain soil health. The interactive advantages of combining organic and inorganic sources of nutrients in integrated nutrient management have shown additive effects in comparison to the use of each component separately (Das *et al.,* 2012). Systematic studies integrating nutrient management with conservation agriculture (residue incorporation/retention) in the key cropping systems adapted to the changes within and outside of agricultural environment are lacking in the region. Such studies are important for extrapolation to broader geographical levels. Therefore, RWC system production-scale long-term field trial guided by key scenarios of agricultural environment was designed and established in eastern Indo-Gangetic plains of South Asia. In the past, on these aspects, there has been no systematic study in the Eastern IGP, which is home to the world's highest rural population density. As part of this comprehensive study, we report the performance of the long-term effect of residual zinc and crop residues on yield and soil properties under rice-wheat cropping system in calcareous soil, a part of the Eastern IGP.

Materials and Methods

Experimental site

The field study was conducted on light textured highly calcareous soil deficient in available zinc (0.56 mg kg^{-1}) at the Research Farm of Rajendra Agricultural University, Pusa, Bihar, India (Longitude, 25.9854^0; Latitude, 85.6807^0; Altitude, 67m above MSL). The field study was established in 1993-94 as a production-scale trial with a long-term perspective involving RWC system. The experimental study was conducted during 2011-12 and 2012-13 as super-imposed treatments in the long-term trial. The climate of study site is sub-tropical humid, with an average annual rainfall of 1130 mm (85–90% of which is received from June to September), daily minimum temperature of 7–9^{o}C in January, daily maximum temperature of 36–41^{o}C in June, and relative humidity of 60-90% throughout the year. Crop production is distributed across the three seasons that occur in this region: winter (*rabi*: November–March), summer (April–May), and rainy (*kharif*: June–October). The summer period is normally fallow period due to water scarcity in the region. The initial soil samples were collected after harvest of the rice crop. Soil samples (0–15cm) were collected from different grids in the plots using anauger of 5cm diameter. The soil samples from each grid cell of a plot were composited, air dried, ground to pass through a 2mm sieve, and stored in plastic jars until analysis was done. The soil samples were analyzed for pH, electrical conductivity (EC), Organic carbon (Walkley and Black carbon), Olsen P (0.5 M $NaHCO_3$ extractable), and 1 N neutral NH_4OAC extractable K (by flame emission spectrophotometer). Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962). The textural class was determined by the United States Department of Agriculture (USDA) system. DTPA- extractable micronutrients were determined by an Atomic Absorption Spectrophotometer (Lindsay and Norvell, 1978).The initial soil characteristics of the experimental soil (0-15 cm) are: pH (1:2) 8.5, EC 0.36 dSm^{-1}, organic carbon 6.2 gkg^{-1}, available N 236 $kgha^{-1}$, available P 19.7 $kgha^{-1}$, available K 100 $kgha^{-1}$, available Fe 15.8 $mgkg^{-1}$, available Mn 3.30 $mgkg^{-1}$ and available Cu 2.28 $mgkg^{-1}$.

Experimental details and management

The experiment was laid out in a split plot design with three replications and plot size of 10 m^2 (5.0 m x 2.0 m). The main plots included different levels of residue incorporation and sub-plots were zinc application levels. The main plot treatment included four levels of crop residues, viz. (T1) –no crop residue (CR_0), (T2)-25 % of straw produced (CR_{25}), (T3)-50 % of straw produced (CR_{50}) and (T4)–100% of straw produced (CR_{100}). The treatments were applied in similar way in each crop every year. The main plot was divided into four sub-plots in which sub-treatments on zinc application levels, viz. (S1) –no Zn (Zn_0), (S2) -2.5 kg Zn ha^{-1}(Zn_{25}), (S3) -5.0 kg Zn ha^{-1} (Zn_{50}) and (S4) -10.0 kg Znha^{-1}(Zn_{100}) were superimposed over crop residue levels. These four levels of Zn were applied only to first crop as a starter dose. The recommended doses of NPK (120:60:40) were applied to each crop of rice and wheat as urea, single superphosphate and muriate of potash. Half of nitrogen and entire dose of P and K were applied at the time of transplanting of rice and sowing of wheat and remaining N fertilizer was applied in the equal splits at tillering and flower initiation stage. Rice and wheat crops were grown continuously under rice-wheat cropping system. Rice cv., Rajshree was grown as 33rd and 35th test crop and wheat cv., HD 2733 as 34th and 36th test crop during the reported period of 2011-12 and 2012-13.

