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Effect of Farmyard Manure, Zn and Fe on Soil Nutrients and Chemical Status in a Pearl Millet–Chickpea Cropping System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A field trial on the pearl millet–chickpea cropping sequence was conducted during the Kharif and Rabi seasons of 2023–24 and 2024–25 at the Agronomy Farm, B. A. College of Agriculture, Anand Agricultural University, Anand, Gujarat, to study the effect of FYM, zinc, and iron on soil chemical properties. The experimental soil was loamy sand ("Goradu" soil), slightly alkaline (pH 7.94), normal in salinity (EC 0.18 dS/m), low in organic carbon (0.32%) and available nitrogen, medium in available phosphorus and potassium, and adequate in zinc and iron The experiment, laid out in a factorial randomized block design with three replications, comprised two levels of FYM (0 and 10

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t/ha), three levels of zinc (0, 12.5, and 25 kg/ha as $ZnSO_4$) and three levels of iron (0, 25, and 50 kg/ha as $FeSO_4$), with treatments applied to pearl millet and residual effects studied in chickpea. Application of FYM (10 t/ha), $ZnSO_4$ (25 kg/ha), and $FeSO_4$ (50 kg/ha) had no significant effect on soil pH, EC and organic carbon (OC) after chickpea harvest in either year or on a pooled basis. However, these treatments increased available N, P_2O_5, K_2O, Zn and Fe in the soil. All zinc fractions (water-soluble plus exchangeable, carbonate-bound, Fe/Mn oxides-bound, organically bound, total Zn and residual Zn) were enhanced by FYM and $ZnSO_4$ application, while all iron fractions (water-soluble plus exchangeable, carbonate-bound, Fe/Mn oxides-bound, organically bound, total Fe and residual Fe) were improved with FYM and $FeSO_4$ application. The results demonstrate that integrated nutrient management using FYM, zinc and iron can improve soil nutrient status and micronutrient fractions in loamy sand soils under a pearl millet–chickpea system.

Keywords: FYM; zinc; iron; chemical properties of soil.

1. INTRODUCTION

Soil chemical properties including pH, electrical conductivity (EC), organic carbon (OC) and nutrient availability are pivotal for sustaining soil fertility and ensuring long-term crop productivity. Organic amendments like farmyard manure (FYM) enhance soil organic carbon, which in turn boosts cation exchange capacity (CEC), essential for holding and exchanging nutrients. In sandy soils, SOC alone can explain up to 76% of the variation in CEC, and when combined with pH, this influence rises to nearly 95% (Scharenbroch, 2021). Moreover, the humus-rich nature of FYM contributes negative charges to the soil matrix, further improving nutrient-holding capacity. Micronutrients such as zinc (Zn) and iron (Fe) are essential for plant physiological functions, yet their bioavailability often suffers due to fixation, leaching, or improperly balanced fertilizer use (Hang *et al*., 2025). Organic matter like FYM can mitigate these challenges by providing chelating agents that reduce micronutrient fixation and improve their mobility in the soil (Bhatt *et al*., 2023). Long-term integrated nutrient management (INM) which combines FYM with inorganic fertilizers has been shown to significantly increase fractions of Zn such as exchangeable, carbonate-bound and organic-bound Zn relative to mineral fertilization alone (Kumar *et al*., 2019). Similar trends have been observed for iron, where organic amendments increase extractable fractions and overall soil availability.

The study was conducted to evaluate the effect of farmyard manure (FYM), zinc and iron on soil chemical properties. Although the experimental soil tested adequate in Zn and Fe, their bioavailability can vary with soil conditions, organic matter and crop uptake. FYM may further influence the solubility and utilization of these micronutrients. Hence, their combined effect was investigated to understand nutrient dynamics improve soil fertility and ensure sustainable crop productivity.

2. MATERIALS AND METHODS

A field experiment was conducted during the Kharif and Rabi seasons of 2023–24 and 2024–25 at the Agronomy Farm, B. A. College of Agriculture, Anand Agricultural University, Anand, Gujarat (22°35′ N, 72°55′ E, 45.1 m MSL) to study the effect of FYM, Zn, and Fe on pearl millet and its residual effect on chickpea. The region has a semi-arid, subtropical climate with ~864–870 mm annual rainfall, mostly from the southwest monsoon.

