Maize Journal (April 2025) 14(1): 47-53

RESEARCH PAPER

Influence of phosphorus and iron interaction on iron fractions in heavy and light textured soils

Vishal Ahlawat[1] • P. S. Sangwan[2] • R. S. Dadarwal[3] • Deepika Dhanda[4]

Abstract In both light and heavy textured soils, exchangeable-Fe significantly decreased with increasing phosphorus (P) application, compared to the control and at each successive P level. The exchangeable-Fe was the lowest among the inorganic Fe fractions, constituting only about 0.02% of the total Fe extracted, regardless of soil texture. Carbonate-Fe significantly increased with higher P application levels, both over control and at each successive rate. Regarding iron (Fe) application, the carbonate-Fe fraction also increased significantly with higher soil-applied Fe, while foliar Fe application had no significant impact on carbonate-Fe. This fraction accounted for approximately 0.02% of total Fe. The Fe-Mn oxide fraction significantly increased with increasing P application in both soil textures, averaging 2.6% of total Fe extracted. Organic matter-bound Fe (OM-Fe) decreased significantly with higher P levels, averaging 1.25% of total Fe, irrespective of soil texture. There was no significant effect of P and Fe application on residual-Fe, which accounted for 2.7% of total Fe extracted. Overall, the study highlights a negative interaction between phosphorus and iron. These findings are useful for developing balanced fertilization strategies, particularly in crops sensitive to iron deficiency, as they suggest that excessive P application may reduce Fe availability and efficiency.

Keywords: Exchangeable-Fe • carbonate-Fe • Fe-Mn oxide • OM-Fe • residual-Fe • P × Fe interaction

✉ Vishal Ahlawat: vahlawat@hau.ac.in

[1,2]Department of Soil Science, [3]Department of Agronomy, [4]Department of Environmental Science, CCS Haryana Agricultural University, Hisar-125004, Haryana, India

Received: 29 November 2024/ Accepted: 10 March 2025

Introduction

Maize (*Zea mays* L.) is a key cereal crop, widely grown for human food, animal feed, and industrial uses. In developing countries, 50-55% of maize production is consumed as food. Maize has high production potential, especially under irrigated conditions. However, its productivity depends heavily on nutrient management, particularly micronutrients like iron (Fe), which is essential for preventing chlorosis and maintaining yield and quality. While soils may contain total iron, plant-available iron can be limited due to soil factors like temperature, humidity, aeration, compaction, pH, and the presence of HCO_3^- and $CaCO_3$. Iron deficiency in Indian soils ranges from 1-35% (mean 12%), and in Haryana, 19% of the geographical area shows deficiency.

In soils, iron occurs in primary minerals as ferromagnesian compounds, and during weathering, it precipitates as ferric oxide and hydroxide (Hodgson, 1963). $Fe^{2}+$ is less strongly held by soil surfaces than Co, Cu, and Zn. When oxidized, these elements form insoluble oxides and phosphates, reducing availability to plants and leaching. In well-oxidized soils, Fe solubility is controlled by $Fe(OH)_3$, by Fe_3 $(OH)_3$ in moderately oxidized soils, and by $FeCO_3$ in highly reduced soils (Lindsay and Schwab, 1982). The Fe^{3+} hydrolysis species Fe $(OH)^{2+}$ and Fe $(OH)^3$ are the major solution species of inorganic Fe, but they are maintained at too low levels to supply available Fe to plants. The dissolution and precipitation of ferric oxides is the major factor controlling the solubility of Fe in well aerated soils.

Materials and methods

Bulk surface soil samples (0-15 cm) were collected from light-textured soil in Balsamand village, Hisar district, and heavy-textured soil in Lalauda village, Fatehabad district, for experiments in screen house and laboratory conditions. The soils were air-dried, ground, passed through a 2 mm sieve, and thoroughly mixed. These processed samples were then used for laboratory and screen house studies. Table 1 presents relevant physico-chemical properties, macro- and micronutrient status, and the analytical methods employed.

