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Significance of manganese fertilization in wheat-based cropping systems of Indo-Gangetic Plain (IGP)

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ABSTRACT

Manganese (Mn) is an essential micronutrient, having critical role in plant nutrition. The Mn is component of several enzymes involved in photosynthesis and other physiological processes. The intensive cultivation of rice-wheat (RW) followed since long times, along with induction of rice in non-rice growing areas, especially in north-western Indo Gangetic Plain (NW-IGP) had led to emergence of Mn deficiency, particularly in wheat crops in RW rotation. Higher leaching losses of soil Mn under submerged rice induces Mn deficiency in the subsequent wheat crops. This paper critically assesses the literature on role of Mn on crop growth, distribution of soil Mn and its dynamics, effect of different soil characteristics on soil Mn availability under different cropping systems prevalent in IGP. Soil ionic composition, moisture status, organic matter status, soil pH, cation exchange capacity are some of the soil parameters dictating Mn dynamics in soil. Higher availability of soil Mn was reported under acidic condition, which decreased with increase in soil pH. Literature suggests positive effects of nitrate and phosphates on soil Mn dynamics and crop yields, whereas bicarbonate and chloride application have negative effects. Plant available Mn or DTPA-Mn varied under different cropping systems showing lower availability under RW system. Fractionation studies showed that labile pools of Mn contribute very less towards total soil Mn, leaving large proportion of soil Mn non-labile in nature, thus unavailable for plant uptake. The release of Mn from soil adsorption sites varied under different cropping systems, modifying Mn supply capacity of soil. Maximum release of Mn was found under frequently irrigated sugarcane-sugarcane cropping system. Such information are essentially required for developing efficient Mn fertilization scheduling to improve the yield and quality of crops in IGPs.

Key words: Mn fractions, Mn release behaviour, Uptake, Wheat-based cropping system

In late 1960s, green revolution occurred in India and helped us to achieve self-sufficiency in food-grain production. The impact of these was majorly felt through the rice-wheat (RW) cropping system of Indo-Gangetic plains (IGP). The IGP occupies nearly 15% of the total geographical area of the country and is known as the ‘food basket’ of the country. The IGP is highly fertile and contributes 50% of the country’s total food grain production (Pal *et al.* 2009). These plains support double and triple cropping with rice (*Oryza sativa)*-wheat (*Triticum aestivum* L.) (RW) being the most important and predominant cropping system. Fifty three percent of IGP lands are under RW in current scenario (Panigrahy *et al.* 2010). Enhancing fertility of IGP soils is considered to be the most effective mean of ensuring national food security. The availability of micronutrients in IGP soils governed by 2 important aspects *i.e.*, variation in agro-climatic and soil physico-chemical properties. However in recent years, following an intensive RW cultivation in a system mode for more than 4 decades has led to several second generation problems; multi-nutrient or more specifically emerging micronutrient deficiency being most critical. The reasons for these micronutrient depletion can be summarised as follows: continuous mono-cropping, intensive cultivation, high nutrient mining, high yielding varieties, increased use of high-analysis macro-nutrient fertilizers without external addition of micronutrients (Dwivedi *et al.* 2012). Extension of rice cultivation in coarse textured and alkaline non-conventional soils of IGP is a major cause of emerging widespread deficiency of micronutrient, particularly, Mn in wheat crop which is aggravating at an alarming rate (Singh *et al.* 2012; Shukla *et al.* 2018). The Mn deficiency leads to not only hidden hunger but also crop-failure and lower content of micronutrient elements in plant edible parts, often associated with significant yield reductions (Meena *et al.* 2008). Although Mn requirement of plants are generally low, but with the increasing use of high analysis micronutrient-free fertilizers, Mn deficiency is likely to be intensified particularly in light textured soils and is going

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to be a major constraint in realising yield potential of high yielding varieties of wheat (Nayyar *et al.* 1990). The Mn deficient soils are usually impoverished siliceous and calcareous sandy soils of neutral or alkaline pH that favour chemical and microbial oxidation and immobilization of plant available Mn^{2+}. Even these soils, however, contain large reserves of total Mn relative to the amounts removed by crop harvests. Therefore, resulting Mn deficiency of susceptible crops is due to insufficient availability of soil Mn to plants rather than an absolute shortage of soil Mn (Rengel 2015).