The soil was loamy sand (Inceptisol), slightly alkaline (pH 7.94), with low organic carbon (0.32%), moderate available N (172.11 kg/ha), medium P (44.16 kg/ha), high K (196.0 kg/ha) and moderate 0.78 ppm Zn and 4.22 ppm Fe.

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with 18 treatment combinations (FYM: 0 and 10 t/ha; Zn: 0, 12.5, and 25 kg/ha $ZnSO_4$; Fe: 0, 25, and 50 kg/ha $FeSO_4$) replicated thrice, totalling 54 plots. The gross plot size was 3.6 × 6.0 m and net plot size 2.7 × 5.0 m with a spacing of 45 cm between rows. Pearl millet (GHB 1129) was sown on June 29, 2023, and June 27, 2024, with a seed rate of 3.75 kg/ha, while chickpea (*GG 5*) was sown on November 23, 2023, and November 21, 2024, using 60 kg/ha seed rate. Sowing was done by drilling method, irrigation was applied as required, and nitrogen was applied in two equal splits—50% at basal and 50% at 30 DAS.

Initial and post-harvest soil samples were analysed for key soil properties including pH, EC, organic carbon, and available N, P_2O_5, K_2O, Zn, and Fe using standard procedures. . Soil samples collected prior to sowing and after harvest were analysed for key chemical properties, including pH, electrical conductivity (EC), organic carbon, and available nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), zinc (Zn), iron (Fe), along with various fractions of Zn and Fe using standard analytical methods.

3. RESULTS AND DISCUSSION

3.1 Effect of FYM

Different levels of FYM and iron application had no significant effect on soil pH, electrical conductivity (EC) and organic carbon (OC) at chickpea harvest, either in individual years or in the pooled analysis. It might be due to rapid FYM (farmyard manure) mineralization in warm, sandy soils of Gujarat contributes to a lack of significant changes in soil properties like pH, EC and organic carbon after just two years. Soil sampling immediately after harvest captures only the quickly processed, residual organic matter, not the full impact of the application. (Table 1).

Table 1 illustrated the highest post-harvest soil available nitrogen was recorded under the F_1 treatment (10 t/ha FYM), with values of 190.62, 193.54 and 192.08 kg/ha in 2024, 2025 and the pooled analysis, respectively. Similarly, Table 2 illustrated the maximum available P_2O_5 concentrations were observed in the F_1 treatment, recording 56.42, 56.51 and 56.47 kg/ha for the respective years and pooled data. The highest available K_2O content was also obtained under F_1, with 211.58 kg/ha in 2024, 214.52 kg/ha in 2025 and 213.05 kg/ha in the pooled analysis.

Significantly higher post-harvest soil zinc availability was recorded under the F_1 treatment (10 t/ha FYM). Among the FYM levels, F_1 also resulted in the highest iron content, with values of 6.86, 6.68 and 6.77 mg/kg in 2024, 2025 and the pooled analysis, respectively. Zinc availability under F_1 was 1.112 mg/kg in 2024, 1.107 mg/kg in 2025 and 1.109 mg/kg in the pooled analysis. (Table 2).

In the FYM treatment at the F_1 level (10 t/ha FYM), a markedly higher concentration of the water-soluble plus exchangeable zinc fraction was recorded, with values of 0.241 mg/kg in 2024, 0.264 mg/kg in 2025 and a pooled average of 0.253 mg/kg. Likewise, the carbonate-associated zinc fraction was greatest under the F_1 treatment, registering 3.76 mg/kg in 2024, 3.93 mg/kg in 2025 and 3.84 mg/kg in the pooled data. The Fe/Mn oxides-bound zinc fraction attained its highest level under F_1, with concentrations of 24.18 mg/kg in 2024, 25.15 mg/kg in 2025 and a pooled mean of 24.66 mg/kg. For the organically bound zinc fraction, F_1 again produced significantly elevated values 2.94 mg/kg in 2024, 3.06 mg/kg in 2025 and 3.00 mg/kg on a pooled basis. Furthermore, the total zinc fraction peaked under F1, with values of 69.09 mg/kg in 2024, 66.71 mg/kg in 2025 and a pooled mean of 67.90 mg/kg. The residual zinc fraction was also superior under the F_1 treatment, with values of 36.27, 35.00 and 35.66 mg/kg for 2024, 2025 and the pooled analysis, respectively (Table). The increase in organically bound fractions of zinc and iron with FYM application can be attributed to the addition of organic matter, which forms complexes with micronutrients, enhances microbial activity that immobilizes these nutrients in biomass, and improves the soil's cation exchange capacity, thereby retaining them in more stable forms.