To study the interactive effects of phosphorus (P) and iron (Fe) on maize, a screen house experiment at Department of Soil Science, CCS Haryana Agricultural University, Hisar was conducted with various treatments. Processed soil was placed in 5 kg plastic pots in 3 replications, arranged randomly, and filled with 4 kg of mixed, air-dried soil. Plastic pots were used to prevent leaching and metal interaction with surfaces. The soil was spiked with P using potassium dihydrogen phosphate (KH_2PO_4) and with Fe using Iron (II) sulfate heptahydrate ($FeSO_4{\cdot}7H_2O$). Phosphorus was applied at rates of 40, 60, and 80 kg ha^{-1}, corresponding to 20, 30, and 40 mg kg^{-1}, respectively. Iron was applied at rates of 10 and 20 kg ha^{-1}, equivalent to 5 and 10 mg kg^{-1}, respectively. Additionally, a 1% $FeSO_4$ solution was prepared and sprayed on plants 30 days after sowing (DAS) for a fourth iron treatment.

A basal dose of nitrogen, potassium, and zinc at 150, 62.5, and 25 kg ha^{-1}, respectively, was added using urea, KH_2PO_4, and $ZnSO_4{\cdot}7H_2O$, each at 200 ml per pot. Soil was thoroughly mixed to ensure even distribution of P and Fe. Ten maize seeds were sown per pot, then thinned to four plants per pot on the seventh day, with plants grown up to 45 DAS. Pots were watered with de-ionized water as needed. The crop was harvested at 45 DAS, and plant samples were ground for chemical analysis. Pre- and post-harvest soil samples were collected for Fe fraction analysis as detailed in Table 1.

The experimental data so obtained was statistically analysed by the methods of analysis of variance (ANOVA) as described by Panse and Sukhatme (1985). The significance of treatment effects was computed with the help of 'F' (variance ratio) test and to judge the significance of differences between means of two treatment, critical differences (CD) was worked out as described by Cochran and Cox (1959) and Gomez and Gomez (1983).

Results and discussion

Iron fractions

Exchangeable-Fe

In light textured soil, the exchangeable-Fe content was decreased significantly with increasing level of P application

Table 1. Initial physico-chemical characteristics of experimental soils

Characteristic	Soil type		Method used
	Light textured	Heavy textured	
Textural class	Sandy loam	Clay loam	USDA system of soil classification for textural class
pH (1:2)	7.9	7.5	Jackson (1973)
EC (dS m^{-1})	1.05	0.14	Richard (1954)
Organic carbon (%)	0.18	0.62	Walkley and Black (1934)
Calcium carbonate (%)	0.5	Nil	Puri (1949)
Available N (kg ha^{-1})	78	166	Subbiah and Asija (1956)
Available P (kg ha^{-1})	13	47	Olsen *et al.* (1954)
Available K (kg ha^{-1})	194	249	Jackson (1958)
DTPA- Fe (mg kg^{-1})	4	56	Lindsay and Norvell (1978)
Fe fractions (mg kg^{-1})			
Exchangeable-Fe	2.5	1.2	Tessier *et al.* (1979)
Carbonate-Fe	2.35	2.01	
Fe-Mn oxide	137.7	354.4	
OM-Fe	23.0	266.2	
Residual-Fe	189.5	387.4	
Total-Fe	8315.6	13268.7	

over control as well as at each successive level of P application (Table 2). Whereas, it increased significantly with increasing level of soil application of Fe, but foliar spray of Fe did not influence the exchangeable-Fe content significantly over control treatment. Significant P x Fe interaction was observed for exchangeable-Fe in light textured soil. The highest amount of exchangeable-Fe was observed under P_0Fe_{10} treatment. The exchangeable-Fe was decreased by 8.9, 15.3 and 29.2% with the application of P at 20, 30 and 40 mg P kg^{-1}, respectively over control while, it was increased by 9.4 and 17.3% when Fe was applied at 5 and 10 mg Fe kg^{-1}, respectively over control.

