

Comparative Effects of Soil and Foliar Iron Application on Nutrient Dynamics in Green Gram

Adarsh Pandey¹, Shakti Om Pathak¹, Karmnath Kumar¹, Nilotpal Das^{2*}, Atin Kumar², and Sharad Sachan³

¹Department of Natural Resources Management, Faculty of Agricultural Sciences, Shree Guru Gobind Singh Tricentenary University, Gurugram-122505, Haryana, India.

²School of Agriculture, Uttarakhand University, Dehradun-248007, Uttarakhand, India.

³Department of Agricultural Economics and Extension, School of Agriculture, Lovely Professional University, Phagwara (Punjab)-144411, India.

*Corresponding author email: rangandas1996@gmail.com

Article history: submitted: November 6, 2025; accepted: March 21, 2026; available online: April 9, 2026

Abstract. Iron deficiency is a common limitation in alkaline soils, restricting nutrient uptake and yield in pulse crops such as green gram (*Vigna radiata* L.). To compare various iron fertilization regimes and their effects on soil properties, nutrient dynamics, and nutrient uptake in green gram, a field experiment was conducted from March to July 2024 at SGT University, Gurugram, Haryana. The experimental design was a randomized block trial with three replicates because the experiment comprised seven treatments, including the recommended dose of fertilizers (RDF: 20:40:40 kg N: P₂O: K₂O ha⁻¹) and soil and foliar applications of FeSO₄. It was found that foliar application of FeSO₄ significantly enhanced soil fertility and plant nutrient status compared to soil application. The highest soil organic carbon was recorded at 30 and 45 DAS with the RDF + foliar spray of 0.6% FeSO₄ (0.41% and 0.40%, respectively), an increase of about 32-35% compared with the control (0.31-0.30%). Likewise, the available nitrogen content increased by 189.12 kg ha⁻¹ to 225.08 kg ha⁻¹ (about 19 percent improvement) under the same treatment. Nutrient levels in plant tissues also increased significantly, and nitrogen content in the straw and grain improved by 40-120 percent and 1.82-3.38 percent, respectively, compared to the control. The experiment shows that foliar iron application is more effective than soil-applied iron in improving nutrient status and plant uptake in alkaline soil. The originality of the study lies in its comparison of soil under staged foliar iron fertilization and its effects on the dynamics of soil nutrients, micronutrient availability, and nutrient use efficiency in the growth of green grass on alkaline soils.

Keywords: foliar nutrition; green gram; iron fertilization; nutrient uptake; soil fertility

1. Introduction

Pulses, also known as leguminous crops, are significant in India, as these crops provide dietary protein, energy, minerals, and vitamins for vegetarians and humans (Kumar *et al.*, 2020). Pulses grow well in dry areas, but their yields are dropping because of too much chemical fertilizer use and a lack of vital micronutrients in the soil (Kavya *et al.*, 2021). Pulses are also intercropped with other crops, such as green gram, which is known for its high protein content, rapid maturity, and nitrogen-fixing capacity (Kumar *et al.*, 2020). Green gram also plays a vital role in crop rotations and enhancing soil fertility due to its leguminous nature (Mohapatra *et al.*, 2023). According to the Indian Institute of Pulses Research [IIPR] (2024), about 30% of the world's mung beans are produced in India

and Myanmar, with an average yield of 7.21 quintals ha⁻¹, while Eastern Asian countries like China, Indonesia, Thailand, Kenya, and Central African countries like Tanzania are among the top producers. Central African countries like Kenya, Mozambique, Tanzania, and Southern African countries like South Africa, Uganda, as well as Latin American countries Brazil and Venezuela are the major importing countries, while North American countries like the USA, Canada, and Asian countries like Bangladesh, Qatar, UAE, and Malaysia are major export destinations (Indian Pulses Export, 2024). India contributes 10% to 12% of the world's total pulse production of green gram and is expected to achieve a new peak in 2022–2023 (Ministry of Agriculture and Farmers Welfare, 2023).



As essential micronutrients are crucial for plant growth, the availability of iron (Fe) plays a vital role in metabolic activity, enzymatic activity, and chlorophyll formation (Gupta *et al.*, 2024). Iron deficiency, however, is a common phenomenon in alkaline and calcareous soils. Iron chlorosis, commonly arising from low solubility, reduces photosynthesis, stunts growth, and affects production and nutrient uptake (Roy *et al.*, 2024). Plants take up iron through both foliar spraying and soil application. Again, foliar spraying quickly addresses deficiencies, while soil application enhances soil nutrient status, crop type, climatic conditions, and soil properties, all of which affect efficiency (Gupta *et al.*, 2024). In leguminous crops like green grams, iron nutrition plays a critical role in nodulation and nutrient accumulation throughout the early growth stages and reproductive development (Roy *et al.*, 2024). This study aims to compare various iron fertilization regimes and evaluate their effects on soil properties, nutrient dynamics, and nutrient uptake in green gram..

2. Materials and Methods

A field investigation was carried out in the summer of 2024 at the Crop Research Center (CRC), SGT University, Gurugram, Haryana. The experimental site is situated in the northwestern agro-climatic zone of Haryana (28.47° N, 76.90° E) at an elevation of 217 meters above mean sea level. Before sowing, initial soil samples were collected from the 0-15 cm depth across the field to form a composite sample. This sample was analyzed following standard methodologies to characterize the soil, which was determined to be sandy loam, slightly alkaline (pH 8.27), with low available nitrogen, and medium levels of available phosphorus and potassium. The experimental design was a Randomized Block Design (RBD) with three replications and seven treatments, three times. The experimental data obtained from different treatments were

