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Harnessing the potential of different sulphur sources and levels for enhancing growth and productivity of cowpea (*Vigna unguiculata* L.)

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Abstract
A field experiment was conducted during the *Kharif* season of 2025 at the AICRP on Arid Legumes, ZARS, GKVK, Bengaluru, to evaluate the effect of different sulphur sources, levels and application methods on the growth and productivity of cowpea (*Vigna unguiculata* L.). The experiment was conducted using cowpea variety KBC-9 in a Randomized Complete Block Design comprising 16 treatments replicated thrice. The treatments involved soil application of sulphur through bentonite and gypsum at different levels, along with foliar application at pre-flowering and pod initiation stages. The results revealed significant differences among the treatments for growth and yield parameters. Treatment T_{16} (100% RDF + 25 kg S ha^{-1} through bentonite + foliar sulphur @ 3 ml L^{-1} at pod initiation) recorded numerically higher plant height (85.12 cm), branches $plant^{-1}$ (9.91), leaf area (1459.1 cm^2 $plant^{-1}$), SPAD reading (70.5), effective nodules (38.82 $plant^{-1}$), dry matter production (18.1 g $plant^{-1}$) and seed yield (1805 kg ha^{-1}). However, T_{14} (100% RDF + 20 kg S ha^{-1} through bentonite + foliar sulphur @ 3 ml L^{-1} at pod initiation) was statistically on par with T_{16} across the recorded growth and yield parameters. Considering its comparable performance with a lower sulphur application rate, T_{14} may be adopted as a suitable sulphur management practice for enhancing cowpea productivity under the agro-climatic conditions of the study.

Keywords: Cowpea, sulphur management, bentonite, foliar application, growth, seed yield

Introduction
Pulses play a vital role in Indian agriculture and contribute significantly to sustainable crop production through biological nitrogen fixation and improvement of soil fertility. Among the important grain legumes, cowpea (*Vigna unguiculata* L.) is widely cultivated in tropical and subtropical regions owing to its adaptability and multipurpose uses. The crop is grown for dry seeds, tender green pods and nutritious fodder. Its inherent drought tolerance, extensive root system and ability to improve soil fertility make it particularly suitable for cultivation under arid and semi-arid environments. Despite its adaptability, cowpea productivity under farmers' field conditions remains below its attainable potential due to several production constraints, particularly nutrient deficiencies and imbalanced fertilizer application. Continuous cultivation, intensive cropping systems and the extensive use of sulphur-free NPK fertilizers have progressively depleted soil sulphur reserves, making adequate sulphur nutrition increasingly important for sustaining crop productivity (Reddy *et al*., 2023) [11]. Sulphur performs several essential physiological and biochemical functions in plants. It contributes to chlorophyll formation, photosynthesis, carbohydrate metabolism and the activity of enzymes involved in various metabolic processes (Gawhale *et al.*, 2024) [4]. Its importance is particularly pronounced in leguminous crops because of its close association with root development, nodulation and biological nitrogen fixation through its involvement in the formation of nitrogenase enzyme and leghaemoglobin. Adequate sulphur availability also supports healthy vegetative growth, dry matter accumulation, flowering, pod development and proper seed filling. Sulphur deficiency can adversely affect chlorophyll formation, nodulation and several metabolic activities, ultimately restricting plant growth and reducing crop productivity. Adequate sulphur nutrition has been reported to improve growth attributes, yield components and seed yield in cowpea. However, information on suitable sulphur management practices, particularly with respect to different sources, levels and application methods, remains inadequate. Therefore, the present investigation was undertaken to evaluate different sulphur management practices for improving the growth and productivity of cowpea.

Material and Methods
A field experiment was conducted during the *Kharif* season of 2025 at the All India Coordinated Research Project (AICRP) on Arid Legumes, Zonal Agricultural Research Station, GKVK, University of Agricultural Sciences, Bengaluru, Karnataka, India. The experimental site is located in Agro-climatic Zone V (Eastern Dry Zone of Karnataka), at 12°58′ N latitude and 77°35′ E longitude, with an altitude of 924 m above mean sea level. The region receives a normal annual rainfall of 948.7 mm, based on the long-term average meteorological data (1972–2024). During

