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Response of Chickpea (*Cicer arietinum L.*) to Different Levels of Sulphur and Iron with Respect to Growth and Yield Performance

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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

Chickpea (*Cicer arietinum* L.) is a rabi pulse crop whose productivity may be constrained by inadequate management of sulphur and iron. A field experiment was conducted during the 2024–25 rabi season at the Agriculture Farm of Mahatma Gandhi Chitrakoot Gramodaya Vishwavidyalaya, Satna, Madhya Pradesh, to evaluate the effects of sulphur and iron levels on chickpea growth and yield. The experiment was arranged in a randomized block design with three replications and nine treatments comprising three sulphur levels (0, 30, and 40 kg ha^{-1}) and three iron levels (0, 3, and 4 ppm). Plant height, primary and secondary branches per plant, pods per plant, seeds per pod, seed yield, and straw yield were recorded. Both sulphur and iron significantly influenced the measured growth and yield attributes. Sulphur at 40 kg ha^{-1} produced the greatest

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plant height at 90 DAS (32.97 cm), primary branches (9.55), secondary branches (20.58), pods per plant (63.41), seeds per pod (2.52), seed yield (24.42 q ha^{-1}), and straw yield (29.90 q ha^{-1}). Iron at 4 ppm produced the greatest plant height at 90 DAS (31.92 cm), primary branches (7.80), secondary branches (17.72), pods per plant (48.88), seeds per pod (2.02), seed yield (22.95 q ha^{-1}), and straw yield (29.64 q ha^{-1}). The respective control treatments recorded the lowest values. These results indicate that 40 kg S ha^{-1} and 4 ppm Fe were associated with improved chickpea performance under the experimental conditions.

Keywords: Chickpea; Cicer arietinum L.; sulphur nutrition; iron nutrition; plant growth; yield attributes; seed yield; straw yield; nutrient management; Chitrakoot.

1. Introduction

Chickpea (*Cicer arietinum L.*) is a leguminous crop belonging to the tribe Ciceratae, family Fabaceae, and subfamily Papilionoideae (Singh & Diwakar, 1995). As one of the earliest domesticated pulses, chickpea is important to global agriculture and nutrition and is among the major legume crops worldwide. In India, it contributes to food security and rural livelihoods, particularly in Madhya Pradesh, Rajasthan, Maharashtra, and Uttar Pradesh, where favourabl eagroclimatic conditions support production. Chickpea is cultivated in two principal forms, desi and kabuli, which are morphologically and genetically distinct. The desi type (microsperma) is characterized by small, angular seeds with a thick, rough seed coat and is often associated with pink flowers. In contrast, the kabuli type (macrosperma) has larger, rounded seeds with a thin, smooth seed coat and white flowers. Carbohydrates and proteins together constitute approximately 80% of the total dry seed mass. Starch content ranges from 41% to 50%, whereas crude protein content ranges from 12.4% to 31.5%. Chickpea also contains approximately 6% fat and nutritionally important minerals, notably calcium and iron, and its protein quality is considered superior to that of several other pulses (Hirdyani, 2014). Chickpea is the world's third most important cool-season food legume, and India is the largest producer, contributing approximately 65% of global production (Food and Agriculture Organization of the United Nations [FAO], 2015). In 2020–21, chickpea occupied 8.12 million ha in India, with production of 7.46 million tonnes and productivity of 895 kg ha^{-1}. Rajasthan ranked third, with 1.859 million ha under cultivation, production of 1.972 million tonnes, and productivity of 1,061 kg ha^{-1} (Directorate of Pulses Development, 2022). Iron is an essential element involved in numerous enzyme systems in which haem or haemin acts as a prosthetic group. These haem-containing enzymes include catalases, peroxidases, and several cytochromes, which are central to respiratory metabolism. Ferredoxin is another important iron-containing protein that mediates oxidation–reduction reactions. Its involvement in photosynthesis, nitrite (NO_2^-) and sulphate (SO_4^{2-}) reduction, and nitrogen assimilation illustrates the importance of iron in plant metabolism. Iron deficiency is commonly expressed as leaf chlorosis caused by reduced chlorophyll content. Iron is the fourth most abundant element in the Earth's crust, and agricultural soils generally contain approximately 1–5% total iron, equivalent to 22.4–112 tonnes ha^{-1} in the plough layer. However, iron availability is strongly influenced by soil pH, calcium carbonate content, organic matter, phosphorus accumulation, ionic imbalances, soil texture, temperature, aeration, moisture, and compaction (Koseoglu, 1995; Lindsay & Schwab, 1982; Lucena, 2003; Mengel et al., 2001).