Crop harvest and parameter analysis

At maturity, wheat crop was harvested manually from ground level. The grains were threshed using a plot thresher. Similarly, rice was harvested at the soil surface and threshed manually. Grain and straw yields of both rice and wheat were estimated by manually harvesting a total area of 4 m^2 from each plot. Grain moisture was determined at the time of yield estimation using a grain moisture meter. The grain and straw samples were taken at the harvest of rice and wheat crops, and washed sequentially in 0.2% liquid detergent solution, 0.01 N HCl solution and deionized water and dried in oven at 70ºC.

Finely ground samples were digested in a di-acid mixture (HNO_3:$HClO_4$; 3:1 v/v) and diluted. Digested samples were analyzed for micronutrients using atomic absorption spectrophotometer. Total uptake of micronutrients by grain and straw was computed. Composite surface (0-15cm) soil samples from each plot of the field experiment were collected at the harvest of wheat crop as 36th crop in rice-wheat rotation. Soil samples were air-dried and pulverized to pass through 2 mm sieve. Available micronutrients were determined by methods described by Lindsay and Norvell (1978). Organic Carbon was determined by rapid titration method as described by Walkley and Black (1934).

Available Nitrogen was determined by alkaline permanganate method (Subbiah and Asija, 1956). Available P_2O_5 was determined by Watanable and Olsen's method (1965). Available Potassium was extracted with neutral 1N-NH_4OAc using soil to extractant ratio of 1:5. The potassium in the extract was determined with the help of flame photometer as described by Jackson (1978). The pH was determined by glass electrode pH meter (Jackson, 1978).

Data analysis

Data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedures of the Statistical Analysis System Institute (2001). Data were either not transformed or transformed using log, square root, or inverse functions as needed to meet the assumptions of normality and equal variance of population distributions. Scenario mean values were separated by Fisher's protected least significant difference test at $P<0.05$. The treatment-by-year interaction was significant; therefore, all the data are presented separately for each year.

Results and Discussion

Crop performance

Rice crop

The grain and straw yields of 35th crop of rice as influenced by zinc and continuous application of crop residue at four levels varied from 3.63 to 4.73 and 5.70 to 6.00 tha^{-1}, respectively (Table 1). Application of zinc significantly enhanced the mean grain and straw yields of rice by 12% each of both, even after 18 years of its application. This may be attributed to decreased levels of available zinc in soil under no-Zn treatment and also to solubilization of native as well as applied zinc at higher levels by different crop residues which produce complexing agents and nutrients after microbial decay of crop residue (Prasad *et al.*, 2010; Singh *et al.*, 2012). The mean grain and straw yield of rice increased by 15% and 16%, respectively, with increasing levels of crop residues incorporation. The highest yield (4.73 t ha^{-1}) was recorded at 100% crop residue level with application of 10.0 kg Zn ha^{-1}. The effects of crop residue and Zn on rice yield were positive. The grain and straw yield of rice increased with increased incorporation of wheat residues from 25% to 100%. Similar results of increased grain and straw yields of rice due to increased incorporation of crop residues have been reported by Kumar and Kumar (2012). Their study further confirmed that increased availability of nutrients by complexing properties of crop residues was the major contributor to increased grain and straw yields of rice. The literature shows similar results by Prasad *et al.*, (2010) and Rathod *et al.*, (2012) under different agro-ecologies and cropping systems.

In T1, the rice grain yield at different levels of starter Zn application were found at par which indicated that residual effects of Zn application were very low which increased the yield but not up to significant level. In general, the grain and straw yields at S1 and S3 levels and T2 and T3 levels either of Zn or crop residue incorporation levels were found significant which also indicated that there was an interaction of residual effect of Zn and incorporation of crop residues on rice grain and straw yields. There was marked increase in yield due to increasing levels of crop residues (T1 to T4) at all the levels of zinc. The literature shows that improvement in organic carbon and microbial population under higher residue levels might be the reason for augmenting the rice productivity (Pandey, 2012; Das *et al.*, 2012).