In case of heavy textured soil, exchangeable-Fe was also decreased significantly over control as well as at each successive level with increasing level of P application (Table 2). With increasing level of soil application of Fe, exchangeable-Fe was also increased significantly but 1% foliar spray resulted decrease in its content but statistically insignificant over control. The P x Fe interaction was also found to be significant. The exchangeable-Fe content was decreased by 5.2, 26.2 and 36.6% at 20, 30 and 40 mg P kg^{-1}, respectively over control. Likewise, the magnitude of increase was 6.5 and 8.7% when Fe was applied at 5 and 10 mg Fe kg^{-1}, respectively over control.

It has been observed that the exchangeable-Fe is the least amongst the inorganic Fe fractions extracted and, on an average, constituted only about 0.02% of total-Fe extracted from the soil irrespective of soil texture. These results are in line of those obtained by Yerriswamy *et al.* (1995) in vertisols of Karnataka and they reported that water soluble, Mn-oxide occluded and organically bound Fe decreased, whereas exchangeable, acid soluble, Pb-displaceable, amorphous Fe-oxide occluded and residual Fe increased with depth.

Table 2. Exchangeable-Fe in light and heavy textured soil as influenced by P and Fe application

Nutrient level	Exchangeable-Fe (mg kg^{-1})				Mean
(mg kg^{-1})	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	2.21	2.41	2.56	2.25	2.36
P_{20}	2.07	2.11	2.29	2.13	2.15
P_{30}	1.82	2.06	2.25	1.86	2.00
P_{40}	1.54	1.78	1.84	1.53	1.67
Mean	1.91	2.09	2.24	1.94	-
CD(p=0.05)	P: 0.04; Fe: 0.04; P x Fe: 0.07				-
Heavy textured soil					
P_0	1.65	1.79	1.84	1.59	1.72
P_{20}	1.59	1.67	1.68	1.58	1.63
P_{30}	1.21	1.31	1.35	1.19	1.27
P_{40}	1.08	1.12	1.13	1.04	1.09
Mean	1.38	1.47	1.50	1.35	-
CD (p=0.05)	P: 0.03; Fe: 0.03; P x Fe: 0.05				-

Carbonate-Fe

The carbonate-Fe was increased significantly (2.50 to 3.86 mg kg^{-1}) with increasing level of P application up to its highest level over control (2.16 mg kg^{-1}) and also at each successive level (Table 3). With respect to Fe application, the carbonate-Fe fraction was also found to increase (3.16 to 3.34 mg kg^{-1}) significantly with increasing level of soil application of Fe while foliar spray of Fe did not show any significant influence on carbonate-Fe fraction and found to be at par (2.62 mg kg^{-1}) with respect to control. The interaction between P x Fe was significant. The carbonate-Fe fraction of light textured soil varied between 1.66 and 4.14 mg kg^{-1} with respect to various treatment combinations of P and Fe. As regards to P application, the percent increase in carbonate-Fe fraction was 15.7, 50.0 and 78.7 at 20, 30 and 40 mg P kg^{-1}, respectively over control. The percent increase in carbonate-Fe was 20.6 and 27.5 with respect to Fe application at 5 and 10 mg Fe kg^{-1}, respectively over control.

In heavy textured soil, the carbonate-Fe fraction was also found to increase (1.86 to 2.29 mg kg^{-1}) significantly with increasing level of P application over control (1.75 mg kg^{-1}) and also at each successive level (Table 3).

