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RESEARCH ARTICLE

Effect of sulphur fertilization on soil adsorption-desorption dynamics, nutrient uptake and yield of sesame in Typic Chromustert

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Abstract

Sesame (*Sesamum indicum* L.), a nutrient-rich oilseed crop, held significant value in Asian diets due to its health benefits and potential to prevent various ailments. However, sesame cultivation was often hindered by poor crop establishment and imbalanced nutrient management - particularly sulphur (S). Sulphur was essential to improve both crop productivity and oilseed quality. This study aimed to evaluate the effects of sulphur fertilization on nutrient uptake and yield of sesame grown in sulphur-deficient soils (7.7 mg kg^{-1}). A laboratory experiment was conducted to understand the adsorption-desorption dynamics of sulphur, which showed that both processes peaked at an added sulphur concertation of 1000 µg mL^{-1} after which a declining trend was observed. Field experiments involved the application of sulphur in the form of $FeSO_4$ and gypsum at rates of 20, 40 and 60 kg ha^{-1} through soil, along with foliar spray K_2SO_4 (0.5 %) at 20 and 40 Days After Sowing (DAS). The treatment that combined N, P_2O_5 and K_2O based on Soil Test Crop Response (STCR) recommendations along with 40 kg S ha^{-1} as $FeSO_4$ and foliar spray application of K_2SO_4 (0.5 %) recorded the highest nutrient uptake (N: 63.89 kg ha^{-1}, P: 7.27 kg ha^{-1}, K: 44.75 kg ha^{-1}, S: 13.44 kg ha^{-1}) and the maximum grain and stalk yields (835 and 2550 kg ha^{-1} respectively). In contrast, the control treatment recorded the lowest yields. In conclusion, the combined application of sulphur through soil and foliar methods, along with balanced NPK fertilization based on STCR significantly improved sesame yield and nutrient uptake. This integrated approach offered a practical and effective solution to manage sulphur-deficient soils in sesame cultivation.

Keywords: balanced nutrition; calcareous; crop productivity; foliar spray

Introduction

Sesame (*Sesamum indicum* L.), an annual herbaceous plant of the order Tubiflorae and family Pedaliaceae, was cultivated worldwide for its edible seeds, oil and distinctive flavour. Known as the "Queen of Oilseeds", sesame was renowned for its exceptional resistance to oxidation and rancidity, making it a valuable crop in both culinary and industrial applications. In India, sesame occupied approximately 19.47 lakh hectares, producing 8.66 lakh tonnes with an average productivity of 412 kg ha^{-1}, whereas Tamil Nadu occupied an area of 4.7 lakh hectares, with average production and productivity of 2.79 lakh tonnes and 589 kg ha^{-1} respectively (1). The major sesame-producing states *viz.* Rajasthan, Gujarat, West Bengal, Maharashtra, Uttar Pradesh, Madhya Pradesh and Andhra Pradesh which accounted for nearly 85 % of the country's total production.

Sesame seeds were valued not only for their aroma and flavour but also for their rich nutrient profile and health benefits (2). The seeds contained high-quality oil, constituting 48-55 % of their composition, which was abundant in polyunsaturated fatty acids (PUFAs) such as linoleic, oleic, palmitic and stearic acids with trace amounts of linolenic acid (3). As a drought-tolerant crop, sesame thrived in semi-arid regions and adapted well to diverse agro-climatic conditions. In Tamil Nadu, the crop benefited from consistent monsoon rainfall, making rainfed conditions ideal for optimal yield. However, despite these favourable conditions, sesame production and productivity remained low due to several factors, including inadequate fertilization schedules.

