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ARTICLE

Ecological Implications of Foliar Zinc and Iron Application on Growth Dynamics and Sustainable Productivity of Chickpea (Cicer arietinum L.)

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ABSTRACT

The physico-chemical analysis of agricultural soil revealed a textured sandy loam at the surface (0–15 cm), with low organic carbon content (0.42%) and moderate levels of nitrogen (157 kg/ha), phosphorus (15.5 kg/ha), and potassium (112.6 kg/ha), under neutral pH conditions (pH 7.4). The chickpea variety PG-186 was used to evaluate the impact of nutrient treatments on plant performance and agroecological outcomes. Experimental findings demonstrated a significant influence of various treatments on the growth, yield, and economic returns of chickpea cultivation. The treatment comprising 100% Recommended Dose of Fertilizers (RDF) along with foliar application of 0.6% $ZnSO_4$ and 0.9% $FeSO_4$ at pre-flowering and pod development stages (T8) resulted in the maximum plant height (15.5 cm, 33.7 cm, 45.0 cm), dry matter accumulation (27.5 g, 245.2 g, 1006.7 g/m²), and number of branches per plant (3.47, 5.00, and 8.63) at 45, 75, and 105 Days After Sowing (DAS), respectively. This treatment also resulted in the highest grain yield (21.00 q/ha) and stover yield (38.67 q/ha), along with a maximum net return of ₹95,392/ha and a benefit-to-cost ratio of 2.32. From an ecological standpoint, this study highlights the vital role of balanced and targeted nutrient management in enhancing agroecosystem productivity while maintaining ecological balance. The integration of micronutrient foliar sprays not only boosts nutrient uptake efficiency and plant health but also reduces dependency on excessive chemical fertilizers, thereby mitigating potential negative impacts on soil ecology. Overall, the findings underscore the ecological importance of optimizing nutrient inputs in legume-based cropping systems to foster sustainable agricultural practices that align with ecological resilience, soil health preservation, and environmental stewardship.

Keywords: Chickpea; Foliar Application; ZnSO4; FeSO4; Growth; Productivity

1. Introduction

Since the early days of Indian civilisation, legumes have been an essential component of the human diet and remain so now all around. Among them, the annual pulse crop from the Leguminosae/Fabaceae family, *Cicer arietinum* L., is sometimes known as chickpea. It also goes by the names "Garbanzo bean" or "Bengal gramme" [1]. Though naturally low in sodium, chickpeas are quite nutritious and provide a great supply of protein (more than cereal grains), dietary fibre, vital fatty acids, vitamins, and minerals. These qualities help explain its major health advantages, making it a nutritional component of great importance for the rising world population [2,3]. Chickpea plays a vital role in biological nitrogen fixation through symbiosis with Rhizobium bacteria, enriching soil nitrogen levels naturally. This reduces the need for synthetic fertilizers, promoting healthier soil microbiomes and fostering sustainable agriculture. Enhanced nitrogen availability supports diverse plant growth, encouraging varied insect and microbial populations. The increased biodiversity within the agroecosystem strengthens resilience against pests and diseases. Ultimately, chickpea cultivation contributes to a more balanced and productive ecosystem [3].

Along with minerals like calcium, iron, and niacin [4], chickpeas are especially prized for their vital vitamins, riboflavin, niacin, thiamine, folic acid, and beta-carotene, a precursor of vitamin A. It is quite important for the diets of people who either choose plant-based nutrition or cannot afford animal-based proteins. Chickpea seeds provide 50–58% carbs, moisture (7–8%), saturated fats (3.8–10.2%), proteins (20–22%), and 1% micronutrient nutritionally [4,5]. However, agricultural problems, such as zinc (Zn) shortages in soils, greatly affect chickpea output, especially in India [6,7]. Many different plant metabolic activities, including internode elongation, flower initiation, seed generation, and protein synthesis, depend on zinc. In metabolic, regulatory, and developmental pathways, it is absolutely vital [8]. Plants lacking zinc show poor water control, which stunts development, lowers leaf size, and delays maturation. Usually harming whole plant health and productivity, symptoms show as pale green leaves that eventually turn reddish-brown with necrotic patches [9].

Analogously, iron (Fe) is another essential element needed for important plant processes, including photosynthesis, seed development, and enzymatic activities. It directly affects nitrogen fixation and chlorophyll production.

Plants deprived of iron develop interveinal chlorosis and, in extreme cases, leaf browning and wilting. In agricultural soils, a deficit of Zn and Fe influences not only plant development but also reduces the micronutrient content in the seeds produced. Human populations eating these nutrient-deficient crops may suffer from similar shortages [10].