Similar trend was observed with regard to Fe application, increasing soil application level also increased the carbonate-Fe fraction significantly (2.19 to 2.32 mg kg^{-1}), while 1% foliar spray of Fe was statistically at par (1.72 mg kg^{-1}) with the control treatment (1.69 mg kg^{-1}). Interaction between P x Fe application produced significant effect on carbonate-Fe fraction. The highest value of carbonate-Fe (2.49 mg kg^{-1}) was observed under combined effect of $P_{40}Fe_{10}$ treatment. The magnitude of increase of carbonate-Fe fraction was in the order of 6.3, 16.0 and 30.9% with the application of P at 20, 30 and 40 mg P kg^{-1}, respectively over control. The per cent increase of carbonate-Fe content was 29.6, 37.3

Table 3. Carbonate-Fe in light and heavy textured soil as influenced by P and Fe application

Nutrient level (mg kg^{-1})	Carbonate-Fe (mg kg^{-1})				Mean
	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	1.66	2.48	2.56	1.94	2.16
P_{20}	2.32	2.66	2.78	2.26	2.50
P_{30}	2.92	3.42	3.90	2.72	3.24
P_{40}	3.56	4.12	4.14	3.60	3.86
Mean	2.62	3.16	3.34	2.62	-
CD (p=0.05)	P: 0.12; Fe: 0.12; P x Fe: 0.24				-
Heavy textured soil					
P_0	1.36	2.06	2.23	1.34	1.75
P_{20}	1.54	2.06	2.24	1.59	1.86
P_{30}	1.76	2.20	2.32	1.84	2.03
P_{40}	2.11	2.45	2.49	2.09	2.29
Mean	1.69	2.19	2.32	1.72	-
CD (p=0.05)	P: 0.03; Fe: 0.03; P x Fe: 0.07				-

and 1.8 with the application of Fe at 5, 10 mg Fe kg^{-1} and 1% foliar spray of iron, respectively over control.

It was also observed that on an average carbonate-Fe fraction was found to be more or less at par with the values of exchangeable-Fe extracted from the soil irrespective of soil texture and this fraction also accounted about 0.023% of total-Fe extracted. Michael and Badiger (1981) reported that there was an increase in the available and easily reducible form of Fe with continuous addition of N without P, K and FYM, successive additions of P, K and FYM enhanced the available and exchangeable forms while the contents of easily reducible Fe decreased.

Fe-Mn oxide

With regard to P application, Fe-Mn oxide fraction of light textured soil was increased significantly (188.07 to 212.47 mg kg^{-1}) with increasing level of P application over control (183.5 mg kg^{-1}) as well as at each successive level of its application (Table 4). It was also found to increase significantly (from 201.94 to 214.59 mg kg^{-1}) with increasing level of soil application of Fe over control (179.90 mg kg^{-1}), while the results was statistically at par with 1% foliar spray of iron treatment. The P x Fe interaction was also found to be significant. The magnitude of increase in Fe-Mn oxide fraction of light textured soil was 2.6, 6.3 and 15.9% at 20, 30 and 40 mg P kg^{-1}, respectively over control. With respect to Fe application at 5, 10 mg Fe kg^{-1} and 1% foliar spray of iron, it was increased by 12.3, 19.3 and 1.4%, respectively over control.

The Fe-Mn oxide content of heavy textured soil (Table 4) was also increased with increasing level of P application over control (371.72 mg kg^{-1}), but significant increase (378.46 and 387.30 mg kg^{-1}, respectively) was observed only at higher levels i.e. 30 and 40 mg kg^{-1}. Similarly, Fe-Mn oxide content was also increased with increasing level of Fe application over control (374.37 mg kg^{-1}) but significant increase was only at 10 mg Fe kg^{-1} level of soil application (382.28 mg kg^{-1}). Interaction between P x Fe application produced significant effect on Fe-Mn oxide fraction. The percent increase in the Fe-Mn oxide content was 0.6, 1.8 and 4.2 when P was applied at 20, 30 and 40 mg P kg^{-1}, respectively over control. The Fe-Mn oxide content was increased by 0.8, 2.1 and 0.8% with the application of iron at 5, 10 mg Fe kg^{-1} as soil application and 1% foliar spray of iron, respectively over control.