Understanding the distribution of soil Mn in different pools of varying liability, and the causal factors which affect their dynamics is of utmost importance to assess the bio-availability of soil Mn towards plant adsorption (Shuman 1979). Leaching losses of Mn are generally high in light textured soils, due to higher solubility of its common salts. Therefore, the movement of Mn in the soil water determines the magnitude of its losses through leaching, run-off and percolation. The distribution of Mn in soil profile is closely related to the composition of parent materials and soil-forming processes. Systematic information regarding profile distribution of Mn and its forms under different cropping systems in major soils of India is scant. In this article, an attempt has been made to understand the dynamics of Mn, its distribution in different pools and their bio-availability under different wheat-based cropping systems.

Role of Mn in plant nutrition

Manganese is one of the main essential micronutrients contributing immensely towards plant growth, nutrition and production, both in terms of quality and quantity of produce. It plays a key role in several physiological processes, particularly photosynthesis as the photosystem II-water oxidizing system has an absolute Mn requirement (Hakala *et al.* 2006). The Mn facilitates the photolysis (light splitting) of water molecules and provides energy for photosynthesis. It is, therefore, not surprising that Mn deficiency substantially impairs photosynthesis, even in the absence of visual leaf symptoms. The negative effect of Mn deficiency in photosynthesis results in marked decreases in soluble sugar concentrations in different parts of plants. It is widely believed that the reduction in photosynthesis is the major reason behind the decline in dry matter production and yield under Mn-deficient conditions. Manganese application contributes to the resistance against not only various soil-borne diseases including take-all in wheat, common scab in potato and root rot in cotton, but also fungal leaf diseases such as tan spot in wheat, powdery mildew in grape and black leaf mold in tomato (Brennan 1992). As a cofactor, Mn is reported to activate over 35 enzymes, several of which catalyze different steps of the lignin and phytoalexins biosynthesis. Impairment of lignin biosynthesis in Mn-deficient plants, especially in the roots, is associated with increased pathogenic attack, particularly soil-born fungi, because lignin serves as a barrier against pathogenic infection (Marschner 2012). The peroxidase enzyme, which generates hydrogen peroxide, is another Mn-dependent enzyme that contributes to pathogen resistance. The hydrogen peroxide produced is not only involved in the stabilization of the cell wall, but is also thought to be directly toxic to pathogens (Heine *et al.* 2011), and therefore acts as a fungicide (Graham and Webb 1991).

Manganese has a relatively low phloem mobility in plants, and as a result, typical leaf symptoms of Mn deficiency first develop in younger leaves. The critical concentration for Mn deficiency is generally below 20 mg/kg of dry weight in fully expanded, young leaves. In the case of dicots, Mn deficiency first results in pale mottled leaves, followed by typical interveinal chlorosis. Under severe Mn deficiency dicots may also develop a number of brownish spots. In cereals, Mn deficiency can cause pale green or yellow patches in younger leaves. The impact of Mn deficiencies on crops includes reduced dry matter production and yield, weaker structural resistance against pathogens and a reduced tolerance to drought and heat stress.

DTPA-extractable Mn in soil under different cropping systems

Manganese is the eleventh most common element making up about 0.085% of the Earth's crust. It is broadly dispersed throughout soils, sediments, water and biological materials. The total Mn content of surface soils of India varies considerably from 20 to 3000 mg/kg and 900 mg/kg on an average (Barber 1995). On the contrary, the available Mn in the surface soils of India has been reported from 0.60 to 164 mg/kg soil with an overall deficiency of 5.6%. (Shukla *et al.* 2018). Rattan *et al.* (1999) reported that the intensification of agriculture characterized by raising of more crops per unit time and space involving heavy dependence of high analysis fertilizers has progressively depleted the soils of their available micronutrients content in surface as well as subsurface layers. Continuous intensive RW cultivation lead to formation of sub-surface hard pan in Haryana, in turn reducing DTPA-extractable Mn (Balloli *et al.* 2000). Chibba *et al.* (2007) reported higher abundance of DTPA-extractable Mn under RW as compared to cotton-wheat cropping system in soils of Bhatinda, Punjab. Similarly, Narender *et al.* (2016) studied distribution of Mn among various cropping system in Haryana and revealed that DTPA- Mn was found highest in cotton-wheat cropping systems followed by sugarcane-sugarcane > pearl millet-wheat > pearl-millet-mustard > fallow-mustard > rice-wheat (Fig 1). The content of DTPA- Mn varied between 6.90 to 11.7 mg/kg in the surface soil layer of all the cropping systems. The DTPA-extractable Mn decreased sharply with increasing soil depth irrespective of cropping systems or soil types. Lu *et al.* (2004) reported downward leaching of soil Mn in a continuous RW system in coarse textured soils of China. The continuous flooding of the soil increased the availability of Mn due to submergence and a decrease in redox potential. However, the concentrations of DTPA-extractable and total Mn increased with depth under flooding condition (Table 1).