While zinc insufficiency is associated with compromised immune function, increased risk of infertility, and mental health problems including depression [11], inadequate iron consumption can induce anaemia, cognitive problems, and impaired physical performance in humans. Correcting these micronutrient shortages has become a global concern; biofortification is a viable and cost-effective approach. By means of agronomic techniques or genetic modification, biofortification seeks to raise crop mineral content, thereby providing a sustainable remedy for malnutrition [12,13]. One practical way to address micronutrient shortages worldwide is fortify chickpeas with iron and zinc. Eating nutritionally enhanced crops can greatly increase daily nutrient intake and help to reduce Fe and Zn deficits related to health risks [14]. These issues led to research on the effects of foliar application of zinc and iron on the growth, productivity, and nutritional value of chickpea.

Zinc (Zn) and iron (Fe) are indispensable in agricultural ecology, improving plant development, soil fertility, and maintaining ecosystem sustainability. While iron helps chlorophyll synthesis and electron transport, therefore enhancing crop productivity and resilience, zinc is necessary for enzyme activation, photosynthesis, and hormone production. These micronutrients help to cycle nutrients by affecting microbial activity and organic matter breakdown, therefore preserving soil condition. By improving plant tolerance to abiotic conditions such as salinity and drought, these supplements help to lower the demand for excessive fertilisers, thus decreasing soil deterioration and groundwater contamination. Moreover, the enrichment of Zn and Fe in crops enhances their nutritional quality, thereby addressing food system micronutrient shortages. Including these micronutrients into environmentally friendly nutrient management helps agriculture to become more ecologically balanced, robust, and sustainable [12–15]. By addressing the above research gap, our study aims to examine the effect of foliar application of zinc and iron on the yield and quality of chickpeas

2. Materials and Methods

The experiment was conducted during the Rabi seasons of 2022-2023 and 2023-2024, using the chickpea variety PG-186 (purchased from GBPUA&T, Pantnagar, India) at the Agriculture Research Farm, Graphic Era Hill University, Dehradun, Uttarakhand. Initially the soil samples were collected with the help of auger tool from the field at 0-15 cm depth and analyzed for different like texture, pH, and available nutrients, found that the soil is sandy loam in texture, having neutral soil reaction (pH 7.4) whereas low in organic carbon (0.39%), moderate nitrogen (157 kg ha^{-1}), available phosphorus (15.5 kg ha^{-1}) and available potassium (112.6 kg ha^{-1}) with natural soil reaction. The experiment was laid out in a randomized block design with 8 treatments and 3 replications viz. Control (T_1), $ZnSO_4$ @ 0.3% at pre-flowering and pod development stage (PF + PD) (T_2), $ZnSO_4$ @ 0.6% (PF + PD) (T_3), $ZnSO_4$ @ 0.9% (PF + PD) (T_4), $FeSO_4$ @ 0.3% (PF + PD) (T_5), $FeSO_4$ @ 0.6% (PF + PD) (T_6), $FeSO_4$ @ 0.9% (PF + PD) (T_7), $ZnSO_4$ @ 0.6% + $FeSO_4$ @ 0.9% (PF + PD) (T_8). The gross and net plot sizes were 4.00 m x 3.00 m and 3.40 m x 2.00 m, respectively. The spacing of 30 cm x 10 cm was adopted for chickpea. The crop was sown in the third week of October, and harvested in the first week of April. The recommended fertilizer dose (20:40:40 kg/ha^{-1} as N: P_2O_5 and K_2O) was applied at the time of sowing through urea, single super phosphate and murate of potash. Gap filling and thinning were conducted as needed to sustain the desired plant population. Treatment implementation was conducted according to standard methods. Foliar applications of zinc and iron were done at the pre-flowering and pod development stages, using 800 litres of water per hectare as per the treatments. The crop was maintained weed-free by applying one spray of pendimethalin 30% EC at 2.5 L/ha at 2 DAS, followed by two hand-weedings at 30 DAS and 60 DAS. The first irrigation was administered before sowing to promote consistent germination, while the second irrigation was applied before the flowering stage. The crop was kept free from pests and diseases through the application of a single spray of Emamectin Benzoate 5% SG at a concentration of 2g/L.

Five randomly chosen and tagged plants from the third row in every experimental plot were used to record different growth factors, including plant height and branch count. This choice guaranteed consistency in data collection and reduced edge effects that can affect plant development by means of variations in environmental exposure. Ten randomly selected plants from the gathered produce were used for yield-related characteristics. Among the other yield factors evaluated were pod length, pod count per plant, pod seed count, and seed index. To assess the chickpea production under the specified experimental conditions, general yield values, including seed yield, biological yield, stover yield, and the harvesting index, were also noted. The financial feasibility of the chickpea crop was ascertained by means of an economic study. Important economic measures evaluated were net return, gross return, cost of production, and benefit-to-cost ratio. The entire cost of farming carried out during the experiment, alon with the current market prices of chickpea, formed the foundation of the economic calculations.