The Fe-Mn oxide fraction was much higher than the exchangeable-Fe and carbonate-Fe fractions in both the textured soil and it constituted on an average 2.64% of total-P extracted from the soil.

OM-Fe

The OM-Fe content of light textured soil was decreased with increasing level of P application over control, but

Table 4. Fe-Mn oxide in light and heavy textured soil as influenced by P and Fe application

Nutrient level (mg kg^{-1})	Fe-Mn oxide (mg kg^{-1})				Mean
	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	172.77	190.58	197.31	172.75	183.35
P_{20}	174.14	195.32	205.85	176.96	188.07
P_{30}	177.81	206.04	215.23	180.83	194.98
P_{40}	194.88	215.83	239.98	199.18	212.47
Mean	179.90	201.94	214.59	182.43	-
CD (p=0.05)	P: 2.69; Fe: 2.69; P x Fe: 5.38				-
Heavy textured soil					
P_0	364.23	374.08	375.80	372.75	371.72
P_{20}	375.15	367.33	376.93	376.57	374.00
P_{30}	372.21	382.87	382.97	375.80	378.46
P_{40}	385.88	385.83	393.42	384.08	387.30
Mean	374.37	377.53	382.28	377.30	-
CD (p=0.05)	P: 4.13; Fe: 4.13; P x Fe: 8.26				-

Table 5. OM-Fe in light and heavy textured soil as influenced by P and Fe application

Nutrient level (mg kg^{-1})	OM-Fe (mg kg^{-1})				Mean
	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	16.35	16.77	17.22	16.13	16.62
P_{20}	15.79	15.83	16.90	15.93	16.11
P_{30}	14.98	15.74	15.94	15.03	15.42
P_{40}	13.40	14.61	14.93	13.48	14.11
Mean	15.13	15.74	16.25	15.14	-
CD (p=0.05)	P: 1.08; Fe: 1.08; P x Fe: 2.17				-
Heavy textured soil					
P_0	253.99	273.39	294.23	251.97	268.39
P_{20}	246.65	262.79	292.23	249.45	262.78
P_{30}	229.00	260.07	291.26	235.66	254.00
P_{40}	220.94	245.33	259.67	222.15	237.02
Mean	237.65	260.39	284.35	239.81	-
CD (p=0.05)	P: 4.00; Fe: 4.00; P x Fe: 8.00				-

significant decrease was observed only at higher levels i.e. 30 and 40 mg P kg^{-1} over control (Table 5). While, with respect to Fe application, significant increase was observed only at 10 mg Fe kg^{-1} level. Foliar application of 1% Fe did not reveal any significant increase but found to be statistically at par with control treatment. The P and Fe interaction was also found to be significant.

In heavy textured soil, the OM-Fe content was found to decrease significantly with increasing level of P application over control and also between any two successive levels of its application (Table 5). On the other hand, with Fe application, the OM-Fe fraction increased significantly over control treatment. Foliar spray of 1% Fe did not show any significant increase in OM-Fe fraction over control. The P and Fe interaction was also found significant. The highest value of OM-Fe content was observed with combined effect of $P_{40}Fe_{10}$ treatment. Similar results were reported by Behra *et al.* (2009) and they found a decrease in concentrations of all four metallic cations bound to organic matter, in addition to Fe and Zn associated with carbonates in all the treatments in surface soil.

It was further observed that OM-Fe fraction extracted from the light textured soil was much less as compared to the OM-Fe fraction extracted from the heavy textured soil. On an average, this fraction accounted 1.25% of total-P extracted irrespective of soil texture. Similar findings was earlier reported by Sharma *et al.* (2008) who observed that irrespective of the different fractions of Fe present, its content was higher in the textured Alfisols and Inceptisol, than in the coarse textured Entisols and Aridisols.