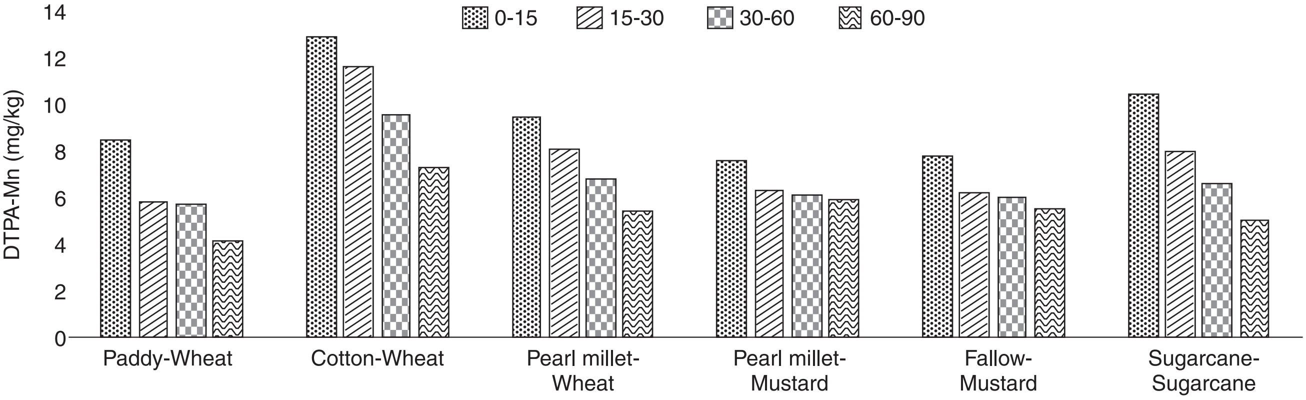

Fig 1 Depth-wise distribution of DTPA-Mn in soils under different cropping systems

Factors affecting Mn availability

In soils, Mn occurs in various forms and its availability is influenced by soil pH, organic carbon content and abundance of absorptive surfaces like $CaCO_3$, clay content, and other physical, chemical and biological conditions of the rhizosphere (Yadav and Meena 2009; Malik *et al.* 2017). The availability of Mn is less available in alkaline soil as their ions are increasingly adsorbed on soil particles with increasing soil pH (Taiz and Zeiger 2002). In acidic soil pH, there is relative abundance of Mn. As the pH is raised, their solubility/availability to plants decreases because ionic Mn precipitates as hydroxides or oxides of Mn. Manganese has three possible oxidation states in the soil: 2+, 3+ and 4+. Its most reduced form, Mn^{2+}, is the only stable form in the soil solution. Both Mn^{3+} and Mn^{4+} are stable only in the solid phase of soils, where they form insoluble oxide and hydroxide minerals of variable structure. Manganese solubility is controlled by the redox potential (Eh) and pH of the soil. A low pH or low Eh favours the reduction of insoluble manganese oxides and increases the solubility of Mn^{2+}. The Mn^{2+} ion is released from solids by spontaneous dissolution or cation exchange, especially under acidic or reducing conditions. Even small changes in the soil redox potential or pH can shift the Mn^{2+} to Mn oxide reaction. As a result, Mn solubility within any particular soil can fluctuate markedly over time, sometimes ranging from deficient to toxic levels (Pearson *et al.* 2005, Wang *et al.* 2008). The mobility of Mn defies classification because it is extremely sensitive to the soil condition *viz*., acidity, wetness, biological activity, *etc*. The Mn toxicity is of relatively less occurrence but, can be observed in waterlogged soil for some sensitive plant species (McBride 1994).

Table 1 Differences in depth-wise distribution of soil Mn between rice-wheat and non-rice-wheat systems

Site	Soil depth (cm)	DTPA-Mn (mg/kg)		
		R-W[a]	Non R-W	S
1[b]	0-20	3.30	7.70	*
	20-40	6.80	6.20	NS
	40-60	11.1	6.10	*
2	0-20	6.00	50.9	**
	20-40	30.7	39.6	NS
	40-60	11.6	20.4	*
3	0-20	16.3	5.20	*
	20-40	20.2	3.80	**
	40-60	13.6	3.80	*
4	0-20	1.20	7.80	*
	20-40	3.80	6.60	NS
	40-60	17.8	7.80	*
5	0-20	6.10	21.0	**
	20-40	5.60	16.2	*
	40-60	22.3	16.9	NS

[a]R-W, Non R-W, upland cropping system without rice S, rice-wheat rotation, the difference significance. * and ** represents significant at $P<0.05$ and $P<0.01$, respectively. NS represents non-significant

There was significant negative correlation between DTPA-Mn with clay (r= -0.51), CEC (r= -0.63) and organic carbon (r= -0.64) (Ibrahim *et al.* 2011). The parent material and soil forming processes also determines Mn content of the soil. As minerals break down during soil formation, Mn is gradually released in a form that is available to plants. Abundance of anions *viz*. NO_3^-, PO_4^{3-}, HCO_3^- and Cl^- were also reported to affect Mn nutrition through various mechanisms in soil, on the root surface, and in the plant system (Narender and Malik 2016). As such deficiency or sufficiency of Mn may not be an expression of the amount of Mn in soluble form but also of ionic species and their strength in soil solution.