subjected to analysis of variance (ANOVA) appropriate for a Randomized Block Design (RBD) to determine the significance of treatment effects. The statistical analysis was performed using standard statistical procedures as described by Gomez and Gomez. Treatment means were compared using the Critical Difference (CD) test at the 5% level of significance ($p \leq 0.05$) to identify significant differences among treatments. The Standard Error of Mean (SEm) was also calculated to assess the variability among the treatment means. The treatments were as follows: T₁: Recommended Dose of Fertilizer (RDF) at 20:40:40 kg ha⁻¹ of N:P₂O₅:K₂O (Control), T₂: RDF + Soil application of 20 kg ha⁻¹ FeSO₄, T₃: RDF + Soil application of 25 kg ha⁻¹ FeSO₄, T₄: RDF + Foliar spray of 0.3% FeSO₄ at 30 days after sowing (DAS), T₅: RDF + Foliar spray of 0.6% FeSO₄ at 45 DAS, T₆: RDF + Foliar spray of 0.3% FeSO₄ at 30 DAS and 45 DAS, T₇: RDF + Foliar spray of 0.6% FeSO₄ at 30 DAS and 45 DAS.

The green gram (*Vigna radiata* L.) variety 'MH 1142' was sown in mid-April 2024 using a spacing of 30 cm between rows and 25 cm between plants. Soil and Plant Analysis: Standard laboratory procedures were employed for all analyses. Soil texture was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962), bulk density by the core method (Blake and Hartge, 1986), and organic carbon by the Walkley and Black method. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-water suspension. Available nitrogen was assessed using the alkaline permanganate method (Subbiah & Asija, 1956), available phosphorus by Olsen's method (Olsen *et al.*, 1954), and available potassium with a flame photometer (Jackson, 1973). Available sulfur was determined turbidimetrically (Chesnin & Yien, 1951), while DTPA-extractable micronutrients (Fe, Zn, Cu, Mn) were quantified using an Atomic Absorption Spectrophotometer (AAS) by Lindsay & Norvell (1978). At harvest, plant samples (grain and straw) were collected, processed, and analyzed for nutrient content.

Total nitrogen was determined using an automatic nitrogen analyzer. Phosphorus, potassium, sulfur, and micronutrient concentrations were analyzed via wet digestion methods, with phosphorus measured by the vanadomolybdo-phosphoric yellow color method, potassium by flame photometry, and sulfur by the turbidimetric method (Piper, 1945). The total uptake of each nutrient (kg ha^{-1}) was calculated using the formula: $[\text{Nutrient content (\%)} \times \text{Yield (\text{kg ha}^{-1})}] / 100$. Nutrient use efficiency and recovery efficiency were computed as per established protocols.

The efficiency of iron utilization by the crop was evaluated using nutrient use efficiency indices such as Agronomic Efficiency (AE) and Recovery Efficiency (RE).

Agronomic Efficiency (AE) was calculated using Equation 1.

$$AE = Y_t - Y_c / F \dots 1)$$

Where:

AE = Agronomic efficiency (kg yield increase per kg nutrient applied)

Y_t = Yield obtained in the fertilized treatment (kg ha^{-1})

Y_c = Yield obtained in the control treatment (kg ha^{-1})

F = Amount of nutrient applied (kg ha^{-1})

Recovery Efficiency (RE) was calculated using Equation 2.

$$RE (\%) = U_t - U_c / F \times 100 \dots 2)$$

Where:

RE = Recovery efficiency (%)

U_t = Nutrient uptake in fertilized treatment (kg ha^{-1})

U_c = Nutrient uptake in control treatment (kg ha^{-1})

F = Amount of nutrient applied (kg ha^{-1})

3. Results and Discussion

A. Response of iron fertilization on soil physico-chemical properties

The effect of iron sulphate fertilization on soil pH, electrical conductivity (EC), and

organic carbon content at two different growth stages (at 30 DAS and at harvesting) of green gram is presented in [Table 1](#).

Soil pH

The soil testing result indicated that initial soil pH fluctuated between 8.23 and 8.34 at 30 DAS and between 8.24 and 8.33 during the harvest stage. [Jat et al. \(2022\)](#) & [Kumar et al. \(2024\)](#) observed similar findings.

Electrical Conductivity

Treatment T_1 and T_6 reported the highest EC, while T_2 and T_3 recorded the lowest at 30 DAS. At harvest, EC varied between 1.58 and 1.62 dSm^{-1} , with T_7 holding the maximum and T_4 the minimum value. The effect of iron sulphate fertilization on soil EC was not significant in the experimental field. [Jat et al. \(2022\)](#) & [Kumar et al. \(2024\)](#) observed similar findings.

Soil Organic Carbon

Soil organic carbon content at different growth stages was significantly affected by iron nutrition. Soil organic carbon varied from 0.31% to 0.41% at 30 DAS and 0.30% to 0.40% at harvest. The highest organic carbon content was recorded under T_7 , both at 30 DAS (0.41%) and at harvest (0.40%), whereas T_1 recorded the lowest values (0.31% and 0.30%, respectively) at both stages. [Timsina et al. \(2024\)](#) observed a similar finding.

B. Effect of iron sulfate application on the availability of soil macronutrients

The study analyzed the availability of soil nitrogen, phosphorus, potassium, and sulfur at different growth stages under various green gram treatments, as shown in [Table 1](#).

Available nitrogen

The available nitrogen content was also highest under the treatment combination T_7 ; RDF and foliar spray of 0.6% FeSO_4 at 30 DAS and 45 DAS, ($225.08 \text{ kg ha}^{-1}$) at 30

DAS and (217.04 kg ha⁻¹) at harvest. Here, treatment T₇ was statistically equivalent to treatments like T₆, T₅, T₄, T₃, and T₂ at both stages.