Iron is indispensable for plant growth and development because it participates in chlorophyll biosynthesis, respiration, chloroplast formation, photosystem activity, enzyme function, carbohydrate oxidation, nitrate reduction to ammonium, and nucleic acid metabolism (Eskandari, 2011; Havlin et al., 2014). Similarly, sulphur is the fourth major essential plant nutrient after N, P, and K because it contributes to protein synthesis, chlorophyll formation, vitamin and flavour-compound formation, and enzyme activation. Plant sulphur requirements are generally similar to phosphorus requirements and correspond to approximately 9–15% of nitrogen requirements; legumes and cruciferous crops often require more sulphur than phosphorus (Havlin et al., 2014; Hawkesford& De Kok, 2006). As a constituent of the sulphur-containing amino acids methionine (21% S) and cysteine (27% S), sulphur plays a central role in plant metabolism (Droux, 2004; Hawkesford & De Kok, 2006; Jamal et al., 2005). Sulphur can also influence the uptake and metabolism of other nutrients (Abdin et al., 2003; De Bona & Monteiro, 2010; Hawkesford & De Kok, 2006).

Sulphur facilitates the conversion of nitrogen into protein and influences the protein content of pulse crops.

It also improves the concentration of sulphur-containing amino acids and can thereby enhance protein content (Droux, 2004). Sulphur deficiency decreases nitrogen concentrations in the shoots and seeds of many legumes.

Consequently, nutrient uptake may decline, reducing crop yield and quality (Malhi et al., 2007; Schonhof et al., 2007).

Recent evidence indicates that basal and foliar sulphur applications can improve chickpea yield, nutrient content, and nutrient uptake, although the magnitude of the response depends on the application rate and method (Prajapat et al., 2026). Integrated nutrient management has also been associated with improved phenology and overall performance of chickpea-based production systems (Himavarsha et al., 2025).

Recent research has further shown that sulphur application combined with sulphur-oxidising bacteria can improve nutrient availability, nutrient uptake, and chickpea yield in calcareous soils (Nabati et al., 2025). Studies of iron nutrition in chickpea have demonstrated genotypic variation in iron accumulation and partitioning, while field-based iron fertilization can increase seed iron concentration under suitable application conditions (Jahan et al., 2023; Jahan &Tar'an, 2023).

However, the available literature has largely examined sulphur or iron nutrition separately, and evidence concerning their combined application under the slightly alkaline, iron-deficient soil conditions of Chitrakoot remains limited. The comparative responses of chickpea growth and yield attributes to graded levels of sulphur and iron under these local conditions have not been adequately documented.

1.1 Objective

The present study was therefore undertaken to evaluate the effects of different levels of sulphur and iron on the growth and yield performance of chickpea under the agro-climatic conditions of Chitrakoot, Madhya Pradesh.

2. Materials and Methods

2.1 Location, Climate and Soil of Experimental Site

The field experiment was conducted during the rabi season of 2024–25 at the Agriculture Farm (Rajola) of Mahatma Gandhi Chitrakoot Gramodaya Vishwavidyalaya, Chitrakoot, Satna, Madhya Pradesh, in the Bundelkhand region of northern Madhya Pradesh. The experimental site is situated at 25°15′ N latitude and 80°84′ E longitude, at an altitude of approximately 306 m above mean sea level. The region has a tropical savanna climate (Aw) under the Köppen classification. Winters are generally cool, with an average temperature of approximately 26.1 °C, although January temperatures may fall to 0–5 °C. Summers begin after mid-March, and temperatures may reach 49 °C in May. A distinct monsoon season extends from June to September and contributes most of the annual rainfall, with an average of approximately 100 mm in mid-June. Mean monthly weather parameters, including maximum and minimum temperature, rainfall (mm), relative humidity (%), wind speed (km h^{-1}), wind direction (°), atmospheric pressure (kPa), and solar radiation (W m^{-2}), were recorded during the 2024–25 cropping season at the Agro-meteorological Observatory, KVK Majhgawan, Satna, Madhya Pradesh.