The over-reliance on NPK fertilizers and the severe depletion of organic matter led to widespread sulphur (S) deficiency, a critical constraint for oilseed crops (4). Sulphur (S) was the fourth major plant nutrient after N, P and K (5). Its importance grew in recent years due to the declining sulphur status in Indian soils, attributed to the extensive use of high-analysis sulphur-free fertilizers, high-yielding crop varieties, intensive agricultural practices and reduced application of sulphur-containing fungicides. Sulphur was vital for plant growth and development, with dry matter accumulation of 0.2-0.5 %. It was required in quantities comparable to phosphorus

(6, 7) and played a crucial role in chlorophyll formation, protein synthesis and the production of amino acids such as cysteine, cystine and methionine, which were essential for oil quality.

Oilseeds had a higher sulphur requirement than other crops due to its role in determining oil quality. To meet the increasing demand for edible oil, improving sesame yield through proper and balanced fertilization was critical. While some studies highlighted the positive effects of sulphur application on sesame productivity and oil quality (8), limited research has focused on sulphur requirements in calcareous alkaline soils, where sulphur fixation posed a significant challenge. In calcareous soils, the presence of calcium carbonate ($CaCO_3$) interfered with sulphur availability by forming calcium sulphate dihydrate ($CaSO_4.2H_2O$), which was sparingly soluble (2.58 g L^{-1}) and reduced the labile sulphur pool i.e., available sulphur form. Additionally, sulphate, a mobile anion, may bound to clay micelles through chemisorption, further limiting its accessibility. These factors underscored the need for targeted sulphur management strategies in such soils. To address these constraints, the present study was designed to evaluate the effect of sulphur fertilization on improving the nutrient uptake and productivity of sesame grown in Typic Chromustert soils. By examining sulphur dynamics and optimizing fertilization schedules, this study aimed to provide insights into overcoming sulphur deficiencies and enhancing sesame cultivation in challenging soil conditions.

Materials and Methods

Experimental soil

The field experiment was carried out in K. Vellakulam village, located in the Kalligudi block of Madurai district, Tamil Nadu, to evaluate the response of sulphur on nutrient uptake and yield of sesame in Typic Chromustert soils, along with an assessment of soil sulphur adsorption-desorption dynamics. The study site was situated in the southern part of Madurai district and received an average annual rainfall of 750 mm, with a mean temperature of 28.8 °C and relative humidity ranged from 45 % to 85 %. The soil of the experimental field belongs to the Peelamedu series, classified as Typic Chromustert under the United States Department of Agriculture (USDA) system. Initial soil properties were detailed in Table 1.

The experiment was conducted using a randomized block design (RBD) with thirteen treatment combinations, each replicated three times. The field was divided into three blocks: each subdivided into 13 plots measuring 5 × 4 m^2. Fertilizers were applied as per the Tamil Nadu Agricultural University Crop Production Guide (CPG 2020) and the STCR method. Baseline doses of DAP (Diammonium phosphate) were applied uniformly, while urea and Muriate of Potash (MOP) were split into three applications. Sulphur was supplied using gypsum, iron sulphate and potassium sulphate as per treatment specifications. Sesame seeds (variety VRI 2) were sown @ 5 kg ha^{-1}, mixed with sand in a 1:5 ratio for uniform distribution and line-sown at 30 cm spacing. All recommended agronomic practices were meticulously followed throughout the cropping period.

Table 1. Treatment Details

T_1	Absolute control
T_2	Recommended dose of N, P_2O_5, K_2O (35:23:23 kg ha^{-1})
T_3	N, P_2O_5, K_2O on STCR basis
T_4	T_3 + sulphur @ 20kg ha^{-1} as gypsum
T_5	T_3 + sulphur @ 40kg ha^{-1} as gypsum
T_6	T_3 + sulphur @ 60kg ha^{-1} as gypsum
T_7	T_4 + foliar spray of K_2SO_4@ 0.5 % at 20 and 40 DAS
T_8	T_5 + foliar spray of K_2SO_4@ 0.5 % at 20 and 40 DAS
T_9	T_3 + sulphur @ 20kg ha^{-1} as $FeSO_4$
T_{10}	T_3 + sulphur @ 40kg ha^{-1} as $FeSO_4$
T_{11}	T_3 + sulphur @ 60kg ha^{-1} as $FeSO_4$
T_{12}	T_9 + foliar spray of K_2SO_4 @ 0.5 per cent at 20 and 40 DAS
T_{13}	T_{10} + foliar spray of K_2SO_4 @ 0.5 per cent at 20 and 40 DAS