The lowest amount of available nitrogen (189.12 kg ha⁻¹) at 30 DAS and (182.46 kg ha⁻¹) at harvest was recorded under the treatment T₁ (NPK - 20:40:40). Iron nutrition resulted in more activity from larger microorganisms, which could lead to a greater breakdown of added and natural nutrients, which might explain the higher amount of available nitrogen measured. A similar finding was observed by [Timsina et al. \(2024\)](#) & [Rathore et al. \(2023\)](#) in green gram.

Available phosphorus

The Highest amount of available phosphorus was recorded under T₇ (16.79 kg ha⁻¹) at 30 DAS and (14.78 kg ha⁻¹) at harvest. Here, treatment T₇ was statistically equivalent to treatments like T₆, T₅, T₄, T₃, and T₂ at both stages. The lowest amount of available phosphorus content (13.80 kg ha⁻¹) at 30 DAS and (11.92 kg ha⁻¹) at harvest was recorded under the treatment T₁: (NPK - 20:40:40). Increased microbial activity may lead to greater mineralization of both applied and native nutrients, which could explain the observed higher levels of available phosphorus. [Rathore et al. \(2023\)](#) observed similar findings in urdbean.

Available potassium

A similar trend of iron fertilization was observed for available potassium, as for available nitrogen and phosphorus. The highest amount of available potassium (174.48 kg ha⁻¹) was recorded under the treatment combination T₇ at 30 DAS. Here, treatment T₇ was statistically equivalent with treatments like T₆, T₅, T₄, T₃ and T₂. At harvest, the highest available potassium (169.44 kg ha⁻¹) was recorded under treatment T₇; T₇ was significantly higher than treatments T₃, T₅, and T₆, whereas it was statistically equivalent to treatments T₄ and T₂. The lowest available potassium

content in soil (146.12 kg ha⁻¹) at 30 DAS and (145.55 kg ha⁻¹) at harvest was recorded under the treatment T₁. Foliar application of Iron sulfate enhances plant growth and productivity, particularly in pulses, by increasing nutrient availability during later growth stages through water-soluble fertilizers. [Rathore et al. \(2023\)](#) observed a similar finding.

Available Sulfur

The Highest available sulfur content in soil was recorded under treatment combination T₇, reaching (13.83 mg kg⁻¹) at 30 DAS and (13.08 mg kg⁻¹) at harvest. At 30 DAS, treatment T₇ was significantly better than treatments such as T₂, whereas it was statistically equivalent to treatments such as T₆, T₅, T₄, and T₃. At harvest, treatment T₇ was significantly higher than treatments T₃, T₅, T₂, and T₆, whereas it was statistically equivalent to treatment T₄. The lowest available sulfur content in soil (11.79 mg kg⁻¹) at 30 DAS and (11.58 mg kg⁻¹) at harvest was recorded under the treatment T₁: (NPK - 20:40:40). Iron sulfate can enhance sulfur availability in soil. Still, its effect on plant uptake is influenced by soil conditions, microbial activity, and the intricate iron-sulfur interaction. [Singh et al. \(2016\)](#) observed similar findings.

C. Soil micronutrient response to applied iron sulfate

The response of iron fertilization on available Zn, Cu, Fe, and Mn content in soil at different growth stages is represented in [Table 2](#).

Available Zinc

Among micronutrients, available zinc content was highest in treatment combination T₇ (0.695 ppm) at 30 DAS and (0.524 ppm) at harvest, with T₁ showing the lowest (0.498 ppm and 0.313 ppm). At 30 DAS, treatment T₇ was significantly better than T₄, T₃, T₂, and T₅, whereas it was statistically equivalent to T₆. At the harvest stage, treatment T₇ was significantly higher than T₅, T₂, T₄, and T₆, whereas it was statistically equivalent to T₃.

Iron and zinc are micronutrient cations that compete for adsorption sites and plant uptake. Application of iron sulfate increases soil Fe^{2+} concentration, thereby suppressing Zn availability and inhibiting Zn uptake in plants due to competition at the root membrane level. [Rathore et al. \(2023\)](#) reported similar findings.

Available Copper (ppm)

Copper availability under T₇ was (0.34 ppm) at 30 DAS and (0.32 ppm) at harvest. Here, treatment T₇ was significantly better than treatments T₂, T₆, T₄, and T₃, whereas it was statistically equivalent to treatment T₅ at both stages. The lowest available Cu content (0.20 ppm) at 30 DAS and (0.19 ppm) at harvest was recorded under the treatment T₁. A study on the impact of FeSO_4 and organic amendments on Cu availability in contaminated soils found that the addition of iron effectively reduced Cu availability due to the formation of amorphous iron oxides and the influence of soil pH and organic matter on Cu fractionation. [Fresno et al. \(2016\)](#) observed similar findings.

Available Fe (ppm)

A similar pattern was observed for available iron, with T₇ showing (3.45 ppm) at 30 DAS and (3.23 ppm) at harvest. At 30 DAS, the treatment T₇ was significant over the treatments like T₄, T₆, T₃, and T₂, whereas it was statistically equivalent with the treatment like T₅, and at the harvest stage, T₇; here, treatment T₇ was significant over the treatments like T₆, T₂, and T₃, whereas it was statistically equivalent with treatments like T₅ and T₄. The lowest available iron content (2.62 ppm) was recorded at 30 DAS, and (2.58 ppm) at harvest, under treatment T₁. Iron sulfate temporarily increases soil iron availability by supplying soluble Fe^{2+} and lowering pH, but its long-term effectiveness is limited by rapid oxidation. Chelated iron, or repeated applications, may be more effective. [Rathore et al. \(2023\)](#) observed similar findings.