The water-soluble plus exchangeable iron fraction attained its significantly highest concentration under the FYM application at the F_1 level (10 t/ha FYM), with values of 2.883 mg/kg in 2024, 3.108 mg/kg in 2025 and a pooled mean of 2.996 mg/kg. In the same treatment, the carbonate-associated fraction also reached its peak, recording 2.331 mg/kg in 2024, 3.141 mg/kg in 2025 and 2.736 mg/kg in the pooled analysis. The Fe/Mn oxides-bound iron fraction registered its maximum under F_1, with concentrations of 269.32 mg/kg in 2024, 274.38 mg/kg in 2025 and a pooled mean of 271.85 mg/kg. Likewise, the organically bound iron fraction was greatest at the F_1 level, showing 34.12 mg/kg in 2024, 33.99 mg/kg in 2025 and 34.06 mg/kg in the pooled data. The total iron fraction also recorded the highest values under F_1, with 18,866.66 mg/kg in 2024, 19,795.13 mg/kg in 2025 and a pooled mean of 19,330.90 mg/kg. Similarly, the residual iron fraction was markedly greater under F_1, with 18,484.42 mg/kg in 2024, 19,480.48 mg/kg in 2025 and 18,982.45 mg/kg in the pooled analysis. (Table 3)

Table 1. Effect of FYM, Zn and Fe on soil pH, EC, OC and available N

Treatment	Soil pH			Soil EC (dS/m)			Soil OC (%)			Available N (kg/ha)		
	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled
Initial	**7.94**			**0.181**			**0.32**			**172.11**		
Level of FYM (t ha^{-1})												
F_0	8.05	8.06	7.73	0.173	0.176	0.174	0.375	0.378	0.376	185.83	184.99	185.41
F_1	8.16	8.13	778	0.174	0.177	0.176	0.376	0.379	0.378	190.62	193.54	192.08
S. Em. ±	0.06	0.05	0.04	0.001	0.002	0.001	0.003	0.003	0.002	1.59	1.49	1.09
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	4.56	4.28	3.07
Level of Zn (kg ha^{-1})												
Zn_0	8.08	8.03	7.73	0.173	0.176	0.175	0.374	0.379	0.377	184.01	184.89	184.45
Zn_1	8.09	8.10	7.76	0.174	0.176	0.175	0.375	0.377	0.376	186.69	190.42	188.55
Zn_2	8.15	8.16	7.78	0.175	0.177	0.176	0.377	0.379	0.378	193.99	192.47	193.23
S. Em. ±	0.07	0.06	0.05	0.002	0.002	0.002	0.004	0.004	0.003	1.94	1.82	1.33
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	5.59	5.24	3.76
Level of Fe (kg ha^{-1})												
Fe_0	8.09	8.08	7.75	0.173	0.177	0.175	0.378	0.380	0.379	183.74	187.00	185.37
Fe_1	8.11	8.10	7.76	0.173	0.176	0.174	0.377	0.381	0.379	189.53	187.44	188.49
Fe_2	8.12	8.11	7.76	0.175	0.176	0.176	0.371	0.375	0.373	191.42	193.34	192.38
S. Em. ±	0.07	0.06	0.05	0.002	0.002	0.002	0.004	0.004	0.003	1.94	1.82	1.33
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	5.59	5.24	3.76
Year	-	-	NS	-	-	NS	-	-	NS	-	-	NS
S. Em. ±	-	-	0.04	-	-	0.001	-	-	0.002	-	-	1.09
C. D. at 5%	-	-	NS	-	-	NS	-	-	NS	-	-	NS
Significant Interaction(s)	-	-	-	-	-	-	-	-	-	-	-	-
CV%	3.72	3.27	3.73	5.41	4.47	4.96	3.98	4.42	4.21	4.38	4.09	4.24