$FeSO_4$ - iron sulphate; K_2SO_4- potassium sulphate

Adsorption and Desorption dynamics

Soil samples from the Peelamedu soil series in Madurai district were collected at a depth of 0-15 cm. The samples were air-dried, manually crushed with a wooden mallet to break up aggregates and sieved through a 2 mm mesh for analysis. For the sulphur adsorption study, 10 g of soil from the experimental field was placed in separate 250 mL polythene bottles. Sulphur was added as K_2SO_4 at concentrations -ranging from 0 to 1600 µg mL^{-1} with increments of 100 µg mL^{-1}. 50 mL of each solution were added to the bottles, which were then shaken on a mechanical shaker for 24 hours (9). The contents were centrifuged and the supernatant was collected.

Sulphur in the supernatant was estimated turbidimetrically as per the procedure highlighted by Chesnin and Yien, 1951 (10). The sulphur adsorbed by the soil at each concentration was determined by calculating the difference between the initial and final sulphur concentrations in the solution. For desorption, the supernatant was removed by centrifugation and the bottles were rinsed five times with 50 mL of 0.5 N NH_4NO_3 solution (11). The collected washings were transferred to a volumetric flask and the volume was made up to 250 mL. Sulphate-sulphur (SO_4^{2-}-S) in the solution was analysed turbidimetrically and the desorbed sulphur was quantified (10).

The amount of S adsorbed was calculated by the following adsorption equation:

X= (Ci-Cf) / (V/W)

X - was the change of the S in soil solution. Positive X values denote adsorption of Sulphur (S) by the soil solid phase whereas the negative values indicate desorption of sulphur by soil.

Ci - initial S concentration added

Cf - final equilibrium concentration of S in solution.

V was the final volume and W was the soil weight. The S sorption capacity was an interpolator from the S sorption isotherm. S sorption data were fitted into Freundlich and Langmuir adsorption equation.

Fitting sulphur sorption curves

Langmuir equation: C/x/m = 1/Kb + C/b

Freundlich equation: log x/m = log K + (1/n) log C

C	=	Equilibrium concentration of sulphur in soil solution (µg mL^{-1})
x/m	=	Amount of sulphur sorbed by soil (µg g^{-1})
K	=	Constant related to binding energy
b	=	S adsorption maxima (µg g^{-1})
n and K =		empirical constants

Observations

The nutrient uptake by the crop was calculated by multiplying the nutrient concentration and the total dry matter production. The uptake of the respective nutrients was then determined using the formula provided below.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient concentration (\%) x total dry matter yield (kg ha}^{-1}\text{)}}{100}$$

The yield attributes, including the number of capsules per plant, the number of seeds per capsule and seed yield were determined by randomly selecting and tagging five plants from each plot, with their averages recorded. Following post-harvest processes such as threshing, winnowing and cleaning, the final yield from each net plot was measured and expressed in kilograms per hectare (kg ha^{-1}).

Results and Discussion

Initial soil characteristics

The soil samples from the experimental site were classified under the Peelamedu soil series and identified as Fine clayey montmorillonitic isohyperthermic Typic Chromustert, according to USDA soil taxonomy. The soil texture was sandy clay, with a bulk density of 1.43 Mg m^{-3} and particle density of 2.49 Mg m^{-3}, resulting in a total porosity of 39.5 %. The soil exhibited a moderately alkaline pH of 8.50, an electrical conductivity of 0.20 dS m^{-1} and 7.5 % free calcium carbonate, indicating calcareous conditions. The organic carbon content was low, at 4.2 g kg^{-1}, highlighting limited organic matter availability. Available nitrogen (205 kg ha^{-1}) and sulphur (7.7 mg kg^{-1}) were also in the low range, which could constrain crop growth and productivity. Available phosphorus (13.1 kg ha^{-1}) and potassium (196 kg ha^{-1}) were in the medium range, suggesting a moderate fertility status for these nutrients.