Available Mn (ppm)

The highest manganese content was also observed under treatment T₇ (1.63 ppm at 30

DAS and 1.48 ppm at harvest). At 30 DAS, treatment T₇ was significantly different from T₃, T₅, T₁, T₄, and T₆. At the harvest stage, T₇ was significantly different from T₅, T₄, and T₃, whereas it was statistically equivalent to T₂ and T₆. The lowest available manganese content (1.38 ppm) at 30 DAS and (1.24 ppm) at harvest was recorded under the treatment T₁ (NPK 20:40:40). The interaction between Fe and Mn in soil is complex, with high Fe levels potentially reducing Mn availability due to plant competitive uptake, influenced by soil type, nutrient levels, and micronutrient application timing. [Pahlavan et al. \(2009\)](#) observed similar findings.

D. Response of iron sulfate to nutrient content and uptake in grain and straw

The effect of iron fertilization on nitrogen, phosphorus, potassium, sulfur, and iron content, as well as uptake of green gram, is represented in [Table 3](#) and [Table 4](#).

Nitrogen

The data clearly indicated that the plant's nitrogen content increased with maturity. The highest nitrogen content in green gram (1.82% in straw and 3.38% in grain) was recorded under the treatment combination T₇; RDF and foliar spray of 0.6% FeSO_4 at 30 DAS and 45 DAS. Here, treatment T₇ was significantly higher than treatments like T₃ and T₅, whereas it was statistically equivalent to treatments like T₂, T₄, and T₆ in nitrogen content in the straw and grain of green gram. The lowest nitrogen content (0.99%) in straw and (2.05%) in grain was recorded under the treatment T₁: (NPK-20:40:40). [Table 4](#) showed the influence of iron fertilizers on nitrogen uptake with plant samples. The data clearly indicated that nitrogen uptake tends to decline as the crop progresses. The highest nitrogen uptake in green gram (41.64 kg ha⁻¹) in straw and (40.90 kg ha⁻¹) in grain was recorded under the treatment combination T₇. Here, treatment T₇ was significantly higher than all other treatments for nitrogen uptake in the straw and grain of green gram. The lowest nitrogen uptake (9.26 kg ha⁻¹) in straw

and (16.81 kg ha⁻¹) in grain was observed under treatment T₁: NPK (20:40:40). Iron is crucial for plants' efficient nitrogen use, acting as a cofactor for enzymes like nitrate reductase and nitrite reductase. It is also essential for chlorophyll production, enabling

plants to absorb, process, and use nitrogen efficiently for healthy growth and high yields. [Rathore et al. \(2023\)](#), [Poonia et al. \(2018\)](#), [Kumar et al. \(2023\)](#), and [Muthumanickam et al. \(2022\)](#) reported similar findings.

Table 1. Influence of treatments on pH, EC, organic carbon, available N, P, and K in soil at 30 DAS and harvest of green gram

Treatments	pH		EC (dSm ⁻¹)		O.C. (%)		Available Nitrogen (kg ha ⁻¹)		Available Phosphorus (kg ha ⁻¹)		Available Potassium (kg ha ⁻¹)	
	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest
T1- NPK (20:40:40) (S.A.)	8.27	8.26	1.62	1.60	0.31	0.30	189.12	182.46	13.80	11.92	146.12	145.55
T2- RDF + 20 kg FeSO ₄ (S.A.)	8.23	8.24	1.59	1.59	0.39	0.38	219.30	210.24	14.95	13.09	171.32	161.41
T3- RDF + 25Kg FeSO ₄ (S.A.)	8.30	8.27	1.59	1.59	0.40	0.39	213.68	210.41	16.06	14.41	172.60	159.64
T4- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS	8.32	8.30	1.60	1.58	0.39	0.38	212.40	208.04	15.85	13.54	170.93	164.68
T5- RDF + 0.6% FeSO ₄ (F.A.) at 45 DAS	8.28	8.26	1.61	1.59	0.39	0.38	218.88	213.66	15.69	13.49	168.83	159.76
T6- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	8.34	8.33	1.62	1.60	0.38	0.38	209.16	202.06	16.65	13.80	167.04	156.27
T7- RDF + 0.6% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	8.31	8.31	1.61	1.62	0.41	0.40	225.08	217.04	16.79	14.78	174.48	169.44
SEm ±	0.59	0.59	0.05	0.06	0.01	0.01	6.63	6.62	0.56	0.53	5.43	2.99
CD (5%)	1.82	1.82	0.16	0.17	0.04	0.04	20.43	20.40	1.73	1.64	16.73	9.22

Note: RDF = recommended dose of fertilizer, DAS = days after sowing, FA = foliar application.

Phosphorus

The data showed that the phosphorus content in green gram plants decreased gradually as crop maturity progressed. The highest phosphorus content was in T₇ (0.46% in straw and 1.18% in grain), significantly higher than most treatments and statistically equivalent to T₂ for grain phosphorus content. The lowest phosphorus content was found in T₁ (0.20% in straw and 0.64% in grain). Likewise, phosphorus uptake was highest under T₇ (10.52 kg ha⁻¹ in straw and 14.28 kg ha⁻¹ in grain), while T₁ showed the lowest uptake (1.87 kg ha⁻¹ in straw and 5.25 kg ha⁻¹ in grain). Iron nutrition enhances root development and surface area, allowing

plants to explore soil for phosphorus. It stimulates the acid phosphatase enzyme, releasing phosphate ions. Improved iron nutrition leads to higher P content in green gram. [Kumar et al. \(2023\)](#), [Rathore et al. \(2023\)](#), [Barla et al. \(2022\)](#), and [Saini et al. \(2017\)](#) reported similar findings.

Potassium

The data indicated a decrease in potassium content as crops matured. The highest potassium content was recorded under the treatment combination T₇ (0.81% in straw and 1.21% in grain), outperforming T₃ to T₆ in straw and T₃ to T₅ in grain. The lowest potassium content was observed under T₁ (0.31% in straw and 0.86% in grain). A

similar trend was observed in Potassium uptake through green gram, with the highest uptake recorded for T₇ (18.53 kg ha⁻¹ in straw and 14.64 kg ha⁻¹ in grain). In comparison, T₁ recorded the lowest (2.90 kg ha⁻¹ in straw and 7.05 kg ha⁻¹ in grain). Iron and potassium uptake in green gram involves active

transport, which relies on photosynthetic energy. Iron maintains chlorophyll levels and the electron transport chain, boosting energy production. It indirectly improves K⁺ ion absorption and translocation, raising K levels in grain and straw. [Barla et al. \(2022\)](#) and [Ah and Vs \(2020\)](#) observed similar findings.