Soil analysis during 2024–25 showed a slightly alkaline pH of 7.4, which may restrict the availability of iron, zinc, and manganese. Electrical conductivity was 0.30 dS m^{-1}, indicating non-saline soil. Organic carbon was low (0.338%), while available nitrogen was also low (205.4 kg ha^{-1}). Available phosphorus (15.38 kg ha^{-1}), potassium (242.0 kg ha^{-1}), and sulphur (24.62 kg ha^{-1}) were in the medium range. Total sulphur was 0.952%, indicating adequate reserves, although availability depends on mineralization. Available iron (2.82 ppm) was below the critical limit of 4.5 ppm, classifying the soil as iron-deficient. Under slightly alkaline conditions, this deficiency may be more pronounced and may cause iron chlorosis in younger leaves.

Among chemical iron sources, anhydrous ferric chloride ($FeCl_3$) may be used to address iron deficiency. Because it is highly soluble in water, it supplies iron in the ferric (Fe^{3+}) form, which may become available to plants after hydrolysis. Ferric chloride may be applied as a foliar spray at lower concentrations (0.2–0.5%) to correct visible deficiency symptoms. For soil application, $FeCl_3$ may be incorporated with organic amendments or chelating agents to minimize precipitation and improve iron availability under alkaline conditions. However, its effectiveness depends on soil reaction, and integrating organic matter or chelated iron may improve efficiency and maintain iron availability in the rhizosphere. Overall, the soil was low in nitrogen and organic carbon, medium in phosphorus, potassium, and sulphur, and deficient in iron. Therefore, integrated nutrient management involving the judicious use of organic manures and inorganic fertilizers is important for maintaining soil health and improving crop productivity under these conditions.

2.2 Details of Experiment, Treatment and Crop Management

Certified seed of the chickpea variety Keshav was sown on 19 October 2024 during the rabi season by seed drill @ 80 kg ha^{-1} with a spacing of 30 × 10 cm. The experiment was laid out in a randomized block design with nine treatments and three replications. The treatments were T_1 (0 kg sulphur ha^{-1} + 0 ppm iron), T_2 (0 kg sulphur ha^{-1} + 3 ppm iron), T_3 (0 kg sulphur ha^{-1} + 4 ppm iron), T_4 (30 kg sulphur ha^{-1} + 0 ppm iron), T_5 (30 kg sulphur ha^{-1} + 3 ppm iron), T_6 (30 kg sulphur ha^{-1} + 4 ppm iron), T_7 (40 kg sulphur ha^{-1} + 0 ppm iron), T_8 (40 kg sulphur ha^{-1} + 3 ppm iron), and T_9 (40 kg sulphur ha^{-1} + 4 ppm iron). The recommended fertilizer dose was 20:60:20 kg N:P:K ha^{-1}. Urea, Diammonium phosphate (DAP), Muriate of potash, gypsum, and ferric chloride were used as sources of N, P, K, S, and Fe, respectively. The crop was managed according to the standard package of practices, and plant-protection measures were applied when required. Data on growth, yield, and quality were recorded periodically and statistically analysed for significance.

The sulphur and iron treatment combinations are summarised in Table 1.

Table 1. Treatment combinations of sulphur and iron applied to chickpea

Treatment	Sulphur level (kg ha^{-1})	Iron level (ppm)
T_1	0	0
T_2	0	3
T_3	0	4
T_4	30	0
T_5	30	3
T_6	30	4
T_7	40	0
T_8	40	3
T_9	40	4

The crop was irrigated twice using a sprinkler system, once after sowing and once before flowering. Gap filling and thinning were undertaken to maintain the plant population. Weeding and hoeing were performed periodically to keep the experimental plots free of weeds. Plant-protection measures were applied when pod borer infestation exceeded the economic threshold level of 1–2 larvae m^{-1} row length or 5–10% pod damage. Quinalphos was sprayed at 2 mL L^{-1} water to control chickpea pod borer.