Table 2. Effect of FYM, Zn and Fe on soil available P_2O_5, K_2O, zinc and iron

Treatment	Available P_2O_5 (kg/ha)			Available K_2O (kg/ha)			Available Fe (mg/kg)			Available Zn (mg/kg)		
	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled
Initial	**44.16**			**196.01**			**4.22**			**0.78**		
Level of FYM (t ha^{-1})												
F_0	52.20	53.50	52.85	196.46	194.25	195.36	6.36	6.23	6.29	1.027	1.012	1.020
F_1	56.42	56.51	56.47	211.58	214.52	213.05	6.86	6.68	6.77	1.112	1.107	1.109
S. Em. ±	0.35	0.33	0.24	1.65	1.59	1.15	0.06	0.05	0.04	0.010	0.007	0.006
C. D. at 5%	1.01	0.95	0.68	4.75	4.58	3.24	0.17	0.15	0.11	0.030	0.020	0.017
Level of Zn (kg ha^{-1})												
Zn_0	52.53	53.69	53.11	198.38	199.49	198.94	6.35	6.29	6.32	1.016	1.023	1.019
Zn_1	54.44	55.19	54.82	203.77	205.00	204.38	6.65	6.47	6.56	1.065	1.063	1.064
Zn_2	55.97	56.13	56.05	209.91	208.67	209.29	6.82	6.61	6.72	1.128	1.093	1.111
S. Em. ±	0.43	0.41	0.30	2.02	1.95	1.41	0.07	0.06	0.05	0.013	0.008	0.008
C. D. at 5%	1.24	1.17	0.84	5.82	5.61	3.94	0.21	0.19	0.14	0.036	0.024	0.021
Level of Fe (kg ha^{-1})												
Fe_0	53.44	54.01	53.72	199.63	200.32	199.97	6.47	6.31	6.39	1.045	1.035	1.040
Fe_1	54.40	55.05	54.72	205.26	204.79	205.02	6.61	6.48	6.55	1.066	1.062	1.064
Fe_2	55.10	55.95	55.52	207.17	208.05	207.61	6.75	6.57	6.66	1.098	1.081	1.090
S. Em. ±	0.43	0.41	0.30	2.02	1.95	1.41	0.07	0.06	0.05	0.013	0.008	0.008
C. D. at 5%	1.24	1.17	0.84	5.82	5.61	3.94	0.21	0.19	0.14	0.036	0.024	0.021
Year	-	-	S	-	-	NS	-	-	NS	-	-	NS
S. Em. ±	-	-	0.24	-	-	1.15	-	-	0.04	-	-	0.006
C. D. at 5%	-	-	0.68	-	-	NS	-	-	NS	-	-	NS
Significant Interaction(s)	-	-	-	-	-	-	-	-	-	-	-	-
CV%	3.38	3.14	3.26	4.21	4.05	4.13	4.69	4.23	4.47	5.03	3.35	4.28

Table 3. Effect of FYM, Zn and Fe on fractions of zinc in 0-15 cm depth of soil

Treatment	Water soluble + exchangeable fraction			Carbonate bound fraction (mg/kg)			Fe/Mn oxides bound fraction		
	2024	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**
Initial	**0.198**			**2.95**			**20.25**		
Level of FYM (t ha^{-1})									
F_0	0.224	0.241	0.232	3.60	3.72	3.66	22.63	23.22	22.92
F_1	0.241	0.264	0.253	3.76	3.93	3.84	24.18	25.15	24.66
S. Em. ±	0.001	0.002	0.001	0.03	0.02	0.02	0.22	0.20	0.15
C. D. at 5%	0.004	0.005	0.003	0.09	0.07	0.06	0.62	0.57	0.42
Level of Zn (kg ha^{-1})									
Zn_0	0.226	0.244	0.235	3.57	3.74	3.66	22.74	23.37	23.05
Zn_1	0.230	0.253	0.241	3.68	3.81	3.74	23.43	24.18	23.81
Zn_2	0.242	0.260	0.251	3.80	3.92	3.86	24.05	25.00	24.52
S. Em. ±	0.002	0.002	0.001	0.04	0.03	0.04	0.27	0.25	0.18
C. D. at 5%	0.005	0.006	0.004	0.11	0.09	0.08	0.76	0.70	0.51
Level of Fe (kg ha^{-1})									
Fe_0	0.230	0.252	0.241	3.64	3.80	3.72	23.22	23.93	23.57
Fe_1	0.232	0.251	0.242	3.68	3.81	3.75	23.47	24.22	23.85
Fe_2	0.235	0.254	0.244	3.73	3.86	3.79	23.52	24.40	23.96
S. Em. ±	0.002	0.002	0.001	0.04	0.03	0.04	0.27	0.25	0.18
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year	-	-	Sig.	-	-	Sig.	-	-	Sig.
S. Em. ±	-	-	0.001	-	-	0.02	-	-	0.15
C. D. at 5%	-	-	0.003	-	-	0.06	-	-	0.42
Significant Interaction(s)	-	-	-	-	-	-	-	-	-
CV%	3.11	3.76	3.48	4.49	3.29	3.92	4.81	4.29	4.55