Table 2. Effect of treatments on available S, Zn, Cu, Fe, and Mn in soil at branching and harvest of green gram

Treatments	S (mg kg ⁻¹)		Zn (ppm)		Cu (ppm)		Fe (ppm)		Mn (ppm)	
	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest	At 30 DAS	After Harvest
T1- NPK (20:40:40) (S.A.)	11.79	11.08	0.498	0.313	0.20	0.19	2.62	2.59	1.38	1.24
T2- RDF + 20 kg FeSO ₄ (S.A.)	12.46	11.21	0.547	0.382	0.28	0.26	2.72	2.64	1.5	1.31
T3- RDF + 25Kg FeSO ₄ (S.A.)	13.71	12.08	0.563	0.485	0.16	0.15	2.76	2.58	1.53	1.32
T4- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS	13.17	11.58	0.581	0.423	0.19	0.18	3.12	2.94	1.54	1.34
T5- RDF + 0.6% FeSO ₄ (F.A.) at 45 DAS	13.38	11.79	0.512	0.418	0.32	0.31	3.21	3.01	1.56	1.4
T6- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	13.63	11.88	0.641	0.469	0.28	0.27	2.96	2.74	1.59	1.42
T7- RDF + 0.6% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	13.83	13.08	0.695	0.524	0.34	0.32	3.45	3.23	1.63	1.48
S _{Em} ±	0.43	0.38	0.02	0.01	0.01	0.01	0.10	0.10	0.04	0.05
CD@ (5%)	1.33	1.17	0.06	0.04	0.03	0.03	0.31	0.31	0.14	0.14

Note: RDF = recommended dose of fertilizer, DAS = days after sowing, FA = foliar application.

Table 3. Effect of treatment on N, P, K, S, and Fe content (%) in grains and straw of green gram

Treatments	Nitrogen (%)		Phosphorus (%)		Potassium (%)		Sulfur (%)		Iron (%)	
	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
NPK (20:40:40) (S.A.)	0.99	2.05	0.2	0.64	0.31	0.86	0.14	0.18	1.17	2.46
RDF + 20 kg FeSO₄ (S.A.)	1.71	3.33	0.29	1.12	0.78	1.17	0.17	0.27	1.36	3.48
RDF + 25 kg FeSO₄ (S.A.)	1.6	2.96	0.27	0.72	0.4	0.72	0.16	0.21	1.52	3.61
RDF + 0.3% FeSO₄ (F.A.) at 30 DAS	1.67	3.08	0.31	0.88	0.44	0.68	0.13	0.23	1.38	3.44
RDF + 0.6% FeSO₄ (F.A.) at 45 DAS	1.64	3.16	0.36	0.92	0.52	1.06	0.16	0.26	1.34	3.38
RDF + 0.3% FeSO₄ (F.A.) at 30 DAS and 45 DAS	1.67	3.22	0.4	0.96	0.74	1.12	0.15	0.27	1.42	3.54
RDF + 0.6% FeSO₄ (F.A.) at 30 DAS and 45 DAS	1.82	3.38	0.46	1.18	0.81	1.21	0.19	0.32	1.53	3.62
SEm±	0.05	0.1	0.01	0.03	0.02	0.03	0.01	0.01	0.05	0.11
CD @ (5%)	0.16	0.31	0.03	0.09	0.06	0.1	0.02	0.02	0.14	0.35

Note: RDF = recommended dose of fertilizer, DAS = days after sowing, FA = foliar application.

Table 4. Effect of treatments on N, P, K, S, and Fe uptake of green gram.

Treatments	Nitrogen		Phosphorus		Potassium		Sulfur		Iron (Fe)	
	(kg ha ⁻¹)		(kg ha ⁻¹)		(kg ha ⁻¹)		(kg ha ⁻¹)		(kg ha ⁻¹)	
	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
T1- NPK (20:40:40) (S.A.)	9.26	16.81	1.87	5.25	2.9	7.05	1.31	1.48	10.94	20.14
T2- RDF + 20 kg FeSO₄ (S.A.)	29.41	33.7	4.99	11.33	13.42	11.84	2.92	2.73	23.41	35.37
T3- RDF + 25 kg FeSO₄ (S.A.)	29.06	33.15	4.9	8.06	7.26	8.06	2.91	2.35	27.56	40.48
T4- RDF + 0.3% FeSO₄ (F.A.) at 30 DAS	25.27	29.14	4.69	8.32	6.66	6.43	1.97	2.18	20.9	32.58
T5- RDF + 0.6% FeSO₄ (F.A.) at 45 DAS	23.81	30.59	5.23	8.91	7.55	10.26	2.32	2.52	19.47	32.73
T6- RDF + 0.3% FeSO₄ (F.A.) at 30 DAS and 45 DAS	34.3	36.39	8.22	10.85	15.2	12.66	3.08	3.05	29.2	40.04
T7- RDF + 0.6% FeSO₄ (F.A.) at 30 DAS and 45 DAS	41.64	40.9	10.52	14.28	18.53	14.64	4.35	3.87	34.91	43.86
SEm±	1.38	1.37	0.28	0.42	0.47	0.45	0.13	0.11	1.23	2.25
CD @ (5%)	4.24	4.21	0.85	1.29	1.44	1.4	0.41	0.35	3.79	6.92

Note: RDF = recommended dose of fertilizer, DAS = days after sowing, FA = foliar application.