3. Results and Discussion

3.1 Effect of Sulphur Levels on Growth and Yield Attributes of Chickpea

The data presented in Table 2 show that different sulphur levels significantly influenced the growth and yield attributes of chickpea. Plant height increased progressively with increasing sulphur levels throughout crop growth. The greatest plant height was recorded with 40 kg S ha^{-1} (S_{40}), measuring 17.87, 22.02, and 32.97 cm at 30, 60, and 90 DAS, respectively. This treatment was significantly superior to S_{30} and the control (S_0), whereas the lowest plant height (13.88, 18.39, and 28.76 cm at 30, 60, and 90 DAS, respectively) was recorded with S_0. The increase in plant height following sulphur application may be attributed to enhanced chlorophyll synthesis, photosynthetic activity, and nutrient utilisation, resulting in vigorous vegetative growth. Janrao (2019) similarly observed the greatest plant height, leaf area index, and dry-matter accumulation with 40 kg S ha^{-1}. Kala et al. (2017) also reported that increasing sulphur levels to 40 kg S ha^{-1} significantly improved chickpea growth parameters.

A similar trend was observed for the number of primary branches per plant. The greatest numbers of primary branches were recorded with S_{40} (3.48, 4.85, and 9.55 at 30, 60, and 90 DAS, respectively), whereas the lowest values were recorded with the control treatment (S_0). Likewise, the number of secondary branches per plant increased significantly with increasing sulphur levels, reaching 20.58 with S_{40} compared with 12.23 with S_0. Sulphur is a constituent of sulphur-containing amino acids and proteins and therefore supports cell division, enzyme activity, and overall plant growth. These findings agree with those of Janrao (2019), who reported that 40 kg S ha^{-1} significantly increased the number of branches per plant in chickpea.

Table 2. Chickpea crop growth and yield influenced by different level of sulphur and iron application

Treatments	Plant height (cm)			No. of primary branches/plant			No. of secondary branches/plant	No. of pods/plant	No. of seeds/pod	Seed yield (q/ha)	Straw yield (q/ha)
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS					
Sulphur levels(kg/ha)											
S0	13.88	18.39	28.76	2.01	3.06	5.26	12.23	26.44	1.31	18.38	19.42
S30	15.56	20.40	31.51	2.7	3.74	6.88	15.34	38.53	1.71	21.77	25.66
S40	17.87	22.02	32.97	3.48	4.85	9.55	20.58	63.41	2.52	24.42	29.9
S.Em±	0.20	0.22	0.22	0.07	0.04	0.09	0.14	0.92	0.01	0.17	0.31
CD (p=0.05)	0.63	0.68	0.69	0.21	0.13	0.27	0.42	2.80	0.04	0.53	0.95
Iron levels(ppm)											
Fe0	14.85	19.46	30.16	2.47	3.63	6.72	14.56	38.45	1.67	20.13	20.78
Fe3	15.63	20.23	31.16	2.71	3.84	7.18	15.87	41.04	1.85	21.49	24.56
Fe4	16.83	21.13	31.92	3.01	4.18	7.8	17.72	48.88	2.02	22.95	29.64
S.Em±	0.20	0.22	0.22	0.07	0.04	0.09	0.14	0.92	0.01	0.17	0.31
CD (p=0.05)	0.63	0.68	0.69	0.21	0.13	0.27	0.42	2.80	0.04	0.53	0.95