Table 3. Effect of FYM, Zn and Fe on fractions of zinc in 0-15 cm depth of soil (CONTD.)

Treatment	Organically bound fraction (mg/kg)			Total Zn fraction			Residual Zn fraction		
	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled
Initial	**2.66**			**63.59**			**37.53**		
Level of FYM (t ha^{-1})									
F_0	2.71	2.81	2.76	64.63	64.73	64.68	35.00	32.90	33.95
F_1	2.94	3.06	3.00	69.09	66.71	67.90	36.27	35.00	35.66
S. Em. ±	0.03	0.02	0.02	0.68	0.74	0.50	0.43	0.33	0.27
C. D. at 5%	0.09	0.06	0.05	1.95	2.11	1.41	1.25	0.94	0.77
Level of Zn (kg ha^{-1})									
Zn_0	2.69	2.79	2.74	65.09	63.52	64.30	34.57	32.55	33.56
Zn_1	2.80	2.90	2.85	66.86	65.80	66.33	35.81	34.33	35.07
Zn_2	3.01	3.10	3.05	68.62	67.84	68.23	36.52	35.04	35.78
S. Em. ±	0.04	0.03	0.02	0.83	0.90	0.61	0.53	0.40	0.33
C. D. at 5%	0.11	0.07	0.06	2.39	2.59	1.73	1.53	1.15	0.94
Level of Fe (kg ha^{-1})									
Fe_0	2.80	2.90	2.85	66.56	64.25	65.40	35.39	33.13	34.26
Fe_1	2.83	2.91	2.87	66.87	66.08	66.47	35.54	34.33	34.93
Fe_2	2.87	2.98	2.92	67.14	66.84	66.99	35.97	34.47	35.22
S. Em. ±	0.04	0.03	0.02	0.83	0.90	0.61	0.53	0.40	0.33
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year	-	-	Sig.	-	-	NS	-	-	Sig.
S. Em. ±	-	-	0.02	-	-	0.50	-	-	0.27
C. D. at 5%	-	-	0.05	-	-	NS	-	-	0.77
Significant Interaction(s)	-	-	-	-	-	-	-	-	-
CV%	5.49	3.66	4.63	5.28	5.81	5.55	6.33	5.00	5.74

3.2 Effect of Zn

Table 1 data shows that application of different $ZnSO_4$ levels had no significant effect on soil pH, electrical conductivity (EC) and organic carbon (OC) at chickpea harvest, either in individual years or in the pooled analysis.

However, after harvest, the Zn_2 treatment (25 kg/ha $ZnSO_4$) resulted in significantly higher available nitrogen, with values of 193.99 kg/ha in 2024, 192.47 kg/ha in 2025 and a pooled mean of 193.23 kg/ha. The Zn_2 treatment was statistically comparable to Zn_1 only in the year 2025. (Table 1) The same treatment also recorded the highest available phosphorus content, measuring 55.97 kg/ha in 2024, 56.13 kg/ha in 2025 and 56.05 kg/ha in the pooled data. Zn_2 was at par with Zn_1 only during the 2025 season. Similarly, available potassium (K_2O) was maximized under Zn_2, with 209.91 kg/ha in 2024, 208.67 kg/ha in 2025 and 209.29 kg/ha in the pooled analysis, indicating the positive influence of zinc in improving overall nutrient availability. Statistically, Zn_2 was at par with Zn_1 only during the 2025 season. (Table 2) Zinc sulfate enhances the availability of nitrogen, phosphorus, and potassium in soil by activating enzymes involved in nitrogen metabolism, stimulating nitrogen-fixing and phosphate-solubilizing microbes, and promoting root growth and exudation that mobilizes nutrients. It also reduces phosphorus fixation through Zn-phosphate complex formation and supports microbial release of potassium from organic and mineral sources. These combined effects improve nutrient retention, solubility, and uptake efficiency, making zinc important not only as a micronutrient but also as a facilitator of macronutrient availability.