Residual-Fe

There was no significant effect of P and Fe application on residual-Fe fraction (Table 6) of light textured soil. The values of residual Fe fraction were found to be more or less similar irrespective of various treatment combinations of P and Fe. Interaction between P and Fe application also produced an insignificant effect on residual-Fe fraction of light textured soil. The range of residual-Fe was from 191.12 to 194.65 mg kg^{-1} under different P and Fe application.

Similar trend was also observed in case of heavy textured soil with regard to residual-Fe fraction and remained unaffected under various P and Fe application levels (Table 6). The P x Fe interaction was also found insignificant. The residual-Fe fraction of heavy textured soil was found to be the highest in treatment combination of $P_{30}Fe_{10}$ (391.54 mg kg^{-1}).

Our results are in line with those of Behera and Singh (2010) who reported that residual Fe constituted a major portion of total Fe in all the layers of soil and did not vary significantly with various treatments.

Table 6. Residual-Fe in light and heavy textured soil as influenced by P and Fe application

Nutrient level (mg kg^{-1})	Residual-Fe (mg kg^{-1})				Mean
	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	191.12	194.52	194.65	192.61	193.22
P_{20}	191.55	190.79	192.72	191.87	191.73
P_{30}	193.81	191.39	191.63	193.09	192.48
P_{40}	194.08	192.04	192.07	193.29	192.87
Mean	192.64	192.19	192.77	192.71	-
CD (p=0.05)	P: NS; Fe: NS; P x Fe: NS				-
Heavy textured soil					
P_0	388.60	389.48	390.16	389.76	389.50
P_{20}	390.02	390.72	391.30	390.02	390.52
P_{30}	388.68	390.80	391.54	390.56	390.40
P_{40}	388.94	390.38	391.26	390.06	390.16
Mean	389.06	390.34	391.06	390.10	-
CD (p=0.05)	P: NS; Fe: NS; P x Fe: NS				-

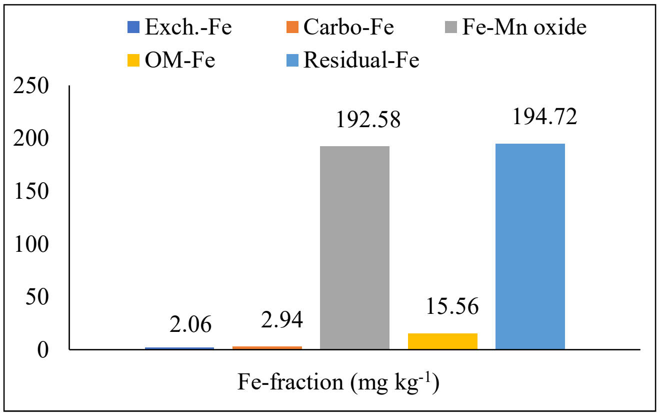

Figure 1. Distribution of various inorganic soil Fe fractions in light textured soil (Sandy loam)

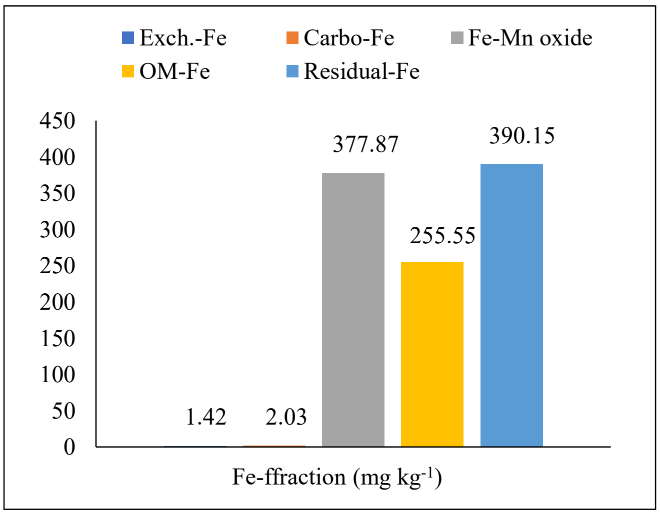

Figure 2. Distribution of various inorganic soil Fe fractions in heavy textured soil (Clay loam)

Residual-Fe was found to be less in case of light textured as compared to heavy textured soil. On an average, this fraction constituted 2.7% of total-P extracted from soil without consideration of soil texture.