Table 5. Effect of treatment on Iron use efficiency and Iron recovery efficiency.

Treatments	Iron use efficiency	Iron
	(kg grain kg ⁻¹ of Fe applied)	Recovery Efficiency (%)
T1- NPK (20:40:40) (S.A.)	-	-
T2- RDF + 20 kg FeSO ₄ (S.A.)	9.55	158.56
T3- RDF + 25 kg FeSO ₄ (S.A.)	11.96	130.39
T4- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS	92.64	1571.82
T5- RDF + 0.6% FeSO ₄ (F.A.) at 45 DAS	54.47	825.97
T6- RDF + 0.3% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	108.44	1339.18
T7- RDF + 0.6% FeSO ₄ (F.A.) at 30 DAS and 45 DAS	68.27	827.94
SEm±	14.85	55.46
CD @ (5%)	46.79	174.75

Note: RDF = recommended dose of fertilizer, DAS = days after sowing, FA = foliar application.

Sulfur

The Highest sulfur content was observed under treatment combination T₇ (0.19% in straw and 0.32% in grain), significantly superior to all treatments in grain and most in straw. The lowest sulfur content was recorded under T₁ (0.14% in straw and 0.18% in grain). Sulfur uptake was highest under treatment combination T₇ (4.35 kg ha⁻¹ in straw and 3.87 kg ha⁻¹ in grain), while T₁ recorded the minimum sulfur uptake (1.31 kg ha⁻¹ in straw and 1.48 kg ha⁻¹ in grain). Iron and sulfur are involved in protein synthesis and enzyme functions, with enhanced iron status supporting chloroplast function and sulfur assimilation in green gram, promoting S uptake and assimilation. [Shivanand and Radder \(2020\)](#), [Saini et al. \(2017\)](#), and [Astolfi et al. \(2021\)](#) observed similar findings.

Iron

Iron content in green gram followed a similar trend to other macro- and micronutrients, with treatment T₇ recording the highest values (1.53% in straw and 3.62% in grain). Treatment combination T₇ was significantly superior to those of T₅, T₂, and T₄ in straw and statistically equivalent to other treatments in grain. The lowest iron content was observed under T₁ (1.17% in straw and 2.46% in grain). Iron uptake also mirrored this trend, with T₇ showing the

highest accumulation (34.91 mg kg⁻¹ in straw and 43.68 mg kg⁻¹ in grain). In terms of grain iron uptake, T₇ was significantly better than T₂, T₅, and T₄, and was statistically equivalent to T₃ and T₆. The lowest iron uptake was found in T₁ (10.94 mg kg⁻¹ in straw and 20.14 mg kg⁻¹ in grain).

Tables 3 and 4 present iron uptake in plant samples after harvest, showing that it was influenced by crop maturity. Foliar application of iron sulfate (FeSO₄) enhanced plant iron content by allowing direct absorption of iron ions through leaf tissues, which in turn improved metabolic activity, activated iron transport genes, and promoted biofortification. Similar results were reported by [Dodiya et al. \(2024\)](#), [Zafar et al. \(2023\)](#), [Kandoliya and Kunjadia \(2018\)](#), [Poonia et al. \(2018\)](#), [Dhaliwal et al. \(2022\)](#), and [Kaur et al. \(2024\)](#).

E. Iron use efficiency and iron recovery efficiency

The study found that the application of iron fertilizers significantly influenced iron use efficiency in green gram ([Table 5](#)). The highest efficiency was observed with the treatment combination T₆ (RDF + 0.3% FeSO₄ at 30 DAS and 45 DAS), followed by T₄ and T₇. The lowest efficiency was recorded under the T₂ treatment (RDF + 20 kg FeSO₄). Additionally, the study revealed

that the highest iron recovery efficiency was observed with treatment T₄ (RDF + 0.3% FeSO₄ at 30 DAS), followed by T₆. Furthermore, the lowest iron recovery efficiency was observed with the treatment combination T₃ (RDF + 25 kg FeSO₄).

4. Limitations and Future Directions

The present research, however, was constrained to a single season, a single location, and a single type of green gram under alkaline soil conditions. Thus, although the results provide valuable insights into iron fertilization strategies, they may require further confirmation across different agro-ecological settings. Future studies should use multi-location, multi-season studies, incorporate other crop varieties, and combine iron fertilization with other micronutrients or biofertilizers to develop more sustainable nutrient application policies. Moreover, future research should examine the physiological processes, the biofortification potential of iron, and the financial viability of foliar iron fertilization in pulse-based agricultural systems. The research will help to enhance nutrient use efficiency, crop productivity, and soil health of pulse production systems.

5. Conclusion

The current study revealed that iron fertilization significantly affects soil nutrient availability, plant nutrient content, and nutrient uptake in green gram grown in alkaline soils. The most effective strategy assessed, which showed the greatest improvement in soil organic carbon, available macronutrients, micronutrients, and nutrient accumulation in both grain and straw, was foliar application of 0.6% FeSO₄ at 30 and 45 DAS, combined with RDF (T₉). This treatment improved organic carbon in soils by approximately 30–35%. It offered readily available nitrogen by almost 19% and significantly increased nutrient uptake of nitrogen, phosphorus, potassium, sulfur, and iron relative to the control. It was also found

that foliar iron nutrition enhanced iron use efficiency and recovery efficiency, underscoring the importance of timely micronutrient application for efficient nutrient utilization.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

Authors declare no use of generative AI in the manuscript preparation process upon submission of the paper.