Under $ZnSO_4$ application, the Zn_2 treatment (25 kg/ha $ZnSO_4$) recorded significantly higher post-harvest soil concentrations of both iron and zinc. Iron levels were 6.82 mg/kg in 2024, 6.61 mg/kg in 2025 and 6.72 mg/kg in the pooled analysis, while zinc levels were 1.128 mg/kg in 2024, 1.093 mg/kg in 2025 and 1.111 mg/kg in the pooled data. The Zn_2 treatment was found statistically at par with Zn_1 in both individual years. (Table 2)

For zinc fractions, the water-soluble plus exchangeable form reached its peak under Zn_2, with values of 0.242 mg/kg in 2024, 0.260 mg/kg in 2025 and 0.251 mg/kg in the pooled mean. The carbonate-bound fraction was likewise maximized under Zn_2, recording 3.80 mg/kg in 2024, 3.92 mg/kg in 2025 and 3.86 mg/kg in the pooled analysis. The Fe/Mn oxide-bound fraction also attained its highest levels in Zn_2, with 24.05 mg/kg in 2024, 25.00 mg/kg in 2025 and 24.52 mg/kg in the pooled mean. Zn_2 treatment was found statistically at par with Zn_1 treatment in only 2024. Organically bound zinc showed the same trend, with significantly greater values of 3.01 mg/kg in 2024, 3.10 mg/kg in 2025 and 3.05 mg/kg in the pooled data. Total zinc content was also maximized under Zn_2, with 68.62 mg/kg in 2024, 67.84 mg/kg in 2025 and 68.23 mg/kg in the pooled analysis. Treatment Zn_2 was found statistically at par with treatment Zn_1, during 2024 and 2025. Similarly, the residual zinc fraction was highest under Zn_2, measuring 36.52 mg/kg in 2024, 35.04 mg/kg in 2025 and 35.78 mg/kg in the pooled mean. Statistically, the Zn_2 application was equivalent to Zn_1 across both annual evaluations. (Table 3)

In contrast, the various iron fractions water-soluble plus exchangeable, carbonate-bound, Fe/Mn oxide-bound, organically bound, total, and residual were not significantly affected by the different levels of $ZnSO_4$ application. (Table 4).

3.3 Effect of Fe

The application of different $FeSO_4$ levels had no statistically significant effect on soil pH, electrical conductivity (EC) and organic carbon (OC) content at chickpea harvest, either in individual years or in the pooled analysis. (Table 1).

However, the Fe_2 treatment (50 kg/ha $FeSO_4$) recorded the highest available nutrient levels in the soil, with nitrogen values of 191.42 kg/ha in 2024, 193.34 kg/ha in 2025 and 192.38 kg/ha in the pooled data. The Fe_2 treatment was statistically comparable to Fe_1 only in the year 2024. (Table 1); phosphorus values of 55.10 kg/ha in 2024, 55.95 kg/ha in 2025 and 55.52 kg/ha (pooled) Statistically, Fe_2 was at par with Fe_1 during the both year and pooled basis; and potassium values of 207.17 kg/ha in 2024, 208.05 kg/ha in 2025 and 207.61 kg/ha (pooled) In 2025, Fe_2 was statistically comparable to Fe_1. (Table 2).

Application of $FeSO_4$ significantly enhanced post-harvest soil availability of both iron and zinc following chickpea cultivation. The values shown in (Table 2) illustrated that Fe_2 treatment (50 kg/ha $FeSO_4$) recorded the highest iron concentrations, with 6.75 mg/kg in 2024, 6.57 mg/kg in 2025 and a pooled mean of 6.66 mg/kg. In 2024, 2025 and on pooled basis, Fe_2 was statistically comparable to Fe_1. The highest zinc