Total-Fe

The total Fe content of light textured soil was found to be increased with increasing levels of both P as well as Fe application over their respective controls but the magnitude of increase was statistically non-significant (Table 7). The maximum increase in total-Fe was noticed at 20 mg P kg^{-1}application while in case of Fe application, it was recorded at highest level of its application i.e. 10 mg Fe kg^{-1}. Interaction between P and Fe application also produced an insignificant effect on total-Fe content of light textured soil. The range of total-Fe was from 8060.0 to 8412.5 mg kg^{-1} under different P and Fe application levels.

With regard to various levels of P and Fe application in heavy textured soil, more or less same trend was observed with respect to total-Fe content (Table 7) as in case of light textured soil, however, the values were found to be much higher as compared to light textured soil. The total-Fe content ranged between 13260 to 13580 mg kg^{-1} under different P and Fe application levels.

Similar observations were recorded by Randhawa and Singh (1997) in a study on iron fractions in alluvium-derived soils of Punjab and observed that the total Fe ranged from 0.8 to 3.3% and free oxides of Fe from 0.3-1.3%. Low values of total Fe in the soils were mainly due to the absence of Fe-bearing minerals such as oxides, hydroxides, oxy-hydroxides and low amount of biotic and ferromanganese minerals.

It has been observed that the percentage contribution of different fractions to the total Fe was in the order: residual > Fe-Mn oxide bound > organically bound > carbonate-Fe bound > exchangeable. These results are in line with those obtained by Yerriswamy *et al.* (1995). They studied different forms of Fe in vertisols of Karnataka and reported that the percentage contribution of different fractions to the total Fe was in the order: residual > amorphous Fe-oxide occluded > organically bound > Mn-oxide occluded > Pb-displaceable > exchangeable > acid soluble > water soluble Fe.

Table 7. Total-Fe in in light and heavy textured soil as influenced by P and Fe application

Nutrient level (mg kg^{-1})	Total-Fe (mg kg^{-1})				Mean
	Fe_0	Fe_5	Fe_{10}	$Fe_{spray\ 1\%}$	
Light textured soil					
P_0	8062.50	8265.00	8412.50	8042.50	8195.60
P_{20}	8157.50	8337.50	8405.00	8255.00	8288.80
P_{30}	8262.50	8292.50	8257.50	8035.00	8211.90
P_{40}	8060.00	8292.50	8402.50	8267.50	8255.60
Mean	8135.60	8296.90	8369.40	8150.00	-
CD (p=0.05)	P: NS; Fe: NS; P x Fe: NS				-
Heavy textured soil					
P_0	13260.0	13542.5	13557.5	13277.5	13409.4
P_{20}	13297.5	13472.5	13487.5	13262.5	13380.0
P_{30}	13365.0	13407.5	13480.0	13410.0	13415.6
P_{40}	13240.0	13402.5	13580.0	13317.5	13385.0
Mean	13290.6	13456.3	13526.3	13316.9	-
CD (p=0.05)	P: NS; Fe: NS; P x Fe: NS				-

It was also observed that total-Fe extracted from light textured soil was much less as compared to the values obtained from the heavy textured soil. Similar results were earlier reported by Sharma *et al.* (2008) and they also observed that irrespective of the different fractions of Fe present, its content was higher in the textured Alfisols and Inceptisol, than in the coarse textured Entisols and Aridisols.

Conclusion

The contribution of different fractions to the total Fe was in the order: residual-Fe > Fe-Mn oxide bound > organically bound > carbonate-Fe bound > exchangeable. The total-Fe extracted from light textured soil was much less as compared to the values obtained from the heavy textured soil.

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