Under a Randomised Block Design (RBD), the gathered data underwent statistical analysis via Analysis of Variance (ANOVA). By lowering variation within blocks, this statistical method helped ascertain the relevance of treatment effects. Using the OPSTAT statistical program supplied by Chaudhary Charan Singh Haryana Agricultural University, data analysis was conducted, guaranteeing consistent and reliable interpretation of results.

3. Results and Discussion

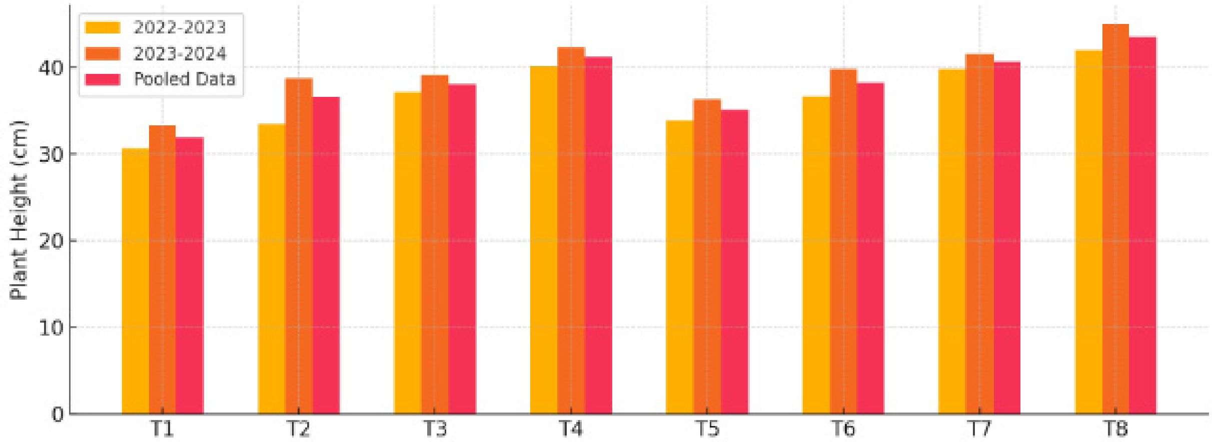
3.1. Plant Height and Number of Branches/Plant

The results indicate that plant height and the number of branches per plant of Chickpea were significantly influenced by the various treatments **(Supplementary Materials TS1)**. The pooled data over two years concluded that $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8) recorded statistically higher plant height (43.52 cm) at harvest which was statistically at par with $ZnSO_4$ at 0.9% (PF + PD) (T_4) and $FeSO_4$ at 0.9% (PF + PD) (T_7). It may be attributed to increased iron availability, which stimulates metabolic and enzymatic activities, boosting plant growth. Additionally, zinc application influences auxin synthesis, which enhances plant growth and improvement. Similar research findings were reported by Kumar *et al*. (2020), who observed that the highest plant height (43.33 cm at 80 DAS) was achieved with the application of $FeSO_4$ at 6 kg + $ZnSO_4$ at 4 kg.

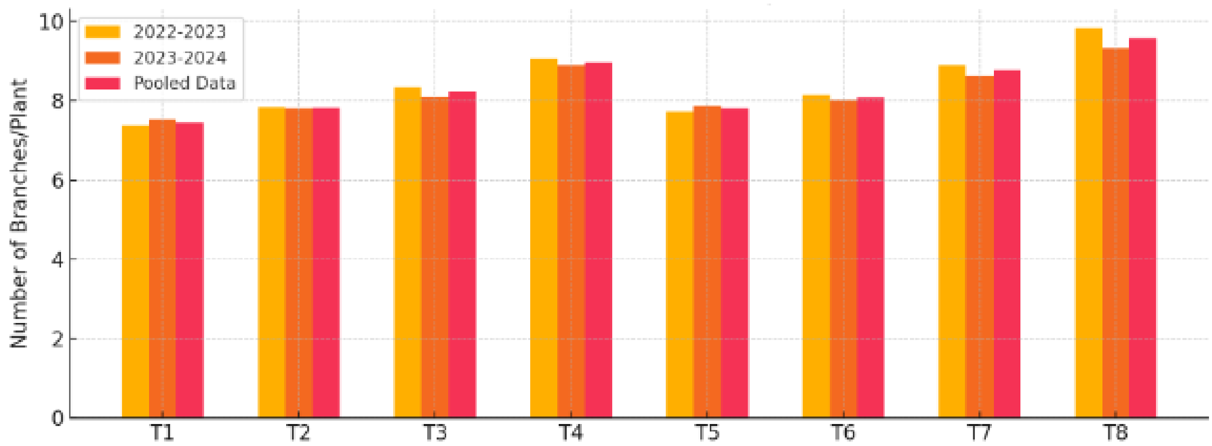
At harvest, the maximum number of branches per plant (9.59/plant) as observed in the pooled data over two years was obtained with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8) as presented in **Table 1**. It was statistically equivalent to $ZnSO_4$ at 0.9% (T_4), $FeSO_4$ at 0.9% (PF + PD) (T_7), and substantially greater than other treatments (**Figure 1**). It may be attributed to the foliar application of zinc and iron. These nutrients are quickly absorbed by the plant's leaves and transported to the growing tips, where they stimulate auxin activity, thereby promoting shoot development. Gangola and his colleague [15] reported the maximum number of branches per plant (30.96 at harvest), with RDF + 0.5% $ZnSO_4$ + 0.5% $FeSO_4$.