Interactive effect of Mn and anion concentration in soil on Mn uptake and yield of wheat

In most parts of the world, unbalanced use of fertilizers prevails, and are not based on plants requirement. These unbalanced fertilizer application often hamper crop yield, apart from compromising soil health. Balanced application of Mn fertilizer significantly increased grain/straw yields of wheat in several cases (Malakauti and Ziaeian 2002). Narender and Malik (2015) studied the effect of phosphate and bicarbonate on applied Mn fertilizers in Haryana and its ultimate bearing on grain yield of wheat. They reported

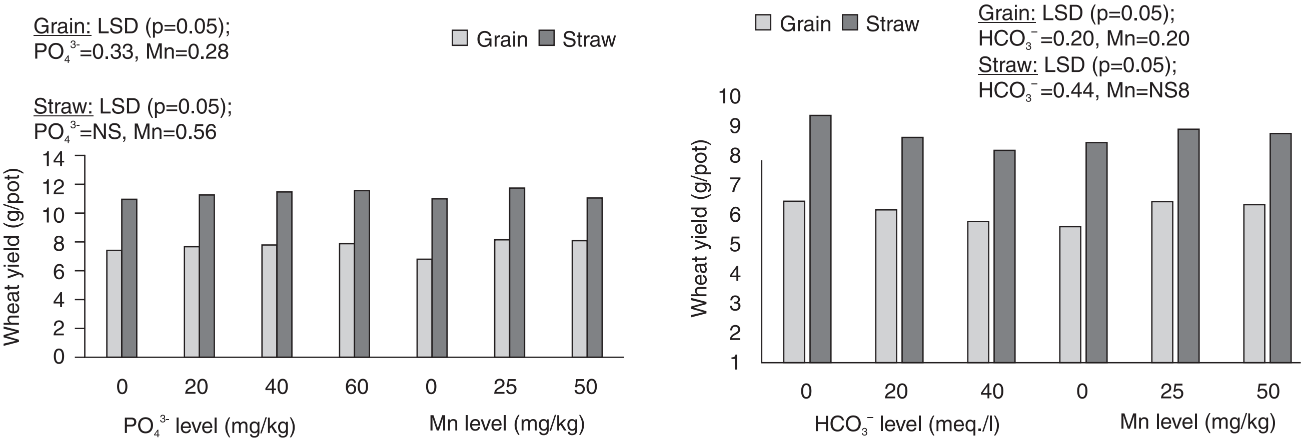

Fig 2 Effects of phosphate and bicarbonate ions on yield increments of wheat due to Mn application

a significant increase in grain yield with phosphate under Mn application whereas it significantly decreased when bicarbonate salts are applied in higher doses. The highest yields of wheat were recorded with 60 mg PO_4^{3-} /kg with 25 mg Mn/kg and no addition of HCO_3^- (Fig 2). Similarly, Abbas *et al.* (2011) evaluated yield response of wheat to five different levels (0, 4, 8, 12 and 16 kg/ha) of Mn along with 150-100-60 kg NPK/ha application. Average of two years results showed a positive and significant response of wheat to Mn application. The highest grain yield of 4.59 t/ha was achieved with application of 16 kg Mn/ha along with NPK against 3.96 t/ha from NPK alone (Table 2). Munns and James (2003) and Thomson *et al.* (2001) reported a negative response of wheat crop performance to HCO_3^- and Cl^- application.

The Mn uptake by plants are positively correlated with soil Mn application, and often augmented by application of organic manures (Habashy *et al.* 2008; Karimian *et al.* 2012). The long-term effect of manure and fertilizer on soil fertility status under sorghum-wheat cropping system was studied by Sonune *et al.* (2003) in a semi-arid climate conditions of Vidharbha, Maharashtra. The results indicated that application of recommended dose of nitrate, phosphate, potash and FYM in soil increased the soil available Mn compared with control. Application of organic compost as well as AM + organic compost reported to increase Mn concentrations in plants in a calcareous soil (Habashy *et al.* 2008). Jhanji *et al.* (2014) studied Mn utilisation efficiency of six wheat cultivars during various developmental stages at two Mn levels *i.e.* 0 and 50 mg Mn/kg in pots. Irrespective of cultivars and development stage, both biomass accumulation and Mn concentration was higher under high Mn doses. Higher Mn utilization efficiency was reported under higher Mn doses in case of efficient genotypes (Table 3).