Authorship Contribution Statement

Adarsh Pandey: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; Karmnath Kumar: Conceptualization, Methodology, Writing – review & editing; Shakti Om Pathak: Methodology, Validation, Formal analysis, Investigation, Writing – review & editing; Nilotpal Das: Validation, Writing – review & editing; Atin Kumar & Sharad Sachan: Validation, Formal analysis, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the Department of Natural Resources Management, Faculty of Agricultural Sciences, Shree Guru Gobind Singh Tricentenary University, Gurugram, Haryana, India, for providing the necessary facilities and support that enabled the successful completion of this research.

References

- Ah, A., and Vs, K. (2020). Studies on nutrient uptake by rabi sorghum [*Sorghum bicolor* (L.) Moench] as influenced by fortified organics with iron and zinc. *International Journal of Chemical Studies*, 8(4), 2109–2113.
<https://doi.org/10.22271/chemi.2020.v8.i4w.9938>

- Astolfi, S., Celletti, S., Vigani, G., Mimmo, T., and Cesco, S. (2021). Interaction between sulfur and iron in plants. *Frontiers in Plant Science*, 12, 670308. <https://doi.org/10.3389/fpls.2021.670308>
- Barla, S., Sahoo, H. K., and Patra, B. P. (2022). Productivity and nutrient uptake influenced by zinc and iron on summer mungbean. *International Journal of Plant & Soil Science*, 990–995. <https://doi.org/10.9734/ijpss/2022/v34i242728>
- Blake, G. R., and Hartge, K. H. (1986). Bulk density. In *Soil Science Society of America book series* (pp. 363–375). <https://doi.org/10.2136/sssabookser5.1.2ed.c13>
- Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal*, 54(5), 464–465. <https://doi.org/10.2134/agronj1962.00021962005400050028x>
- Chesnin, L., & Yien, C. H. (1951). Turbidimetric determination of available sulfates. *Soil Science Society of America Journal*, 15(C), 149–151. <https://doi.org/10.2136/sssaj1951.036159950015000c0032x>
- Dhaliwal, S. S., Sharma, V., Shukla, A. K., Kaur, J., Verma, V., Kaur, M., Singh, P., Brestic, M., Gaber, A., and Hossain, A. (2022). Interactive effects of molybdenum, zinc and iron on the grain yield, quality, and nodulation of cowpea (*Vigna unguiculata* (L.) walp.) in North-Western India. *Molecules*, 27(11), 3622. <https://doi.org/10.3390/molecules27113622>
- Dodiya, S., Pisal, R., Chaudhary, K., and Katariya, H. (2024). Integrated approach to enhancing cowpea yield, quality and nutrient composition using foliar supplements. *International Journal of Statistics and Applied Mathematics*, 9(1S), 38–42. <https://doi.org/10.22271/math.2024.v9.i1sa.1543>
- Fresno, T., Moreno-Jiménez, E., and Peñalosa, J. M. (2016). Assessing the combination of iron sulfate and organic materials as an amendment for an arsenic and copper contaminated soil. A chemical and ecotoxicological approach. *Chemosphere*, 165, 539–546. <https://doi.org/10.1016/j.chemosphere.2016.09.039>
- Gupta, S., Bara, B. M., and Lal, G. M. (2024). Effect of Foliar Spray of Micronutrients on Growth and Yield of Greengram (*Vigna Radiata* L. Wilczek). *Plant Archives*, 24(2). <https://doi.org/10.51470/plantarchives.2024.v24.no.2.065>
- Jackson, M. L. (1973). *Soil chemical analysis*. New Delhi, India: Prentice-Hall of India Pvt. Ltd. <https://www.scirp.org/reference/ReferencesPapers?ReferenceID=1453838>
- Jat, H., Yadav, K. K. and Singh, D. P. (2022). Effect of soil and foliar application of Zn and Fe on soil fertility after harvest of maize. *Biological Forum – An International Journal*, 14(1), 637–640. <https://www.researchtrend.net/bfij/pdf/111%20Effect%20of%20Soil%20and%20Foliar%20Application%20of%20Zn%20and%20Fe%20on%20Soil%20Fertility%20after%20Harvest%20of%20Maize%20Hemraj%20at.pdf>
- Kandoliya, R. U. and Kunjadia, B. B. (2018). Effect soil and foliar application of zinc and iron on micronutrients uptake by wheat in calcareous soil of Saurashtra region. *European Journal of Biotechnology and Bioscience*, 6, 65–69. <https://www.biosciencejournals.com/assets/archives/2018/vol6issue4/6-4-27-611.pdf>
- Kaur, M., Oberoi, H. K., Dhaliwal, S. S., and Rani, K. (2024). Impact of biofortification with iron (Fe) micronutrient on maize fodder in semi-arid region of Indo-Gangetic plains of India. *Journal of Plant Nutrition*, 47(12), 1943–1954. <https://doi.org/10.1080/01904167.2024.2325953>
- Kavya, P., Singh, S., Hinduja, N., Tiwari, D. and Sruthi, S. (2021). Effect of foliar application of micronutrients on growth and yield of greengram (*Vigna radiata* L.). *Legume Research-An International Journal*, 44(12), 1460–1464. <https://doi.org/10.18805/LR-4445>
- Kumar, D., Shahi, U. P., Kumar, A., Kumar, R., Kumar, S., and Tiwari, H. (2024). Effect on Soil Fertility with Zinc And Iron Fertilization in Maize (*Zea Mays* L.). *Plant Archives*, 24(SI). <https://doi.org/10.51470/plantarchives.2024.v24.sp-gabels.077>
- Kumar, D., Shahi, U. P., Shekhar, C., Kumar, A., Pal, S., and Kumar, S. (2023). Effect of Soil