2025, the total annual rainfall was 1009.4 mm, which was 60.7 mm (6.40%) above normal. During the crop season, the monthly rainfall recorded was 220.0 mm in August, 120.4 mm in September and 138.4 mm in October. The cumulative rainfall for these months was 478.8 mm. The mean monthly maximum temperature ranged from 26.6 to 33.4°C, whereas the mean monthly minimum temperature ranged from 15.2 to 20.8°C. The experimental soil was red sandy loam, classified under the order *Alfisols*. Initial soil samples collected from 0-30 cm depth indicated an acidic soil reaction (pH 5.89), electrical conductivity of 0.29 dS m^{-1} and organic carbon content of 0.32%. The soil was low in available nitrogen (242.04 kg ha^{-1}) and available sulphur (19.50 kg ha^{-1}), while available phosphorus (26.30 kg P_2O_5 ha^{-1}) and potassium (249.60 kg K_2O ha^{-1}) were in the medium range. Cowpea variety KBC-9 was used for the investigation. The experiment was laid out in a Randomized Complete Block Design (RCBD) comprising 16 treatments, replicated thrice. The gross and net plot sizes were 4.5 × 3.0 m and 3.6 × 2.8 m, respectively, with a crop spacing of 45 × 10 cm. The treatments comprised the recommended dose of fertilizers (RDF) alone and different combinations of sulphur sources, levels and foliar application timings. The RDF consisted of 25:50:25 kg N, P_2O_5 and K_2O ha^{-1}, supplied through urea, single super phosphate and muriate of potash, respectively. The calculated quantities of fertilizers were applied as a basal dose at sowing in bands opened 4 cm away from the seed row and mixed thoroughly with the soil. Soil-applied sulphur was supplied at 15, 20 and 25 kg S ha^{-1} through bentonite-S (90% S) and gypsum (19% S). Foliar sulphur was applied at 3 ml L^{-1} at flower initiation, pod initiation or both stages, depending on the treatment.

Treatment Details:

T_1: 100% RDF
T_2: 100% RDF + 15 kg S ha^{-1} through Bentonite
T_3: 100% RDF + 20 kg S ha^{-1} through Bentonite
T_4: 100% RDF + 25 kg S ha^{-1} through Bentonite
T_5: 100% RDF + 15 kg S ha^{-1} through Gypsum
T_6: 100% RDF + 20 kg S ha^{-1} through Gypsum
T_7: 100% RDF + 25 kg S ha^{-1} through Gypsum
T_8: 100% RDF + foliar spray of S @ 3 ml L^{-1} @ pre-flowering stage
T_9: 100% RDF + foliar spray of S @ 3 ml L^{-1} @ pod initiation stage
T_{10}: 100% RDF + foliar spray of S @ 3 ml L^{-1} @ pre-flowering and pod initiation stage
T_{11}: T_2 + foliar spray of S @ 3 ml L^{-1} @ pre-flowering stage
T_{12}: T_2 + foliar spray of S @ 3 ml L^{-1} @ pod initiation stage
T_{13}: T_3 + foliar spray of S @ 3 ml L^{-1} @ pre-flowering stage
T_{14}: T_3 + foliar spray of S @ 3 ml L^{-1} @ pod initiation stage
T_{15}: T_4 + foliar spray of S @ 3 ml L^{-1} @ pre-flowering stage
T_{16}: T_4 + foliar spray of S @ 3 ml L^{-1} @ pod initiation stage

Note: The Recommended dose of fertilizer (RDF) is 25:50:25 kg N, P_2O_5, K_2O ha^{-1};
Sulphur content: Bentonite-S (90% S) and Gypsum (19% S)

Data Collection

Observations on growth and yield attributes were recorded from five randomly selected and tagged plants in the net plot of each treatment across all three replications. Plant height, number of branches per plant, leaf area and SPAD meter readings were recorded at 30 and 60 DAS and at harvest. Leaf area was measured using a leaf area meter, while chlorophyll status was assessed using a SPAD meter. Total dry matter production was determined by separating the plant parts into leaves, stems and reproductive structures, followed by oven drying at 65°C until a constant weight was attained. The number of effective nodules was recorded at 60 DAS by counting healthy, pink-coloured nodules. Yield attributes, including the number of pods per plant, pod length and number of seeds per pod were recorded at harvest. Seed and haulm yields were determined separately from the net plot and expressed on a hectare basis. Harvest index was calculated by using the formula suggested by Donald (1962) [3]. Harvest index was calculated by dividing economic yield by biological yield.

$$\text{Harvest index} = \frac{\text{Grain yield (kg ha}^{-1})}{\text{Biological yield (kg ha}^{-1})}$$

Statistical Analysis

The experimental data recorded for different growth and yield parameters were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD), following the procedure described by Gomez and Gomez (1984) [5]. The significance of treatment effects was tested using the F-test. Standard error of the mean (S.Em. ±) and critical difference (CD) were calculated for each parameter to compare treatment means. Treatment differences were considered statistically significant at the 5 per cent probability level.