Table 1. Effect of foliar nutrition and spraying schedule on seed yield and harvest index of chickpea.

Treatments	Seed Yield (q/ha)			Harvest Index (%)		
	2022–2023	2023–2024	Pooled Data	2022–2023	2023–2024	Pooled Data
T_1	12.17	14.11	13.14	33.64	33.51	33.58
T_2	14.41	16.07	15.24	33.81	33.43	33.62
T_3	15.89	17.22	16.56	33.84	33.50	33.67
T_4	18.03	19.33	18.68	34.44	33.91	34.18
T_5	13.20	15.67	14.43	33.92	33.15	33.54
T_6	15.02	16.67	15.85	33.28	33.47	33.38
T_7	17.47	19.11	18.29	34.49	33.86	34.18
T_8	19.14	21.00	20.07	34.73	35.21	34.97
SEm±	0.72	0.59	0.48	1.42	0.82	0.78
CD 5 %	2.17	1.79	1.47	4.32	2.50	2.38



(a)

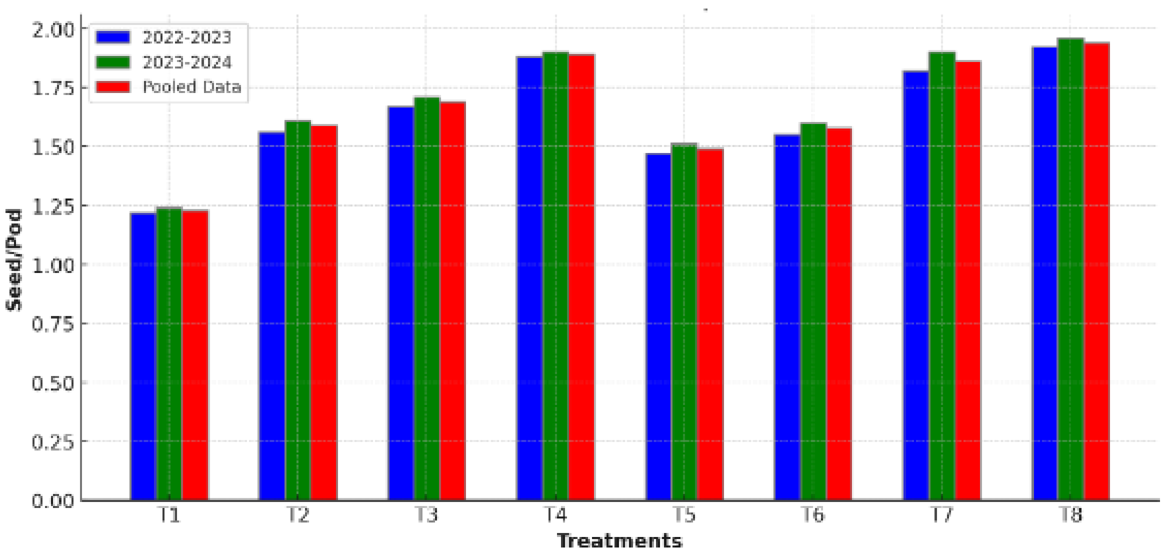


(b)

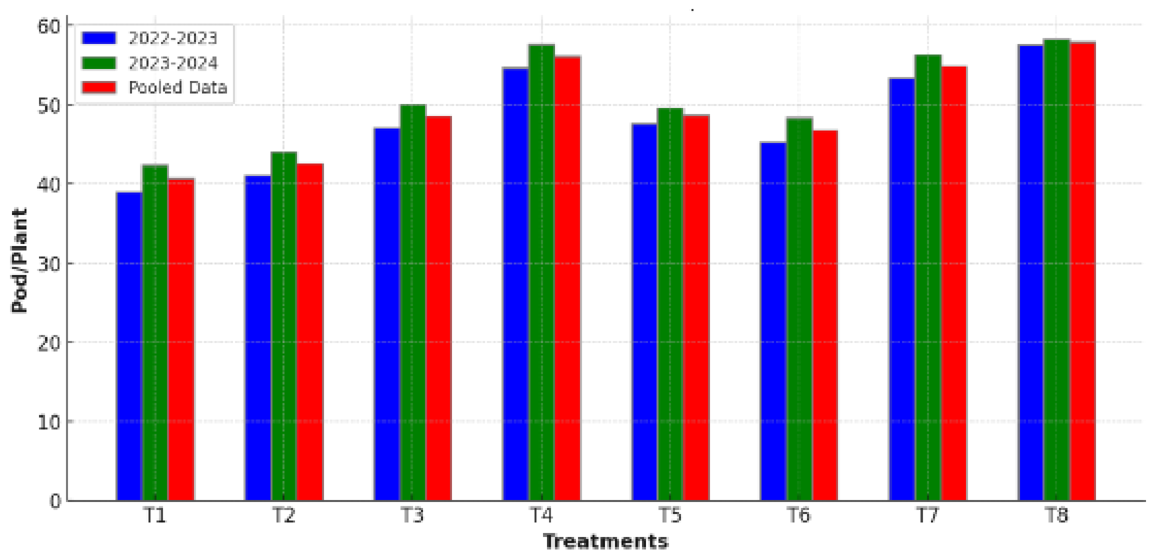
Figure 1. Effect of foliar nutrition and spraying schedule on plant height and the number of branches per plant for the treatment (T1 to T8) across the years 2022-2023, 2023-2024, and pooled data of chickpea. (**a**) Plant height (in cm); (**b**) Number of branches per plant for each treatment.