Wheat crop

The grain and straw yields of 36th crop of wheat ranged from 3.12 to 4.13 and 4.87 to 6.44t ha^{-1}, respectively (Table1). The residual effects of zinc and crop residue levels showed similar trends as observed in rice crop. The wheat yield during initial few years was adversely affected (data not presented here) at higher levels of crop residue incorporation attributing to immobilization of nitrogen and micronutrients by decomposing micro-flora. But during the study period wheat yield increased with increasing levels of crop residues attributing to build-up of organic carbon, nitrogen levels and micronutrients that accelerated faster rate of decomposition of crop residues. Heterotrophic microorganisms use crop residue as a source of organic carbon, nutrient and energy, and degrade the crop residues in soil. The extent of nutrient availability depends not only on type of organic additives but also on the build-up of autochthonous microorganisms. The grain and straw yields increased by 8% and 7%, respectively, with increasing levels of crop residues from T1 to T4.

The wheat yield at T1 and T2 levels was at par indicating the starter Zn level did not influence the yield; however, interaction effects of grain and straw yields were found non-significant.

The highest grain and straw yields were found in the plot receiving 100% crop residue (T4) incorporation along with S4. The results obtained in the present investigation are corroborated by those obtained by Prasad *et al.*, (2010), Rathod *et al.*, (2012) and Das *et al.*, (2012).

Micronutrient uptake

The increase in rice and wheat yields with Zn application was mainly due to increase in Zn uptake by rice and wheat (Table 2). Crop residue application increased Zn uptake by rice and wheat to the tone of 60% and 57%, respectively.

Crop residues on decay produce a variety of biochemical substances (organic acids, polyphenols, amino acids and polysaccharides), which stimulate the solubility, transport, and availability of Zn. Different levels of crop residues augmented Cu uptake by rice and wheat by49% and 36%, respectively. The effects of crop residue and Zn on Cu uptake by rice and wheat were statistically significant. Similar results have also been reported by Prasad *et al.,* (2010) in calcareous soils under rice-wheat system.

Incorporation of crop residues increased Fe uptake by rice and wheat by19% and 39%, respectively (Table 3). The effects of crop residue on Fe uptake by rice and wheat were significant but effect of Zn on Fe uptake by rice and wheat was non-significant (Prasad *et al.,* 2010).

Effectiveness of crop residues may be ascribed to their ability after degradation to form water soluble complexes with Fe and other ions. Perhaps, humic substances and organic acids formed after decomposition of crop residue by microflora may help in the translocation of Fe within the plant.

The most significant influence of crop residues in increasing the solubility and availability of Fe in the soil is through solubilization of native soil insoluble Fe and enhanced diffusion and mass flow in the immediate vicinity of plant (O'Connor *et al.,* 1971; Dhaliwal *et al.,* 2012). Crop residues enhanced Mn uptake by rice and wheat by18% and 56%, respectively. Similarly, effect of residual Zn on Mn uptake by rice and wheat varied from 21% and 26%, respectively (Table 3).

Chemical properties of post-harvest soil

Soil pH

The soil pH decreased from 8.16 to 8.14 (Table 4) due to residual Zn levels over control; however, at all the levels of applied Zn, the pH was same (8.14). Increasing crop residue levels significantly decreased the pH from 8.26 to 8.01. Decrease in soil pH may be attributed to incorporation of crop residue and acid produced by organic matter after incorporation resulting in decrease in pH. Similar results have been reported by Dhaliwal *et al.,* (2012) in the rice-wheat system

Organic Carbon

Organic carbon (OC) content in soil with continuous incorporation of crop residues either alone or along with residual Zinc application varied from 0.69 to 1.11% and it increased after eighteenth year of crop residue incorporation from 0.71 to 1.06 % (Table 4). Increasing residual Zn levels also increased the OC content from 0.83 to 0.90%. Residual effect of Zn application increased the biomass production resulting in addition of higher quantity of roots and stubbles, which might have built up OC level in soil.