Results and Discussion

Table 1: Influence of sulphur nutrition on growth parameters of cowpea

Treatments	Plant height (cm) at harvest	Number of branches plant $^{-1}$ at harvest	Leaf area plant $^{-1}$ (cm ^{2}) at 60 DAS	SPAD meter readings at 60 DAS	Number of effective nodules plant $^{-1}$ at 60 DAS	Total dry matter production (g plant $^{-1}$)
T_1	50.96	6.87	861.4	55.0	27.16	12.2
T_2	61.45	7.55	1073.3	59.7	30.94	14.1
T_3	69.13	8.48	1211.9	62.9	33.52	15.0
T_4	74.43	8.84	1324.5	65.7	35.09	15.7
T_5	59.52	7.45	1042.3	58.7	30.16	13.8
T_6	67.38	8.14	1188.6	62.1	32.70	14.7
T_7	71.66	8.56	1265.6	63.8	34.24	15.4
T_8	53.14	7.04	908.3	55.7	28.10	12.9
T_9	55.31	7.15	949.1	56.5	28.74	13.1
T_{10}	57.63	7.25	988.4	57.6	29.49	13.4

T_{11}	63.70	7.73	1106.0	60.7	31.52	14.2
T_{12}	65.39	7.81	1147.9	61.3	32.16	14.6
T_{13}	77.49	9.15	1376.6	66.7	36.31	16.7
T_{14}	83.46	9.58	1411.2	69.4	38.34	17.8
T_{15}	80.06	9.32	1390.9	68.1	37.18	17.0
T_{16}	85.12	9.91	1459.1	70.5	38.82	18.1
S.Em.±	3.92	0.46	74.44	2.81	1.65	0.87
C.D. at 5 %	11.33	1.33	214.98	8.13	4.77	2.53

Influence of sulphur nutrition on growth parameters of cowpea

The data presented in Table 1 revealed that sulphur nutrition significantly influenced the growth parameters of cowpea. T_{16} (100% RDF + 25 kg S ha $^{-1}$ through bentonite + foliar spray of S @ 3 ml L $^{-1}$ at pod initiation stage) recorded numerically higher plant height (85.12 cm), number of branches plant $^{-1}$ (9.91), leaf area (1459.1 cm² plant $^{-1}$), SPAD meter reading (70.5), number of effective nodules plant $^{-1}$ (38.82) and total dry matter production (18.1 g plant $^{-1}$), followed by T_{14}, T_{15} and T_{13}. The lowest values for these parameters were recorded with T_1 (100% RDF). The better performance of T_{16} may be attributed to the combined and sustained availability of sulphur through bentonite and foliar application at pod initiation, which ensured adequate sulphur supply during active crop growth. Adequate sulphur nutrition promotes protein synthesis, enzyme activity and efficient nitrogen metabolism, thereby supporting cell division, elongation and overall plant growth. The resulting improvement in leaf area and chlorophyll status would have enhanced light interception and photosynthetic activity, leading to greater assimilate production and dry matter accumulation. Jat *et al*. (2013) [6] reported improved plant height, branches and dry matter accumulation in cowpea with sulphur application, while Sahu *et al*. (2021) [12] observed improved plant height, branching, leaf area and dry matter accumulation with sulphur nutrition. The greater number of effective nodules under T_{16} could be attributed to the role of sulphur in nodule initiation, development and biological nitrogen fixation. Sustained sulphur availability may have favoured *Rhizobial* activity and nitrogenase function, resulting in better nodule effectiveness. Similar findings were reported by Phogat *et al*. (2021) [9] and Tejaswini *et al*. (2023) [16]. The higher dry matter production was consequently a cumulative response to improved branching, leaf area, chlorophyll status, nodulation and photosynthetic efficiency. Similar observations were reported by Singh and Nariya (2017) and Yadav *et al*. (2026) [15, 17]. Thus, the integrated application of bentonite sulphur with foliar sulphur at pod initiation in T_{16} resulted in better growth and physiological performance of cowpea, whereas RDF alone was comparatively less effective, indicating the importance of sulphur supplementation for improving crop growth.