Table 4. Effect of FYM, Zn and Fe on fractions of iron in 0-15 cm depth of soil

Treatment	Water soluble + exchangeable fraction			Carbonate bound fraction			Fe/Mn oxides bound fraction		
	(mg/kg)								
	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled
Initial	**2.320**			**2.158**			**240.55**		
Level of FYM (t ha^{-1})									
F_0	2.57	2.83	2.70	2.17	2.97	2.57	250.28	248.71	249.49
F_1	2.88	3.11	3.00	2.33	3.14	2.74	269.32	274.38	271.85
S. Em. ±	0.03	0.02	0.02	0.02	0.02	0.02	1.93	1.89	1.35
C. D. at 5%	0.08	0.07	0.05	0.06	0.07	0.05	5.55	5.44	3.82
Level of Zn (kg ha^{-1})									
Zn_0	2.70	2.93	2.81	2.22	3.03	2.63	260.70	260.02	260.36
Zn_1	2.73	2.94	2.83	2.24	3.06	2.65	259.98	260.68	260.33
Zn_2	2.75	3.04	2.89	2.30	3.08	2.69	258.72	263.94	261.33
S. Em. ±	0.04	0.03	0.02	0.03	0.04	0.02	2.37	2.32	1.66
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of Fe (kg ha^{-1})									
Fe_0	2.62	2.88	2.75	2.18	3.00	2.59	255.45	255.091	255.27
Fe_1	2.70	2.94	2.82	2.25	3.07	2.66	258.50	262.17	260.33
Fe_2	2.85	3.08	3.00	2.33	3.10	2.72	265.45	267.38	266.41
S. Em. ±	0.04	0.03	0.02	0.03	0.04	0.02	2.37	2.32	1.66
C. D. at 5%	0.10	0.09	0.07	0.07	0.08	0.06	6.80	6.66	4.67
Year	-	-	Sig.	-	-	Sig.	-	-	Sig.
S. Em. ±	-	-	0.02	-	-	0.02	-	-	1.35
C. D. at 5%	-	-	0.05	-	-	0.05	-	-	3.82
Significant Interaction(s)	-	-	-	-	-	-	-	-	-
CV%	5.37	4.62	4.98	4.88	4.07	4.42	3.87	3.76	3.81

Table 4. Effect of FYM, Zn and Fe on fractions of iron in 0-15 cm depth of soil (CONTD)

Treatment	Organically bound fraction			Total Fe fraction			Residual Fe fraction		
	(mg/kg)								
	2024	2025	Pooled	2024	2025	Pooled	2024	2025	Pooled
Initial	**27.89**			**17104.56**			**16831.64**		
Level of FYM (t ha^{-1})									
F_0	28.89	29.75	29.32	17977.23	18354.99	18166.11	17708.22	18070.88	17889.55
F_1	34.12	33.99	34.06	18866.66	19795.13	19330.90	18484.42	19480.48	18982.45
S. Em. ±	0.36	0.32	0.24	199.47	149.49	124.63	190.55	149.46	121.08
C. D. at 5%	1.04	0.92	0.68	573.28	429.64	351.72	547.64	429.55	341.70
Level of Zn (kg ha^{-1})									
Zn_0	31.04	31.24	31.14	18130.74	18849.17	18489.96	17770.83	18552.00	18161.41
Zn_1	31.52	31.97	31.74	18371.88	19134.54	18753.21	18093.79	18835.59	18464.69
Zn_2	31.95	32.40	32.17	18763.23	19241.48	19002.35	18424.35	18939.45	18681.90
S. Em. ±	0.44	0.39	0.30	244.30	258.92	152.65	233.37	183.05	148.30
C. D. at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS
Level of Fe (kg ha^{-1})									
Fe_0	29.71	30.79	30.71	17912.12	18137.92	18025.02	17476.44	17846.15	17661.30
Fe_1	30.00	31.80	31.56	18226.95	19041.29	18634.12	17933.60	18741.47	18337.54
Fe_2	32.18	33.01	32.79	19126.77	20045.98	19586.38	18878.92	19739.42	19309.17
S. Em. ±	0.41	0.39	0.30	244.30	258.92	152.65	233.37	183.05	148.30
C. D. at 5%	1.17	1.13	0.83	702.12	526.20	430.77	670.71	526.09	418.50
Year	-	-	NS	-	-	Sig.	-	-	Sig.
S. Em. ±	-	-	0.24	-	-	124.63	-	-	121.08
C. D. at 5%	-	-	NS	-	-	351.72	-	-	341.70
Significant Interaction(s)	-	-	-	-	-	-	-	-	-
CV%	5.95	5.23	5.60	5.63	4.07	4.89	5.47	4.14	4.83

levels of 1.098 mg/kg in 2024, 1.081 mg/kg in 2025 and 1.090 mg/kg in the pooled data. In 2024 and 2025, Fe_2 was statistically at par with Fe_1.