Higher OC content of soil with crop residue incorporation might be attributed to the fact that continuous addition of organic matter through crop residue increased the microbial population which enhanced the decomposition of crop residue resulting in increased OC content. Similar observations have also been reported by Prasad *et al.,* (2010), Nayak *et al.,* (2012) and Adhikari *et al.,* (2012). The interaction effect between Zn and crop residue level was also significant, where a variation in OC content from 0.69 to 1.11% was recorded. The results indicated that the effect of crop residue was more apparent when applied along with Zn as compared to Zn alone.

Increasing levels of crop residues increased the OC at all levels of residual Zn (S3 to S4), except at S2. Increasing levels of Zn could not increase the OC significantly at any levels of crop residues incorporation; however, significantly increased the OC content in soil at the highest levels of crop residues between no Zn (0.98%) and 10 kg Zn ha^{-1} application (1.11%).

Table.1 Effect of zinc and crop residue (CR) levels on grain and straw yields of rice (35th crop) and wheat (36th crop)

Zn level (kgha^{-1})	Grain yield (t ha^{-1}) Crop residue level (% of straw produced)					Straw yield (t ha^{-1}) Crop residue level (% of straw produced)				
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
Rice (35th crop)										
S1	3.63	3.83	4.05	4.10	3.90	5.07	5.38	5.67	5.78	5.48
S2	3.90	3.97	4.23	4.43	4.13	5.45	5.57	5.93	6.23	5.80
S3	3.93	4.07	4.35	4.56	4.23	5.57	5.77	6.12	6.40	5.96
S4	4.08	4.23	4.43	4.73	4.37	5.72	5.97	6.22	6.60	6.13
Mean	3.89	4.03	4.27	4.46		5.45	5.67	5.98	6.25	
CD (p = 0.05)	T				0.29					0.31
	S				0.18					0.20
	T x S				NS					NS
Wheat (36th crop)										
S1	3.12	3.22	3.46	3.76	3.39	4.87	5.03	5.40	5.87	5.29
S2	3.26	3.40	3.50	3.85	3.50	5.08	5.31	5.47	6.00	5.47
S3	3.24	3.54	3.59	3.92	3.57	5.06	5.52	5.60	6.12	5.58
S4	3.26	3.57	3.67	4.13	3.66	5.08	5.56	5.73	6.44	5.70
S1	3.22	3.43	3.56	3.92		5.02	5.36	5.55	6.11	
CD (p = 0.05)	T				0.29					0.40
	S				0.11					0.24
	T x S				NS					NS

NS: Non-significant

Table.2 Effect of zinc and crop residue levels on Zn and Cu uptake (gha^{-1}) by rice (35th crop) and wheat (36th crop)

Znlevel (kgha^{-1})	Crop residue level (% of straw produced)										Crop residue level (% of straw produced)									
	Zn uptake by rice					Zn uptake by wheat					Cu uptake by rice					Cu uptake by wheat				
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
S1	153.4	204.5	226.6	255.9	210	150.4	159.9	185.8	215	177.8	36.7	44.4	49	63.5	48.4	576	608	720	804	677
S2	182.1	216.7	247.0	288.2	234	164.1	186	211.6	249	202.7	40.9	48.3	49.5	64	50.7	612	653	739	833	709
S3	205.5	249.7	253.6	314.6	256	173.4	207.3	235.3	272	222.0	46.1	47.6	54.9	68.2	54.2	612	713	767	859	738
S4	224.2	267.9	296.2	367.1	289	181.4	223.9	254.7	321	245.3	50.1	52.8	54.3	63.6	55.2	640	739	788	917	771
Mean	191	235	256	306		167.3	194.3	221.9	264.3		43.4	48.3	51.9	64.8		610	678	753	853	
CD (p=0.05)	T	26.7				T	17.8				T	4.67				T	37.3			
	S	17.3				S	9.23				S	2.89				S	21.1			
	TxS	NS				TxS	NS				TxS	NS				TxS	NS			

NS: Non-significant

Table.3 Effect of zinc and crop residue (CR) levels on Fe and Mn uptake (gha^{-1}) by rice (35^{th} crop) and wheat (36^{th} crop)