3.2. Number of Seed/Pod and Pod/Plant

Results indicated a significant increase in the number of seeds per pod and pods per plant with different treatments as presented in **Supplementary Materials TS2**. Maximum number of seed/pod (1.94) and pod/plant (57.93) was obtained with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8). It was statistically at par with $ZnSO_4$ at 0.9% (PF + PD) (T_4) and $FeSO_4$ at 0.9% (PF + PD) (T_7), and significantly greater than the rest of the treatments. The maximum number of pods per plant (58.32) was obtained with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8). $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8) resulted in a 37.8% and 20.77% increase in number of pods per plant compared to control (T_1) and $FeSO_4$ at 0.6% (PF + PD) (T_6), respectively (**Figure 2**). This may be due to the fact that foliar application of zinc and iron facilitates improved assimilate translocation to the reproductive structures, enhances photosynthesis, and supports better flower development and pollination. These findings align with the research of Valenciano *et al.* [16], which demonstrated that the application of Zn to *Cicer arietinum* enhances the growth parameters and yield of the plant.



(**a**)



(**b**)

Figure 2. This graph represents the effect of foliar nutrition and spraying application at different schedules on the seed per pod of chickpea. This graph compares both the Seed per Pod and Pod/Plant data across the treatments (T1 to T8) for the years 2022-2023 and 2023-2024, as well as the pooled data. (**a**) Seed/Pod data comparison; (**b**) Pod/Plant data comparison.

3.3. Seed Yield and Harvest Index

In the current investigation, a significant variation was observed in the yield of chickpea among the various treatments as presented. maximum seed yield (20.47 q/ha) was achieved with $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8) application. Seed yield enhanced by the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8) by 48.83% and 21.95% was obtained over control (T_1) and $ZnSO_4$ at 0.9% (PF + PD) (T_3), respectively **(Figures 3** and **4)**. It might be due to the reason that adequate supply and efficient utilization of both macro and micronutrients in chickpea cultivation contributed to enhanced growth and yield attributes. Iron facilitated chlorophyll metabolism and photosynthesis, promoting greater assimilation of nutrients. Meanwhile, zinc played a vital role in carbohydrate and protein synthesis, synergistically leading to increased grain yield in chickpea.