Zinc fractions including water-soluble plus exchangeable, carbonate-bound, Fe/Mn oxide-bound, organically bound, total, and residual—were not significantly influenced by $FeSO_4$ application. (Table 3)

For iron fractions, the water-soluble plus exchangeable form showed its maximum concentration under Fe_2, with 2.852 mg/kg in 2024, 3.083 mg/kg in 2025 and 2.968 mg/kg in the pooled analysis. The carbonate-bound fraction was also significantly affected, peaking in Fe_2 with 2.329 mg/kg in 2024, 3.101 mg/kg in 2025 and 2.215 mg/kg in the pooled mean. Fe_1 treatment was found statistically at par with Fe_0, in 2025 and pooled basis, respectively. The Fe/Mn oxide-bound fraction reached 265.45 mg/kg in 2024, 267.38 mg/kg in 2025 and 266.41 mg/kg pooled under Fe_2. Statistically, Fe_2 was found to be at par with Fe_1 in only 2025. Similarly, the organically bound fraction was highest in Fe_2, with 32.18 mg/kg in 2024, 33.01 mg/kg in 2025 and 32.79 mg/kg pooled. Total iron content also attained its peak under Fe_2, recording 19,126.77 mg/kg in 2024, 20,045.98 mg/kg in 2025 and 19,586.38 mg/kg pooled. The residual fraction followed the same trend, being greatest in Fe_2 with 18,878.92 mg/kg in 2024, 19,739.42 mg/kg in 2025 and 19,309.17 mg/kg in the pooled analysis. (Table 4). The increase in the carbonate-bound fraction of iron after $FeSO_2$ application is mainly because Fe^{2+} ions get adsorbed onto calcium carbonate surfaces in the alkaline soil. Formation of actual iron carbonate minerals, like siderite, is unlikely under field conditions because Fe^{2+} tends to oxidize or interact with other soil components. This carbonate-bound Fe represents a stabilized form that is less soluble but still contributes to the soil's micronutrient pool

3.4 Interaction Effect

Statistical analysis indicated that all interaction effects (FYM × Zn, FYM × Fe, Zn × Fe and FYM × Zn × Fe) were non-significant for the measured parameters, including soil pH, electrical conductivity (EC), organic carbon (OC), available N, P_2O_5, K_2O and the different fractions of Zn and Fe, in both years (2024 and 2025) and in the pooled analysis. This shows that the combined application of FYM, Zn and Fe did not produce any synergistic or antagonistic effects on these soil properties, and the observed changes were primarily due to the individual effects of the treatments, the lack of significant interaction is likely because the individual treatments acted independently. Which is consistent with the findings of Keram *et al*. (2012) and Sutariya *et al*. (2013). (Table 1, 3 and 4)

4. CONCLUSION

The integrated application of FYM (10 t/ha), $ZnSO_4$ (25 kg/ha), and $FeSO_4$ (50 kg/ha) along with 100% recommended dose of fertilizers (RDF; 80:40:00 NPK) significantly improved the soil's chemical properties, enhanced fertility, and positively influenced the zinc and iron fractions of the soil. These results demonstrate that combining organic and micronutrient fertilizers can sustainably enhance soil nutrient availability, making it a practical strategy for improving crop productivity in semi-arid sandy soils.

5. SCALABILITY

The treatment can be scaled to larger agricultural fields in regions with similar soil types and climatic conditions, as it uses readily available fertilizers and FYM, which are cost-effective and easy to handle.

6. RECOMMENDATIONS

Farmers are encouraged to adopt this integrated nutrient management approach for crops like pearl millet and chickpea to maintain soil fertility and improve micronutrient status. Long-term application may further enhance organic carbon and micronutrient retention.

7. LIMITATIONS

The study was conducted over two cropping seasons; therefore, longer-term trials are needed to assess the cumulative impact on soil organic carbon, micronutrient dynamics, and crop yields under varying environmental conditions. Additionally, site-specific soil variability and initial nutrient status may influence the effectiveness of these treatments.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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