Zn level ($kgha^{-1}$)	Crop residue level (% of straw produced)										Crop residue level (% of straw produced)									
	Fe uptake by rice					Fe uptake by wheat					Mn uptake by rice					Mn uptake by wheat				
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
S1	719	747	799	810	769	576	608	720	804	677	512	538	532	554	534	395	504	556	654	527
S2	749	786	866	929	832	612	653	739	833	709	526	582	594	626	582	448	560	613	685	576
S3	790	823	840	983	859	612	713	767	859	738	551	603	624	676	614	485	596	653	742	619
S4	806	879	919	1030	909	640	739	788	917	771	596	628	651	718	648	531	624	693	813	665
Mean	766	809	856	938		610	678	753	853		546	588	600	643		465	571	629	724	
CD (p = 0.05)	T				28.7	T				37.3	T				41	T				31
	S				21.2	S				21.1	S				34	S				29
	TxS				NS	TxS				NS	TxS				NS	TxS				NS

NS: Non-significant

Table.4 Effect of residual starter Zn and crop residue incorporation on properties related with soil health in post-harvest soil of wheat (36^{th} crop)

Zn levels ($kg\ ha^{-1}$)	Crop residue level (% of straw produced)									
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
	pH					Organic Carbon (%)				
S1	8.30	8.21	8.11	8.01	8.16	0.69	0.77	0.88	0.98	0.83
S2	8.23	8.19	8.12	8.03	8.14	0.70	0.77	0.90	1.08	0.86
S3	8.24	8.17	8.14	8.01	8.14	0.72	0.79	0.92	1.08	0.88
S4	8.28	8.19	8.10	8.00	8.14	0.74	0.82	0.94	1.11	0.90
Mean	8.26	8.19	8.12	8.01	-	0.71	0.79	0.91	1.06	-
CD	T		0.06			CD	T		0.09	
(P = 0.05)	S		0.01			(P =	S		0.02	
	TX S		NS			0.05)	TX S		0.11	

Table.5 Effect of residual starter Zn and crop residue incorporation on available major nutrients (kgha^{-1}) in post-harvest soil of wheat (36th crop)

Zn level (kgha^{-1})	Crop residue level (% of straw produced)														
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
	Nitrogen					P_2O_5					K_2O				
S1	220	229	240	249	234	19.23	24.60	29.60	33.83	26.82	131	141	152	159	145
S2	222	233	243	251	237	19.53	25.03	30.90	33.87	27.33	133	143	154	161	148
S3	225	235	244	253	239	20.63	27.30	31.53	34.47	28.48	136	145	155	163	150
S4	226	235	246	255	240	23.07	27.87	32.10	34.83	29.47	138	147	156	165	151
Mean	224	233	243	252	-	20.62	26.20	31.03	34.25	-	134	144	154	162	-
CD(P = 0.05)	T				3	T				1.45	T				2
	S				1	S				0.72	S				1
	T x S				3	T x S				1.45	T x S				2

Table.6 Effect of zinc and crop residue incorporation on available micronutrient cautions (mgkg^{-1}) in Post-harvest soil of wheat (36th) under rice-wheat cropping system

Zn level (kgha^{-1})	Crop residue level (% of straw produced)																			
	Available Zn					Available Cu					Available Fe					Available Mn				
	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean	T1	T2	T3	T4	Mean
S1	0.38	0.43	0.52	0.78	0.53	3.09	3.25	3.51	3.73	3.40	16.33	16.93	18.30	19.0	17.64	4.30	4.39	4.72	4.89	4.58
S2	0.40	0.42	0.58	0.91	0.58	3.11	3.23	3.47	3.67	3.37	16.27	16.57	18.37	19.23	17.61	4.29	4.42	4.70	4.85	4.57
S3	0.41	0.44	0.68	1.05	0.65	3.09	3.18	3.46	3.63	3.34	15.87	16.33	18.07	18.93	17.30	4.29	4.35	4.68	4.91	4.56
S4	0.42	0.44	0.95	1.21	0.76	3.11	3.16	3.40	3.58	3.31	15.40	16.17	17.90	18.57	17.01	4.32	4.36	4.69	4.80	4.54
Mean	0.40	0.43	0.68	0.99		3.10	3.21	3.46	3.65		15.97	16.50	18.16	18.93		4.30	4.38	4.70	4.86	
CD (p = 0.05)	T				0.05	T				0.05	T				0.26	T				0.07
	S				0.04	S				0.01	S				0.15	S				0.03
	Tx S				0.08	TxS				0.04	Tx S				0.15	Tx S				0.05