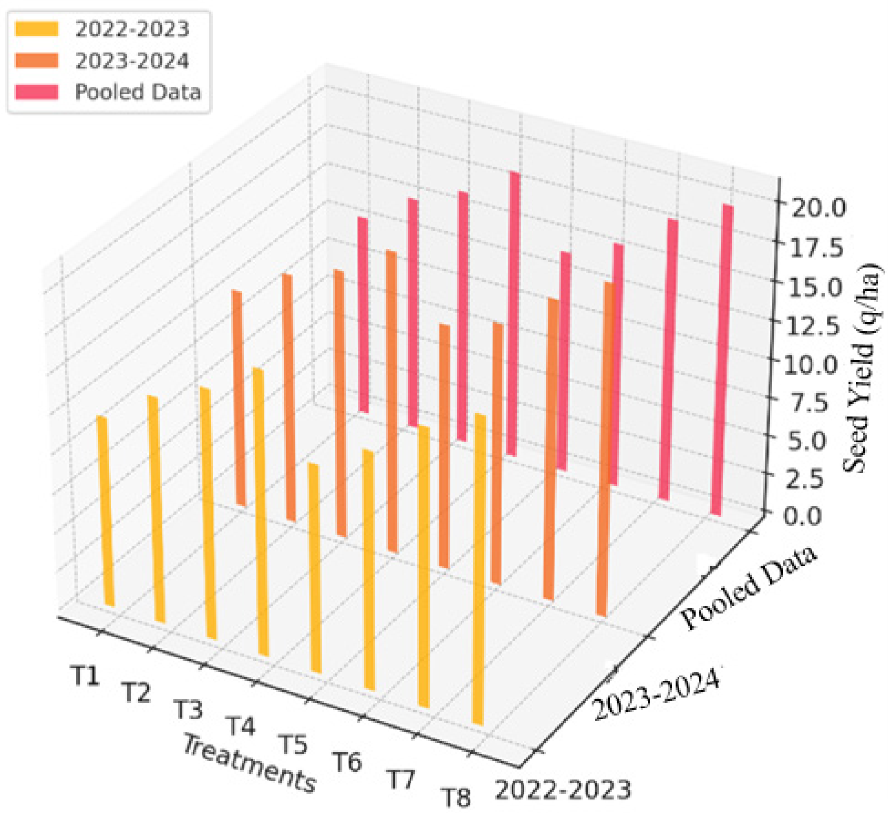


Figure 3. Effect of foliar nutrition and spraying schedule on seed yield of chickpea.

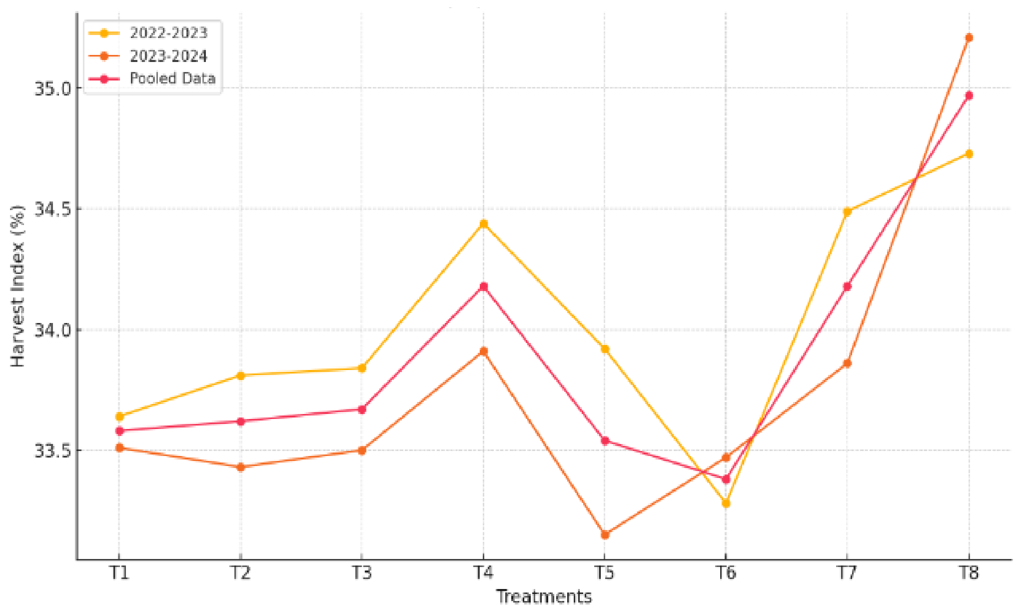


Figure 4. Effect of foliar nutrition and spraying schedule on harvest index of chickpea.

The minimum seed yield (14.11 q/ha) was recorded under the control treatment (T_1). The significantly lower grain yield observed with the advised dose of NPK may be ascribed to the minimised availability of both major and micronutrients in the soil, leading to decreased nutrient uptake **(Table 1)**. This, in turn, can result in lower photosynthate production, which adversely affects yield-attributing characteristics and ultimately results in reduced yield.

Minimum growth was observed in the crops which were not treated with fertilizer. Iron is a crucial micronutrient for plants, essential for antioxidant enzymes that protect chloroplasts and are part of the heme group for chlorophyll production. Soil factors influence its uptake, and foliar sprays can effectively remedy iron deficiency in plants like chickpeas. Zinc is vital for overall plant growth and development, enhancing water efficiency, nodulation, and nitrogen fixation. High soil pH and low organic matter can reduce zinc availability, which in turn impacts yields. Zinc also plays a key role in various metabolic processes and boosts seed germination and seedling vigour [17].

3.4. Economics

Maximum cost of cultivation (₹ 41108.00/ha) was obtained with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8). The minimum cost of cultivation (₹ 40108.00/ha) was recorded under the control treatment (T_1). This is due to the additional cost of micronutrients associated with all treatments except the control (T_1).