Table 2: Influence of sulphur nutrition on yield parameters and yield of cowpea

Treatments	Number of pods plant $^{-1}$	Pod length (cm)	Number of seeds pod $^{-1}$	Seed yield (kg ha $^{-1}$)	Haulm yield (kg ha $^{-1}$)	Harvest Index
T_1	18.06	15.10	13.82	1266	2615	0.308
T_2	21.80	16.55	15.28	1452	2899	0.328
T_3	24.19	17.59	16.36	1586	3113	0.342
T_4	25.78	18.22	17.02	1657	3224	0.342
T_5	21.22	16.39	15.02	1423	2832	0.333
T_6	23.54	17.26	16.06	1558	3037	0.342
T_7	24.77	17.91	16.62	1629	3175	0.344
T_8	18.95	15.47	14.05	1313	2687	0.314
T_9	19.68	15.76	14.38	1340	2746	0.315
T_{10}	20.52	16.07	14.68	1384	2798	0.323
T_{11}	22.41	16.78	15.57	1492	2953	0.335
T_{12}	23.09	17.04	15.79	1517	3000	0.336
T_{13}	26.45	18.68	17.57	1699	3317	0.343
T_{14}	27.46	19.22	18.18	1776	3379	0.359
T_{15}	27.00	18.88	17.82	1734	3357	0.348
T_{16}	27.89	19.79	18.53	1805	3392	0.365
S.Em.±	0.94	0.82	0.66	88.18	120.64	0.011
C.D. at 5 %	2.71	2.37	1.91	254.68	348.44	0.031

Influence of sulphur nutrition on yield parameters and yield of cowpea

The data presented in Table 2 revealed that sulphur nutrition significantly influenced the yield parameters and yield of cowpea. T_{16} (100% RDF + 25 kg S ha $^{-1}$ through bentonite + foliar spray of S @ 3 ml L $^{-1}$ at pod initiation stage) recorded higher number of pods plant $^{-1}$ (27.89), pod length (19.79 cm), number of seeds pod $^{-1}$ (18.53), seed yield (1805 kg ha $^{-1}$), haulm yield (3392 kg ha $^{-1}$) and harvest index (0.365), followed by T_{14}, T_{15} and T_{13}. The lowest values for these parameters were recorded with T_1 (100% RDF), with 18.06 pods plant $^{-1}$, 15.10 cm pod length, 13.82 seeds pod $^{-1}$, 1266 kg ha $^{-1}$ seed yield, 2615 kg ha $^{-1}$ haulm yield and 0.308 harvest index. The improvement in yield attributes under T_{16} may be attributed to the combined and sustained supply of sulphur through bentonite and foliar application at pod initiation, which ensured adequate sulphur availability during the critical reproductive phase. Improved sulphur nutrition enhances photosynthetic activity and assimilate production, while its role in protein synthesis and enzymatic processes supports flowering, pod setting and seed development. Consequently, the greater number of pods, longer pods and higher number of seeds pod $^{-1}$ under T_{16} contributed to increased seed yield. Similar improvement in

yield attributes and yield with sulphur nutrition has been reported by Singh and Singh (2017) [14] in cowpea and Patel *et al*. (2018) [7] in greengram. The higher seed yield under T_{16} could be attributed to the combined effect of improved vegetative growth and yield attributes, together with efficient translocation of photosynthates towards developing reproductive sinks. Foliar sulphur application at pod initiation may have ensured sulphur availability during seed development, thereby promoting better seed filling. Patel *et al*. (2022) [8] reported higher seed and stover yields in cowpea with sulphur application, while Ahmadi *et al*. (2024) [1] also reported improved seed yield and yield attributes with increasing sulphur levels. The higher haulm yield under T_{16} was associated with greater vegetative biomass resulting from improved plant height, branching, leaf area and dry matter production. Adequate sulphur availability supports meristematic activity, cell multiplication and biomass production, while its continuous supply through soil and foliar application improves nutrient utilization. Similar results were reported by Raj *et al*. (2023) [10]. The higher harvest index under T_{16} may be attributed to more efficient partitioning of assimilates from source tissues towards developing reproductive organs. Adequate sulphur availability during pod initiation and seed development would have favoured seed formation and allocation of a greater proportion of total biomass towards economic yield. Similar observations were reported by Das (2017) and Saket *et al*. (2017) [2, 13]. The consistently better performance of T_{16}, T_{14}, T_{15} and T_{13} indicates the advantage of integrating soil-applied sulphur with foliar sulphur, particularly at pod initiation. T_{14} remained statistically on par with T_{16} for seed yield, haulm yield and harvest index, suggesting that 20 kg S ha $^{-1}$ through bentonite combined with foliar sulphur was sufficient to produce a comparable response under the experimental conditions.

Conclusion

The study revealed that integrated sulphur management significantly improved the growth and productivity of cowpea. Among the treatments, T_{16} (100% RDF + 25 kg S ha $^{-1}$ through bentonite + foliar application of sulphur @ 3 ml L $^{-1}$ at pod initiation) recorded numerically higher growth and yield parameters. However, T_{14} (100% RDF + 20 kg S ha $^{-1}$ through bentonite + foliar application of sulphur @ 3 ml L $^{-1}$ at pod initiation) was statistically on par with T_{16}. Considering the comparable performance of T_{14} with a lower soil-applied sulphur dose, it may be considered a suitable sulphur management option for achieving higher growth and productivity of cowpea under the agro-climatic conditions of the study.

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