Available macro-nutrients

Available nitrogen

Data illustrated in table 5 indicated that levels of crop residues, residual starter zinc and their interaction significantly influenced available nitrogen content of soil. Significant buildup of available N was recorded with graded levels of zinc and also with residue incorporation as presented in table 5. Application of crop residue and residual starter Zn increased available N content in soil by13% and 3%, respectively. This increase was higher over absolute control and initial value, which indicates the buildup of available N in soil. Kumar *et al.,* (2010) and Kumari and Singh (2012) also reported the positive effect of residues on available N status of soil in rice-wheat cropping system.

Available phosphate and potash

A critical analysis of data on available P_2O_5 and K_2O as given in table 5 revealed that there was positive effect of residual starter Zn, crop residue levels and their interactions on these two soil nutrients. The overall variation in available P_2O_5 was observed up to 81%, whereas available K_2O varied up to26%. The increase in available P_2O_5 was found positively influenced by Zn levels (S1 to S4) by 10% and due to crop residue levels by 66%. Similarly, increasing levels of Zn linearly increased the available K_2O content in soil by 4%. The positive variation in available K_2O (21%) was obtained with increasing levels of crop residue. Addition of organic matter, in general, increased non-symbiotic nitrogen fixing bacteria (Kumari and Singh, 2012). Heterotrophic microorganisms act on organic materials, degrade in soil and consequently release these nutrients in soil. The extent of availability of nutrients depends not only on the type of organic additives but also on the buildup of microorganisms (Prasad *et al.,* 2012). Enhanced microbial mineralization might have resulted in increase of available P_2O_5 and K_2O in the present investigation. The increase in phosphatase activity due to crop residue or organic sources incorporation and increase in available P_2O_5 and K_2O in soil has also been reported by earlier workers (Singh *et al.,* 2012; Sanjay *et al.,* 2011). They further described that with lapses of time, the amount of K mineralized, increased significantly and raised the available K pool in soil due to release of more organically bound K in course of decomposition of organic waste.

Available micronutrients

Available Zn

The residual effect of starter Zn and crop residue incorporation on available Zn in soil after harvest of 36th crop of wheat under rice-wheat cropping system is elaborated in table 6. Available Zn in post–harvest soil varied from 0.38 to 1.21 mg kg^{-1} due to different treatment combinations. The data revealed that increasing Zn application levels (S1 to S4) increased the available Zn status of soil by 43%, although the value was below the critical level of 0.78 mg kg^{-1} as reported by Sakal and Singh (1979) for such calcareous soils in the region. The increases in available Zn due to crop residue incorporation were higher with increasing levels by 147%; however, available Zn at T1 (0.40 mg kg^{-1}) and at T2 (0.43 mg kg^{-1}) were significantly at par. The buildup of available Zn due to crop residues incorporation has also been reported earlier (Singh *et al.*, 2010; Walia *et al.*, 2010; Tripathi and Kumar, 2013). This buildup has been reported due to addition of Zn through crop residue and/or exploitation of native Zn by chelation through decomposition product of crop residues. Organic matter was also found to increase the efficiency of applied Zn as inorganic fertilizer (Walia *et al.,* 2010).

The interaction effect between Zn and crop residue levels was significant which suggested that not only the addition of Zn through $ZnSO_4$ or crop residue incorporation enhanced the buildup of available Zn but also the solubilization of native Zn by the organic acids produced during the decomposition of crop residue was responsible for buildup of available Zn in post-harvest soils.