Gross returns (GR), net returns (NR), and benefit-cost ratio (B:C ratio) varied significantly as a result of the application of zinc and iron. Maximum gross return (₹ 163660 /ha) achieved with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8). Minimum gross return (₹ 106857.50 /ha) was recorded under control (T_1) **(Figure 5)**. It might be due to the optimal combination of zinc and iron, which maximized crop yield and market value. This effective nutrient mix led to superior financial returns compared to other treatments. Control had the lowest gross return because it did not benefit from these additional nutrients. Although physiological stress was noted, foliar application of ZnO or $ZnSO_4$ up to 900 g ha^{-1} significantly raised Zn content in Castelão and Moscatel grapes without showing obvious toxicity signs. While winemaking raised Zn levels in both varietals, Castelão grapes showed more marked Zn enrichment. This work proposes that regulated Zn supplementation can improve grape nutritional value without affecting fruit quality [18]. Two different modes of $ZnSO_4$ applications were tested: soil application of $ZnSO_4$ at 25 kg ha-1 combined with a 0.5% $ZnSO_4$ foliar spray significantly improved all the parameters. The maximum net return of ₹ 70,322 ha-1 was obtained with the treatment involving the soil application of $ZnSO_4$ at 25 kg ha-1, plus a 0.5% $ZnSO_4$ foliar spray. In comparison, we observed a higher yield and gross return.

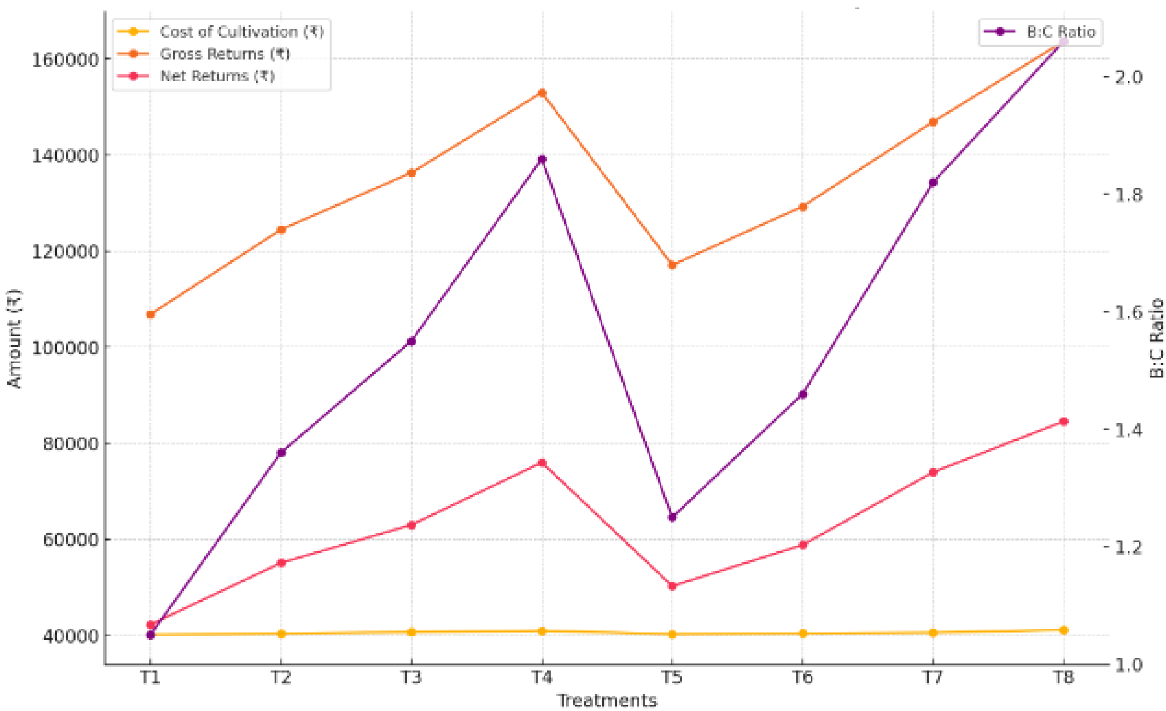


Figure 5. Effect of foliar nutrition and spraying schedule on the economics of chickpea.

Using foliar spraying of zinc sulphate ($ZnSO_4$) at 0.6% mixed with ferrous sulphate ($FeSO_4$) at 0.9% at both pre-flowering and pod development phases (T8), the greatest net return of ₹ 84,552 per hectare was attained. Although it was greatly better than all other treatments, this treatment showed a statistically equivalent performance to the application of $ZnSO_4$ at 0.9% (T4) and $FeSO_4$ at 0.9% (T7) at the same developmental stages. By contrast, the control group (T1) showed the lowest net return of ₹ 42,249 per hectare; no further micronutrient supplementation was given in this group. The significant rise in net returns under T8 and other high-performance treatments can be ascribed to the better nutrient availability and increased crop development brought about by zinc and iron supplements. From enzyme activation to chlorophyll production and photosynthesis, these vital micronutrients are involved in many physiological and biochemical processes that finally result in higher crop output and profitability.