- and Foliar Application of Zn and Fe on Nutrient Status of Hybrid Maize (*Zea mays L.*). *International Journal of Plant & Soil Science*, 35(19), 1110–1119. <https://doi.org/10.9734/ijpps/2023/v35i193650>
- Kumar, R., Baba, A. Y., Singh, K., Bhusan, A. and Kumar, M. (2020). Proficiency of sulfur and iron fertilization on yield, yield attributes and economical parameters of green gram (*Vigna radiata L.*) cultivar "SUBH-51". *Plant Archives*, 20(2), 8557–8560. <https://www.researchgate.net/publication/347946021>
- Kuttum, L., Swaroop, N., Thomas, T., and Barthwal, A. (2022). Interactive Effect of Zinc and Iron on Physico-Chemical Properties of Soil of Field Pea. *Asian Journal of Microbiology Biotechnology and Environmental Sciences*, 523–527. <https://doi.org/10.53550/ajmbes.2022.v24i03.015>
- Lindsay, W. L., and Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, 42(3), 421–428. <https://doi.org/10.2136/sssaj1978.03615995004200030009x>
- Ministry of Agriculture and Farmers' Welfare. (2023). *Government promoting use of drones in agriculture* (Release ID: 1899193). Press Information Bureau, Government of India.
- Mohapatra, S., Ghosh, G. K., Santra, G. H., Snigdha, A., Sethi, D., Das, S. P., and Kundu, M. C. (2023). Performance of summer green gram in response to combined soil and foliar application of major essential nutrients. *Ecology Environment and Conservation*, 29(02), 605–609. <https://doi.org/10.53550/eec.2023.v29i02.011>
- Muthumanickam, K., Chaudhary, S. K., Singh, S. P., Kumar, R., and Naik, B. M. (2022). Combined application of chemical fertilizers, organics and foliar spray of zinc and iron on yield, quality and water productivity of aerobically grown rice (*Oryza sativa*) in calcareous soil. *Journal of Plant Nutrition*, 46(13), 2990–3001. <https://doi.org/10.1080/01904167.2022.2161390>
- Olsen, S. R. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture. <https://www.scirp.org/reference/referencespapers?referenceid=1117235>
- Pahlavan-Rad, M. R., and Pesarakli, M. (2009). Response of wheat plants to zinc, iron, and manganese applications and uptake and concentration of zinc, iron, and manganese in wheat grains. *Communications in Soil Science and Plant Analysis*, 40(7–8), 1322–1332. <https://doi.org/10.1080/00103620902761262>
- Piper, C. S. (1945). Soil and plant analysis (Vol. 59, No. 3, p. 263). LWW. https://journals.lww.com/soilsci/citation/1945/03000/soil_and_plant_analysis.9.aspx
- Poonia, T., Bhunia, S. R., and Choudhary, R. (2018). Effect of Iron Fertilization on Nitrogen and Iron Content, Uptake and Quality Parameters of Groundnut (*Arachis hypogaea L.*). *International Journal of Current Microbiology and Applied Sciences*, 7(03), 2297–2303. <https://doi.org/10.20546/ijcmas.2018.703.269>
- Rathore, K. M., Sharma, M. K., Manoj, Yadav, V. K., Yadav, R. K., Meena, H., and Ghasil, B. P. (2023). Effect of Iron, Zinc and Microbial Inoculants on Soil Health and Nutrient Uptake of Urdbean (*Vigna mungo L.*) in Vertisols. *Journal of Experimental Agriculture International*, 45(10), 6–17. <https://doi.org/10.9734/jeai/2023/v45i102195>
- Roy, S., Singh, K., and Dawson, J. (2024). Effect of boron and iron on growth and yield of green gram (*Vigna radiata L.*) article type. *International Journal of Research in Agronomy*, 7(5), 366–368. <https://doi.org/10.33545/2618060x.2024.v7.i5e.701>
- Saini, A. K., and Singh, R. (2017). Effect of Sulphur and Iron Fertilization on Growth and Yield of Greengram [*Vigna radiata L.*]. *International Journal of Current Microbiology and Applied Sciences*, 6(6), 1922–1929. <https://doi.org/10.20546/ijcmas.2017.606.224>
- Shivanand, and Radder, B. M. (2020). Effect of iron sulphate application on yield, nutrients

- uptake, phosphorus and iron fractions in soil at harvest of soybean [*Glycine max* (L.) Merr.] in Vertisols of Karnataka. *Journal of Oilseeds Research*, 37(1). <https://doi.org/10.56739/jor.v37i1.136377>
- Singh, O., Kumar, S., Dwivedi, A., Dhyani, B. P., and Naresh, R. K. (2016). Effect of sulphur and iron fertilization on performance and production potential of urdbean [*Vigna Mungo* (L.) Hepper] and nutrients removal under inceptisols. *Legume Research - an International Journal, Of*. <https://doi.org/10.18805/lr.v0iof.10763>
- Subbiah, B. V. and Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils. <https://www.scirp.org/reference/References/Papers?ReferenceID=2138694>
- Timsina, P., David, A. A., Swaroop, N., Thomas, T., Bharose, R., and Saran, J. (2024). Effect of NPK, Zinc and Iron on Soil Health and Yield Parameters of Green Gram (*Vigna radiata* L.) var SML-668. *Journal of Advances in Biology & Biotechnology*, 27(7), 769–780. <https://doi.org/10.9734/jabb/2024/v27i71036>
- Walkley, A., and Black, I. A. (1934). An Examination of the Degtjareff Method for Determining Soil Organic Matter, and A Proposed Modification of The Chromic Acid Titration Method. *Soil Science*, 37(1), 29–38. <https://doi.org/10.1097/00010694-193401000-00003>
- Zafar, M., Ahmed, S., Munir, M. K., Zafar, N., Saqib, M., Sarwar, M. A., Iqbal, S., Ali, B., Akhtar, N., Ali, B., Hussain, S., Saeed, M., Al-Sadoon, M. K., and Gulnaz, A. (2023). Application of zinc, iron and boron enhances productivity and grain biofortification of mungbean. *Phyton*, 92(4), 983–999. <https://doi.org/10.32604/phyton.2023.025813>