In another experiment, Narender and Malik (2016) observed higher Mn uptake by wheat cultivar WH 1105 with higher level of NO_3^- application along with Mn fertilizer application. The maximum uptake of Mn by wheat crop was recorded at 90 mg NO_3^-/kg application. All the levels of NO_3^- with Mn proved significantly superior over control in respect of Mn uptake by wheat. However, Mn uptake by wheat decreased significantly with each increment in the level of bicarbonate and increased significantly with increasing level of Mn application. The maximum Mn uptake

Table 2 Effect of Mn fertilization on grain and straw yield of wheat

Treatments Mn (kg/ha)	Straw yield (Mg/ha)			
	2005-06	2006-07	2005-06	2006-07
Control (0)	4.05b*	3.88^{d}	5.66^{b}	5.68^{b}
4	4.22^{b}	4.17^{c}	5.97^{ab}	5.98^{ab}
8	4.47^{a}	4.33^{bc}	6.17^{a}	5.97^{ab}
12	4.53^{a}	4.58^{ab}	6.07^{a}	6.13^{a}
16	4.55^{a}	4.62^{a}	6.13^{a}	6.10^{a}

*Means followed by same letter do not differ significantly at P≤0.05.

Table 3 Manganese in wheat cultivars as affected by Mn application

Wheat cultivar	Mn levels (mg/kg)	Mn uptake (mmol/plant)	
		Tillering	Anthesis
PBW 550	0	15.6	112
	50	838	963
BW 9178	0	23.0	107
	50	475	898
HD 2967	0	29.7	146
	50	219	887
PBW 636	0	55.7	81.3
	50	274	1000
PDW 291	0	25.4	34.0
	50	223	644
PDW 314	0	13.3	19.1
	50	412	683
LSD (P≤0.05)	Treatment	15.6	20.8
	Cultivars	27.0	36.0
	Interaction	38.2	50.9

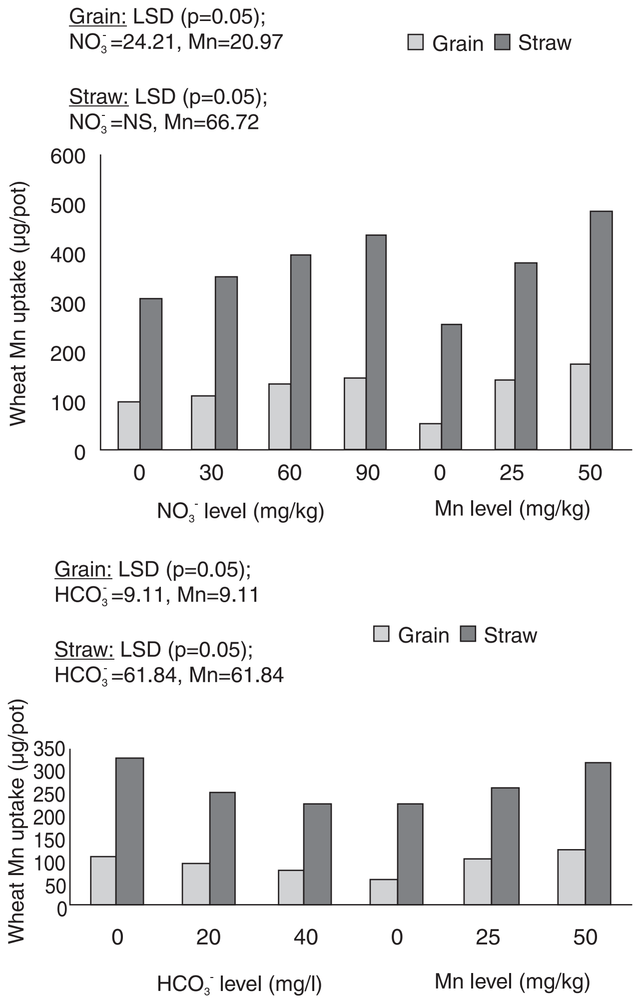

Fig 3 Effects of nitrate and bicarbonate ions on Mn uptake by wheat

by wheat crop was recorded at 50 mg Mn/kg without any addition of bicarbonate application (Fig 3). These result indicated that salinity can restrict Mn uptake by wheat roots and consequently lower their concentration in grain and straw. In general, addition of Mn to soil registered a higher Mn concentrations in plant tissues (Shankar *et al.* 2014) and application of organic manures in conjunction with phosphate fertilizer significantly improved the availability of Mn in soil *vis-à-vis* plant Mn content (Karimian *et al.* 2012).