The highest B:C ratio (2.06) was recorded with the application of $ZnSO_4$ at 0.6% + $FeSO_4$ at 0.9% (PF + PD) (T_8). The minimum B:C ratio (1.05) was recorded under control (T_1). It might be due to the reason that treatments with zinc and iron effectively boosted crop yields, increasing profits relative to costs **(Table 2)**. The highest B:C ratio in T8 reflects optimal nutrient use and high returns. These treatments improved productivity, resulting in enhanced economic efficiency. Control (T1) had the lowest ratio due to the absence of additional nutrient benefits, resulting in lower yields and profits. With the maximum Zn growth (56.9%), reported in DBW 173 under combined application, foliar application of $FeSO_4$ and $ZnSO_4$ considerably boosted grain Fe (5.1–6.1%) and Zn (5.2–43.8%). Demonstrating its potency in large-scale field circumstances, $ZnSO_4$ alone had a considerable favourable influence on grain Zn (40.3%, $p \leq 0.001$), protein content, yield, and hectolitre weight [19]. These findings show the possibility of Zn and Fe foliar treatments to raise grain nutritional quality and yield [20–30]. The highest gross returns (Rs 35420/ha), net returns (Rs 15238/ha), and B:C ratio (1.75) were recorded with treatment T4 (500 ppm thiourea + 0.2% zinc sulphate (mixed solution) spray at the vegetative and reproductive stages), while in treatment T1 (control), the gross returns (Rs 28420/ha), net returns (Rs 12020/ha), and B:C ratio (1.73) were recorded [31–33].

Table 2. Effect of foliar nutrition and spraying schedule on cost of cultivation, gross returns, net returns, and B:C ratio of chickpea.

Treatments	Cost of Cultivation (₹)	Gross Returns (₹)	Net Returns (₹)	B:C
T_1	40108	106857.50	42249.50	1.05
T_2	40383	124478.33	55085.33	1.36
T_3	40658	136315.83	62987.83	1.55
T_4	40933	153013.33	75990.33	1.86
T_5	40258	117116.67	50258.67	1.25
T_6	40408	129306.67	58828.67	1.46
T_7	40558	146938.33	73970.33	1.82
T_8	41108	163660.00	84552.00	2.06
SEm±	-	5387.53	3000.38	0.07
CD 5 %	-	16341.38	9100.72	0.22

Foliar application of Zn and Fe could enhance agroecological resilience in semi-arid regions when used judiciously. These micronutrients improve plant vigor, drought tolerance, and resistance to diseases, which are critical under water-limited conditions. By boosting crop productivity and nutritional quality without heavily relying on soil amendments, they support resource-efficient farming. Improved plant health may also sustain pollinator services and microbial interactions over time. However, balanced application is essential to avoid unintended ecological disruptions, ensuring long-term sustainability and resilience of the agroecosystem.

4. Conclusion

The most effective treatment in improving the growth and yield of chickpea, based on the results of the present research, is the application of $ZnSO_4$ at 0.6% in conjunction with $FeSO_4$ at 0.9% through both soil (PF) and foliar (PD) application (T8). Along with improved plant height, biomass accumulation, and nodulation, which are indicators of plant development, this treatment greatly raised seed output. Furthermore, it helped to increase the benefit-to-cost (B:C) ratio, thereby rendering chickpea farming an economically feasible method. The combined action of zinc and iron in vital physiological and biochemical processes helps to explain the improved crop performance noted with this treatment. While iron is vital for chlorophyll synthesis, respiration, and nitrogen metabolism, zinc is needed for enzyme activation, protein synthesis, and hormone control. Together with the appropriate dosage of fertilisers (RDF), these micronutrients guaranteed an optimal nutrient supply throughout the crop development cycle, therefore enhancing plant vigour and production. Moreover, our results underline the possibility of foliar micronutrient treatment as a quick approach to improve nutrient absorption, especially in areas with limited soil nutrient availability. Using zinc and iron in line with conventional chickpea farming methods presents a sustainable way to raise crop yields while preserving soil condition. This approach minimises nitrogen losses, lessens the demand for too high fertiliser inputs, and lessens the environmental effects connected with strong agricultural practices by improving nutrient usage efficiency. The research emphasises generally the need to use balanced micronutrient management techniques to maximise chickpea output and financial rewards. Especially in environmentally sensitive places, applying such sustainable agronomic techniques not only helps farmers by raising profitability but also improves long-term agricultural sustainability through soil fertility conservation and resource-efficient farming.

Supplementary Materials

The supporting information can be downloaded at https://journals.bilpubgroup.com/public/RE-SI-9642-Supplementary-File.docx.

Author Contributions

P.B. and K.G.: Writing & editing original draft; A.D., D.K., R.V., and G.K.: Visualization, Validation, Supervision, and Project administration; D., S.G., S.K., A.R. and S.S.: Review & editing, Visualization, Validation, Supervision, Project administration; V.K.P., P.S., A.M., A.G., and P.V.: Visualization, Validation, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study does not include any human or endangered plant systems for the experiment.

Informed Consent Statement

Informed consent was obtained from all participants involved in the study.

Data Availability Statement

All data generated or analysed during this study are included in this published article and its supplementary materials.

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Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

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