Crop residue incorporation alone applied @100% straw produced for 18 complete years (data not presented here) was able to raise the available Zn status of soil up to the extent of 0.78 mg kg^{-1} which is equivalent to the critical level of zinc. The crop residues applied to the extent of even 50 per cent of straw produced along with the starter dose of Zn at least 10 kg Zn ha^{-1} or in the case of 100% crop residue along with any of the four given treatments of Zn increased the available Zn content in soil above critical level (0.78 mg kg^{-1}).

Available Fe

It was observed that increasing levels of Zn significantly decreased the available Fe content in soil by 4%, however, available Fe at S1 (17.64 mg kg^{-1}) and S2 (17.61 mg kg^{-1}) were significantly at par (Table 6). The antagonistic effect of Zn on Fe has already been reported by earlier workers (Prasad *et al.*, 2009; Singh *et al.*, 2012; Prasad *et al.*, 2012). Increasing levels of crop residue incorporation significantly increased the available Fe content in soil and this increase was more pronounced at the highest level, i.e. T4 by 19%.

This increase in available Fe may be due to solubilization of native Fe by organic acids produced from crop residue. The interaction effect was also found significant which indicated that at zero level of crop residue, the decrease in the available Fe was sharp due to Zn application. Similarly, at zero level of Zn application, the increase in available Fe was more marked with increasing levels of crop residue.

Available Cu

The available Cu content in post-harvest soil (36^{th} crop) due to different treatment combinations of residual effect of starter Zn and crop residues varied from 3.09 to 3.73 mg kg^{-1} (Table 6). Residual effect of starter Zn reduced the available Cu content by 3%, which might be due to ionic competition with Zn. Similar observation was also recorded by Sakal *et al.*, (1996). Increasing levels of crop residue enhanced the available Cu by 18%, which might be due to addition of Cu through crop residues. Buildup of OC in soil increased the availability of Cu due to chelation properties of organic matter. The interaction effect was also found significant. This suggested that different levels of crop residues react differently at different levels of Zn and vice-versa. There was more buildup of available Cu in absence of Zn application. The reduction in available Cu was more due to Zn application at higher level of crop residue incorporation. Such result was due to the fact that at higher crop residue level the buildup of Zn was also more resulting in increased competition between Cu and Zn. The antagonistic effect of Zn on Cu has also been reported by Sakal *et al.*, (1985); Prasad *et al.*, (2009) and Sharma *et al.*, (2013).

Available Mn

The effect of Zn and crop residue on available Mn content of post-harvest soil (after 36^{th} crop) was very much similar to those on Fe and Cu (Table 6). Increasing levels of crop residue incorporation significantly increased the available Mn (13%), while Zn application decreased the available Mn (1%). The overall variation in available Mn in soil ranged from

4.29 to 4.91 mg kg^{-1}. The depressing effect of Zn on the availability of Mn has also been reported by Sharma and Bapat (2000). The interaction effect was found significant, which suggested that different levels of crop residues react differently at different levels of Zn. Singh *et al.,* (2012) also reported significant effect on micronutrient status in soil after combined use of NPK and Zn with organic manure and it enhances the nutrient uptake by crops. Crop residues incorporation can improve micronutrients availability.

In conclusion, our results after super-imposing of treatments on a 18-year rice–wheat rotation trial reported in this paper demonstrate significant effects of crop residues incorporation and Zn application on soil macro-nutrients, micro-nutrients, their availability, soil chemical productivities and crop productivity. Maximum rice and wheat yields were obtained at 100% crop residues incorporation along with 10 kg residual application of starter Zn ha^{-1}. The increased yields of rice and wheat were also attributed to higher micronutrients uptake at higher levels of residue incorporation and Zn application. The crop residue incorporation also enhanced the soil health by soil chemical properties as pH and organic carbon and Zn addition further improved the availability of both macronutrients (NPK) and micronutrient, Zn. But with increased levels of Zn application, the Fe, Cu and Mn availability decreased in the soil. The crop residues incorporation can augment micronutrient availability in the calcareous soils. Our results highlight the research need to understand the mechanisms and availability of macro- and micronutrients under different crop residue incorporation levels and micronutrient application in rice-wheat cropping system, which is crucial for developing innovative nutrient application technologies and associated agronomy for higher yield potential.

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