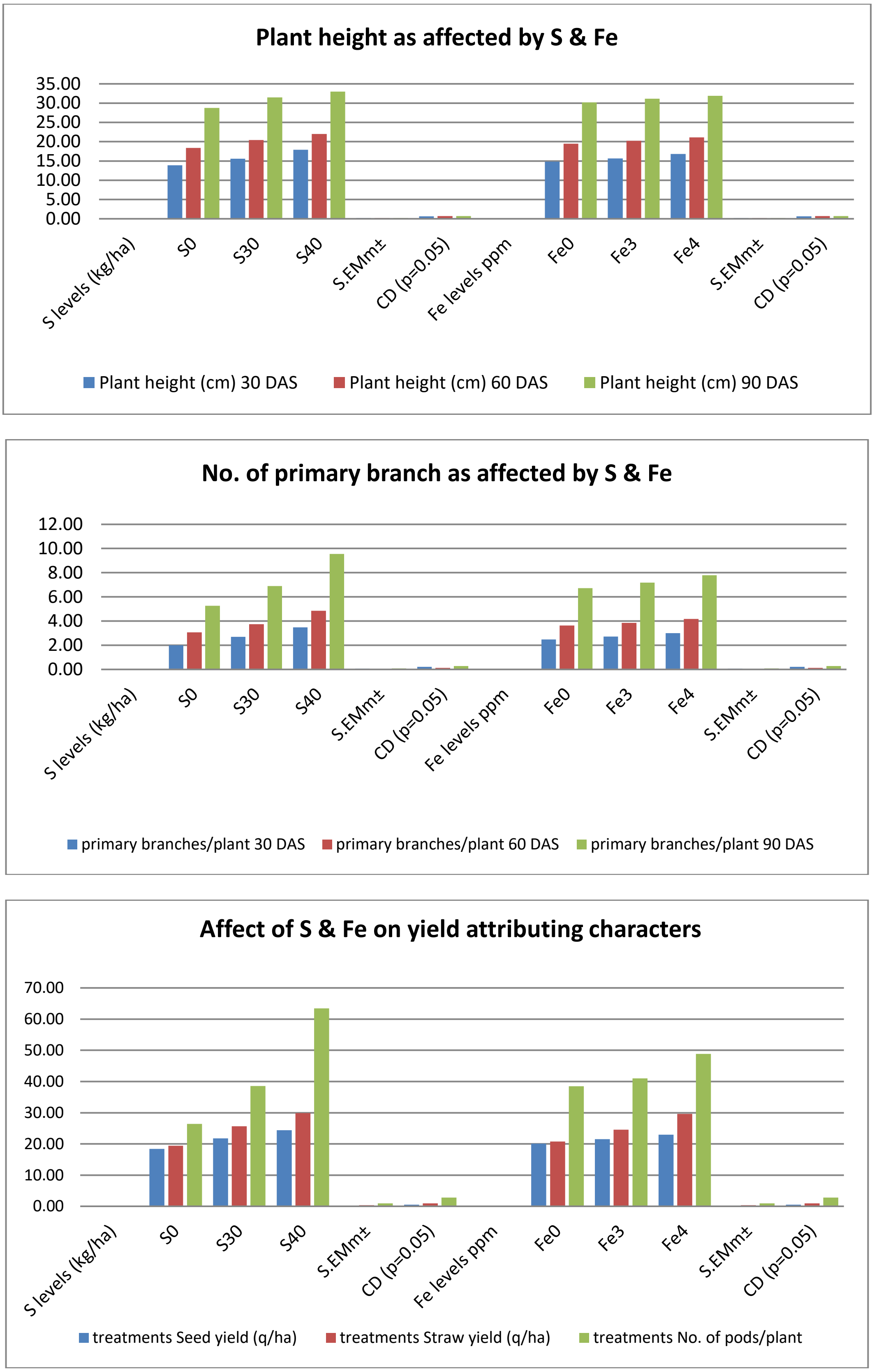

Fig. 1. Bar graph showing yield attributing characters

Yield-attributing characters were also significantly influenced by sulphur application. The greatest numbers of pods per plant (63.41) and seeds per pod (2.52) were recorded with S_{40}, whereas the lowest values (26.44 pods per plant and 1.31 seeds per pod) were recorded with the control. The increase in reproductive system attributed to improved photosynthetic efficiency, protein synthesis, and assimilates translocation from source to sink under adequate sulphur nutrition. Nawange et al. (2011) similarly found that sulphur application up to 40 kg ha^{-1} significantly increased pods per plant, seeds per pod, and other yield attributes of chickpea. Comparable results were reported by Kala et al. (2017) and Yadav et al. (2016), who observed improvements in yield attributes with 40 kg S ha^{-1}.

Seed and straw yields were significantly increased by sulphur fertilization. The greatest seed yield (24.42 q ha^{-1}) and straw yield (29.90 q ha^{-1}) were recorded with S_{40}, followed by S_{30} (21.77 and 25.66 q ha^{-1}, respectively), whereas the lowest seed yield (18.38 q ha^{-1}) and straw yield (19.42 q ha^{-1}) were recorded with the control treatment (S_0). The yield increase may be attributed to improved vegetative growth, pod formation, nutrient uptake, and translocation of photosynthates to developing seeds. Sulphur also contributes to protein synthesis, enzyme activation, nitrogen metabolism, and chlorophyll formation, thereby supporting crop productivity.