Distribution of soil Mn into different pools

Understanding the distribution mechanism of soil Mn in different pools aids us to know its retention in soils and further release for plant uptake (Shuman 1979). There are different fractions of soil Mn with varying lability, *viz.* exchangeable (EX), carbonate bound (CARB), organic matter bound (OM), Mn oxide bound (MnOX), amorphous Fe oxide bound (AFeOX), crystalline Fe oxide bound (CFeOX) and residual fraction (RES) (Tessier *et al.* 1979). Among all these pools, Narender and Malik (2016) reported highest concentration of Mn was associated with RES followed by MnOX > AFeOX > CFeOX > EX > CARB > OM (Fig 4). All pools of soil Mn increased significantly with the increasing level of Mn. Application of nitrate and phosphates in higher doses favoured higher concentration of soil Mn in all pools. On the contrary, application of bi-carbonates and chlorides had a negative impact on soil Mn pools (Narender and Malik, 2015). Knowledge of different soil Mn pools, their lability is pre-requisite in assessing their availability to plants. This in turn determines Mn uptake by field crops. The alternate flooding (reduced stage) in rice and upland (oxidized stage) conditions in wheat effects transformation of Mn (Manchanda *et al.* 2006).

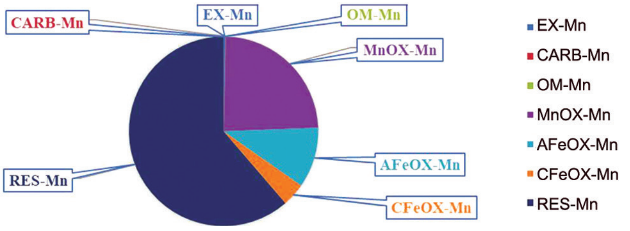

Fig 4 Distribution of soil Mn into different pools

Narender *et al.* (2016) studied distribution of soil Mn in different pools under different cropping systems (Table 4). The results revealed that EX-Mn fraction constituted approximately 0.74% of the total soil Mn. The CARB-Mn and OM bound-Mn accounted for 0.26% and 0.03% of total soil Mn, respectively. Manganese in MnOX fraction was quite high (81.50 mg/kg) whereas AFeOX-Mn and CFeOX-Mn was 44.51 mg/kg and 17.68 mg/kg soil, respectively. Manganese was found highest in residual fraction (206.1 mg/kg) which constituted 58.08% of total soil Mn. Oxide-Mn is readily reduced to available forms and is an important source of Mn for plants (Behera and Singh, 2009).

Narender *et al.* (2016) studied correlation coefficient (r) between Mn fractions and physico-chemical properties in different cropping system and observed that DTPA-Mn was negatively correlated with pH and calcium carbonate ($CaCO_3$) whereas, a positive correlation existed with clay. The EX-Mn and CARB-Mn were only significantly and positively correlated with sand whereas it was negatively correlated with silt and clay. The OM-Mn was significantly and positively correlated with organic carbon and negatively correlated with calcium carbonate (Table 5). The oxide-bound fractions showed a significant and positive correlation with organic carbon and clay whereas they were negatively correlated with pH, calcium carbonate and sand suggesting presence of minor amounts of oxide minerals in silt and clay fraction but absent in sand fraction. Residual fraction showed a significantly positive correlation with calcium carbonate and sand. Total Mn was found significant and positively correlated with organic carbon, silt and clay whereas negatively correlated with sand.

Soil Mn release under different cropping systems

The magnitude of release of soil Mn is govererned by many factors, *i.e.* type and amount of clay, Mn status, alternate wetting and drying cycles, pH, moisture content *etc*. Gotoh and Patrick (1972) studied availability of Mn in

Table 4 Total soil Mn and pools of Mn expressed as amount extracted and percentage of total Mn under different cropping systems