The present findings agree with those of Makol et al. (2020), who reported improved chickpea growth, nutrient uptake, and yield with 40 kg S ha^{-1} under a rice–chickpea cropping system. Nawange et al. (2011) also reported that 40 kg S ha^{-1} produced the greatest seed yield (1,665 kg ha^{-1}) and stalk yield (2,665 kg ha^{-1}). Similarly, Kala et al. (2017) observed that increasing sulphur levels to 40 kg S ha^{-1} improved growth, yield attributes, nutrient content, and yield. Yadav et al. (2016) reported that 40 kg S ha^{-1} increased grain yield and nutrient uptake compared with lower sulphur levels. More recently, Yadav et al. (2024) reported that sulphur application up to 40 kg ha^{-1} increased growth rate, yield attributes, and seed yield relative to the control. Overall, sulphur application improved chickpea growth, yield attributes, and productivity, and S_{40} was the most effective level under the experimental conditions.

3.2 Effect of Iron Levels on Growth and Yield Attributes of Chickpea

The data presented in Table 2 show that iron application significantly influenced chickpea growth and yield attributes. Plant height increased progressively with increasing iron levels. Fe_4 (4 ppm) recorded the greatest plant heights of 16.83, 21.13, and 31.92 cm at 30, 60, and 90 DAS, respectively, and was significantly superior to Fe_3 and Fe_0. The lowest plant heights (14.85, 19.46, and 30.16 cm) were recorded with Fe_0. The increase in plant height following iron application may be attributed to the role of iron in chlorophyll synthesis, photosynthetic activity, respiration, and energy transfer, which support cell division and vegetative growth. Janmohammadi et al. (2012) similarly reported an increase in chickpea plant height following iron application. Tului et al. (2021) also reported that iron activates physiological and biochemical processes associated with vegetative growth.

The number of primary branches per plant increased significantly with increasing iron levels. The greatest numbers of primary branches were recorded with Fe_4 (3.01, 4.18, and 7.80 at 30, 60, and 90 DAS, respectively), whereas the lowest values were recorded with Fe_0. Similarly, the number of secondary branches per plant was significantly greater with Fe_4 (17.72) than with Fe_0 (14.56). The increase in branching may be attributed to enhanced photosynthetic efficiency and nutrient translocation under adequate iron nutrition. Iron also regulates enzyme activity and auxin synthesis, thereby supporting vegetative growth. These findings agree with those of Janmohammadi et al. (2012) and Rathod et al. (2022), who reported increases in primary and secondary branches following iron application.

Iron application also significantly influenced yield-attributing characters. The greatest numbers of pods per plant (48.88) and seeds per pod (2.02) were recorded with Fe_4, whereas the lowest values (38.45 pods per plant and 1.67 seeds per pod) were recorded with Fe_0. The improvement in reproductive attributes may be associated with enhanced chlorophyll synthesis, carbohydrate production, and assimilate translocation from source to sink, resulting in improved flower retention and pod development. Dhaliwal et al. (2021) reported that foliar iron application improved chickpea productivity and iron accumulation. Rathod et al. (2022) also reported that combined iron and zinc application increased pods per plant and other yield components.

Seed and straw yields were significantly influenced by iron application. The greatest seed yield (22.95 q ha^{-1}) and straw yield (29.64 q ha^{-1}) were recorded with Fe_4, and these values were significantly superior to those with Fe_3 and Fe_0. The lowest seed yield (20.13 q ha^{-1}) and straw yield (20.78 q ha^{-1}) were recorded with Fe_0. The yield increase may be attributed to improved chlorophyll formation, photosynthetic rate, nutrient uptake, enzyme activity, and partitioning of photosynthates to reproductive organs. Iron is an essential component of cytochromes and ferredoxin, which participate in electron transport during photosynthesis and respiration and thereby contribute to biomass production and seed yield.