Cropping system	Total-Mn (mg/kg)	EX-Mn		CARB-Mn		OM-Mn		MnOX-Mn		AFeOX-Mn		CFeOX-Mn		RES-Mn	
		(mg/kg)	(%)^y	(mg/kg)	(%)^y	(mg/kg)	(%)^y	(mg/kg)	(%)^y	(mg/kg)	(%)^y	(mg/kg)	(%)^y	(mg/kg)	(%)^y
Rice-Wheat	334	2.67	0.79	1.11	0.33	0.07	0.02	84.6	25.2	49.0	14.6	29.9	8.95	167	49.9
Cotton-Wheat	366	3.19	0.87	0.94	0.25	0.09	0.02	87.2	23.8	47.4	12.9	24.9	6.80	202	55.2
Pearl millet-Wheat	356	2.51	0.70	1.05	0.29	0.16	0.04	61.3	17.2	41.0	11.4	15.4	4.33	235	65.9
Pearl millet-Mustard	369	3.17	0.85	1.14	0.30	0.11	0.02	66.1	17.8	35.8	9.69	6.59	1.78	256	69.4
Follow-Mustard	356	2.28	0.63	0.74	0.20	0.07	0.01	88.1	24.7	42.3	11.8	11.7	3.28	211	59.2
Sugarcane-Sugarcane	337	2.00	0.59	0.56	0.16	0.14	0.04	101	30.0	51.3	15.2	17.4	5.16	164	48.6
Mean	353	2.63	0.74	0.92	0.26	0.10	0.03	81.5	23.1	44.5	12.6	17.6	5.05	206	58.0

^{y}Expressed as percentage of total

water logged soil over a wide range of closely controlled potential and pH conditions. They found that at pH 5 almost all of the soil Mn was converted from reducible into water-soluble plus exchangeable. Similarly, according to Hassan (1990), the solubility of Mn was controlled by MnO_2 at the beginning of the flooding period, whereas $MnCO_3$ (rhodochrosite) controlled this solubility up to 15 weeks. The release behaviour of Mn under different cropping systems were studied by Narender *et al* (2017). The release of adsorbed Mn increased after initiation of incubation, and reached maxima after 10 days (Fig 5). After attaining the maxima, the level of DTPA extractable Mn sharply fell down with time, attaining a stable value after some time. This stable value of DTPA-Mn signified attainment of an equilibrium between the plant available Mn and the adsorbed Mn on different soil components viz. oxides, carbonates, organic matter, clay particles *etc*. The results revealed continuous release of soil adsorbed Mn upto 50 days in cotton-wheat and sugarcane-sugarcane cropping system, after which an equilibrium was reached and DTPA-Mn was stable thereafter. In RW system, the Mn release stabilised after 40 days, whereas under pearl millet-wheat, pearl millet-mustard and fallow-mustard cropping system, the period was only for 10 days after initiation of the incubation (Figure 5). Frequent irrigation regimes under cotton-wheat and sugarcane-sugarcane cropping system, caused a drop in soil Eh, further promoting solubilisation of adsorbed soil Mn. These explains the late attainment of equilibrium between adsorbed Mn and plant available Mn. On the other hand, the above said equilibrium was attained in less duration under pearl millet-wheat, pearl millet-mustard and fallow-mustard cropping systems, where the irrigation regimes are less frequent.

Green *et al.* (2003) indicated that once the critical Eh needed for dissolution of Mn is reached, time becomes the limiting factor that determines soluble Mn concentrations. Manganese is both weakly sorbed and is unstable under reducing conditions and at pH levels below 7.1. The Mn^{2+} can be precipitated as a carbonate species in locations where pH was 7.1 or higher (Willow and Cohen 2003). The solubility of Mn oxide is a major determining factor regarding Mn release in soils. The Mn in highly contaminated soils was also associated with fractions more easily dissolved than oxides, such as sulfides of Mn^{2+} (Da Silva *et al.* 2002). Ghasemi-Fasaei *et al.* (2012) reported significant positive correlation between Mn adsorption and soil clay content, organic carbon and cation exchange capacity, indicating the major role of soil clay particles and organic matter in Mn adsorption.

Hence it can be concluded that nitrate has a positive effect on soil Mn, crop Mn uptake, and ultimately on crop productivity. On the contrary, bi-carbonates and chlorides portray an antagonistic relation with these plant and soil parameters, resulting in acute Mn deficiency in saline, saline-alkali soils. These saline-sodic anions tend to increase root osmotic pressure, prohibiting Mn uptake by plant roots. Maximum amount of soil Mn is present as residual Mn

Table 5 Correlation coefficient (r) between Mn fractions and soil physico-chemical properties in different cropping systems

	pH	EC	OC	$CaCO_3$	Sand	Silt	Clay
			All cropping system				
DTPA-Mn	-0.583*	0.111	0.127	-0.630*	-0.177	0.112	0.300*
EX	-0.069	-0.127	0.166	0.170	0.496*	-0.489*	-0.473*
CARB	-0.101	-0.220	0.209	0.430*	0.462*	-0.464*	-0.546*
OM	-0.034	-0.236	0.337*	-0.289*	-0.232	0.248	0.162
MnOX	-0.414*	0.240	0.643*	-0.582*	-0.538*	0.424*	0.737*
AFeOX	-0.489*	-0.133	0.642*	-0.682*	-0.899*	0.838*	0.954*
CFeOX	-0.663*	-0.249	0.952*	-0.635*	-0.731*	0.737*	0.656*
RES	0.230	0.115	-0.645*	0.561*	0.850*	-0.798*	-0.893*
Total	0.043	0.248	0.544*	0.175	-0.812*	0.827*	0.739*