These findings are supported by earlier studies. Dhaliwal et al. (2021) reported that foliar application of mineral, chelated, and nano forms of iron increased iron uptake, grain yield, and straw yield of chickpea, with nano-fertilisers showing the greatest response. Pal et al. (2019) observed that foliar ferrous sulphate application increased grain iron concentration and yield relative to the control. Pal et al. (2021) reported that the simultaneous foliar application of zinc sulphate, ferrous sulphate, and urea increased iron accumulation in different plant parts and improved grain productivity through agronomic biofortification. The beneficial effects of iron on growth and yield have also been associated with its involvement in nitrogen metabolism, chlorophyll biosynthesis, and photosynthate translocation. Tului et al. (2021) reported that iron activates metabolic pathways involved in photosynthesis, enzyme activation, and auxin synthesis, leading to increased plant height and biomass accumulation. Pal et al. (2023) also observed that iron application improved photosynthetic efficiency, symbiotic parameters, and chickpea productivity under field conditions.

Pal et al. (2019) reported that foliar application of ferrous sulphate and urea improved grain yield and iron biofortification in chickpea. Janmohammadi et al. (2012) also reported improvements in chlorophyll content, plant height, branching, and biological yield following iron fertilization in chickpea cultivars. Overall, the present investigation showed that 4 ppm iron (Fe_4) improved plant growth, branching, yield attributes, and productivity under the experimental conditions. This response may be associated with the role of iron in chlorophyll formation, photosynthesis, respiration, enzyme activation, and nutrient metabolism. The results are consistent with those of Dhaliwal et al. (2021), Janmohammadi et al. (2012), Pal et al. (2019, 2021, 2023), Rathod et al. (2022), and Tului et al. (2021).

4. Discussion

The present investigation showed that sulphur and iron application significantly improved chickpea growth, yield attributes, and productivity. Increases in plant height, primary and secondary branches, pods per plant, seeds per pod, seed yield, and straw yield with increasing sulphur and iron levels may be associated with the essential roles of these nutrients in plant metabolism. Sulphur is a constituent of sulphur-containing amino acids, proteins, and enzymes and contributes to chlorophyll formation, photosynthesis, nitrogen metabolism, and biological nitrogen fixation. Iron is involved in chlorophyll biosynthesis, electron transport, respiration, enzyme activation, and photosynthetic processes. Adequate availability of both nutrients supported vegetative growth, dry-matter accumulation, and the translocation of photosynthates from source to sink, thereby improving reproductive development and yield. The response to 40 kg S ha^{-1} and 4 ppm Fe indicates that these levels created favourable physiological conditions for nutrient uptake, biomass production, and seed formation under the experimental conditions.

Similar responses to sulphur application up to 40 kg ha^{-1} have been reported for chickpea growth, yield attributes, and seed yield (Kala et al., 2017; Makol et al., 2020; Nawange et al., 2011; Yadav et al., 2024). Iron fertilization has likewise been reported to improve chickpea growth, nutrient uptake, photosynthetic activity, and productivity (Dhaliwal et al., 2021; Janmohammadi et al., 2012; Pal et al., 2019, 2021, 2023; Rathod et al., 2022; Tului et al., 2021). The present findings are therefore consistent with previous studies and indicate that balanced sulphur and iron nutrition can improve chickpea growth and yield under the conditions of Chitrakoot.

5. Conclusion

The study showed that sulphur and iron application improved chickpea growth and yield under the agroclimatic conditions of Chitrakoot, Madhya Pradesh. Among the sulphur treatments, 40 kg S ha^{-1} produced the greatest plant height, numbers of branches, pods per plant, seeds per pod, seed yield, and straw yield. Similarly, 4 ppm iron performed better than the lower iron levels and the control for the principal growth and yield parameters. These responses may be associated with the role of sulphur in protein synthesis and nutrient metabolism and the role of iron in chlorophyll formation, photosynthesis, and enzyme activity. On the basis of the observed results, 40 kg S ha^{-1} and 4 ppm Fe were effective for improving chickpea productivity at the experimental site. Further validation across seasons and soil types is required before wider recommendations are made.

6. Limitation

The experiment was conducted during one rabi season at a single location, which limits the wider applicability of the findings. Although the treatment structure suggests a factorial arrangement, treatment-combination and sulphur × iron interaction effects were not clearly reported. The method and timing of iron application also require clarification. Economic returns, nutrient uptake, and residual soil-fertility data were not presented. Multi-season and multi-location studies with complete interaction analysis are therefore needed to confirm the reliability and practical relevance of the observed responses.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

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

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