*Significant at the $P \leq 0.05$, respectively

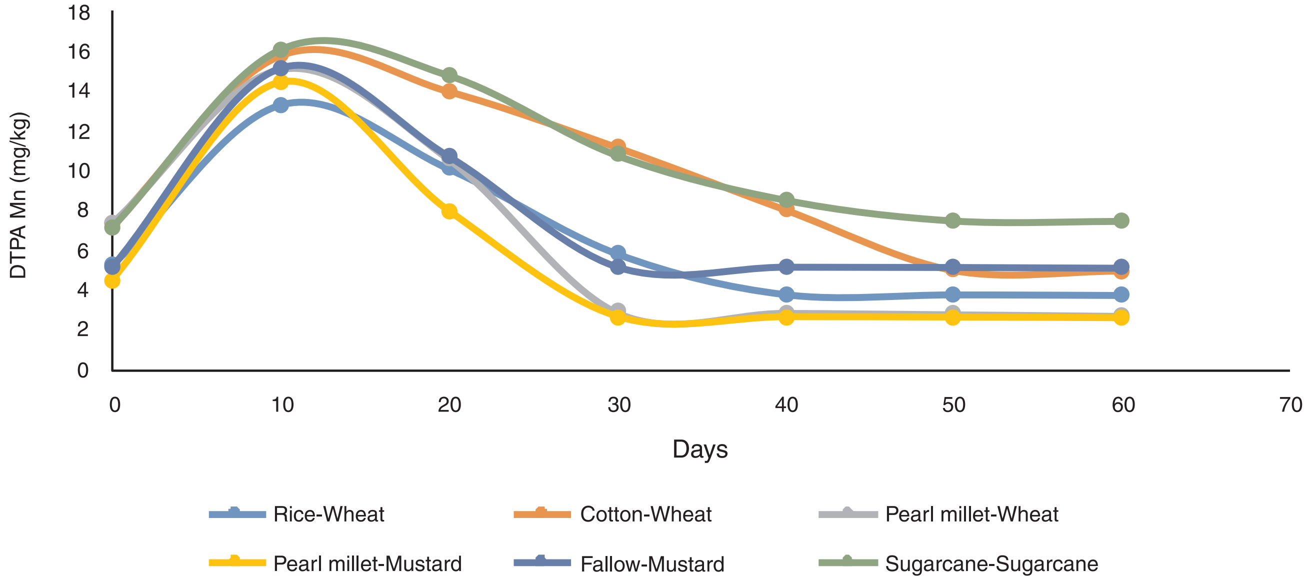

Fig 5 Release behaviour of soil adsorbed Mn under different cropping systems

followed by MnOX, AFeOX, CFeOX, EX, CARB and OM bound Mn, respectively. This distribution may be ascribed to the nature of parent materials, climatic conditions and susceptibility of Mn to change from oxidized to reduced sates and *vice versa*. Total Mn in soils is not a very good indicator of Mn phytoavailability. Therefore, DTPA extractable-Mn is normally used as the indicator of amount available for plant uptake. Readily soluble Mn includes that in solution and the easily exchangeable fraction. This fraction is an important source of Mn to plants but, at the same time, its content in soils is known to vary by orders of magnitude within short periods of time and so its level at any particular time may not be well related to plant Mn uptake. Adsorbed forms of soil Mn are held on soil surface by forces ranging from weak electrostatic to strong ligand-exchange bonds and, although not principal forms of soil Mn, they influence plant availability as they are in pseudo-equilibrium with the readily soluble form. Carbonate-bound Mn includes that chemisorbed or co-precipitated with calcite and related carbonate minerals. Plant available Mn is reduced by adsorption or precipitation with carbonates. Oxide-Mn (*i.e.* MnOX, AFeOX and CFeOX) is readily reduced to available forms and is an important source of Mn for plants. The non-labile pools acts as a reservoir of soil Mn and provides Mn for plant uptake in the long-run especially in frequently irrigated crops *i.e.*, rice, wheat, sugarcane *etc*. Thus, instead of Mn application to arid soils, amending the soils for alkalinity/salinity can correct Mn deficiency of these soils.

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