The cation exchange capacity (CEC) of the soil was 17.50 C mol (p^+) kg^{-1}, with exchangeable Ca and Mg recorded at 12.80 and 6.40 C mol (p^+) kg^{-1} respectively, which indicated a well-balanced cationic environment. Micronutrient analysis revealed DTPA-extractable levels of 2.42, 3.21, 7.74 and 2.34 mg kg^{-1} for Fe, Cu, Mn and Zn respectively which were adequate for most crops. The total nitrogen, phosphorus and potassium contents were 0.046 %, 0.031 % and 0.648 % respectively reflecting the soil's inherent nutrient reserves. These results suggested that while the soil had moderate fertility for some nutrients, targeted interventions particularly for sulphur and organic carbon, were essential to enhance productivity.

Effect of different levels of sulphur on adsorption and desorption of S in Peelamedu soil series

The adsorption of sulphur increased with increasing sulphur concentrations up to 1000 µg mL^{-1}, after which a declining trend was observed. The maximum sulphur adsorption (481.00 µg g^{-1}) was recorded at 1000 µg mL^{-1}. The percentage of sulphur sorption ranged from 19.03 % to 55.17 %, with higher adsorption percentages observed at lower sulphur concentrations. Notably, the adsorption trend did not follow a linear pattern, as the adsorption rate declined at higher sulphur concentrations in the equilibrium solution. This behaviour could be attributed to the high levels of exchangeable calcium (12.80 C mol (p^+) kg^{-1}), exchangeable magnesium (6.40 C mol (p^+) kg^{-1}) and calcium carbonate (7.70 %) in the soil, which promoted sulphate sorption through co-adsorption mechanisms, forming $CaSO_4$ and $MgSO_4$. These findings aligned with earlier studies (12, 13), which reported similar interactions between sulphur and calcareous soils. Previous studies also reported similar findings, stating that the rate of adsorption gradually decreased at higher concentrations, resulting in a hyperbolic shape of the curve (14).

The adsorption data were analyzed using Langmuir and Freundlich isotherms, with the Langmuir isotherm resulting the best fit. The Langmuir model yielded a maximum sulphate sorption capacity (b) of 182.6 mg kg^{-1}, bonding energy (K) of 2.32 and a maximum buffering capacity of 395 mg kg^{-1}. The Langmuir equation showed a strong positive correlation (R^2 = 0.86**) between equilibrium sulphur concentration (C) and sulphur adsorption (x/m). Previous research noted that soils with higher maximum buffering capacity exhibited greater affinity for sulphate sorption (14). Additionally, earlier studies emphasized that maximal soil buffering capacity was critical for sulphate retention and release (15), as it integrated the concentrated and extensive components of adsorption.

Sulphur desorption ranged from 6.91 to 201.39 µg g^{-1}, following a quadratic relationship. The desorption rate increased with added sulphur up to 1000 µg mL^{-1}, beyond which it declined. The highest desorption value (201.39 µg g^{-1}) was observed at 1000 µg mL^{-1} of added sulphur. The percentage of sulphur desorption varied between 28.48 % and 41.87 %, with higher desorption percentages recorded at lower adsorption levels. These adsorption and desorption dynamics were presented in Fig. 1, Tables 2 and 3. The reduced hysteresis observed in sulphur desorption for the Peelamedu soil series could be attributed to the lower sesquioxide concentration (4.38 %) in the soil, which limited the retention of adsorbed sulphate. The findings were consistent with earlier studies, that SO_4^{2-} adsorbed on the colloidal surface was easily released to the solution phase, whereas chemisorbed SO_4^{2-} moved slowly to the exchangeable site to maintain equilibrium, which was then released into the labile pool (16).

Overall, the results indicated that sulphur adsorption and desorption in the Peelamedu soil series were influenced by the soil's calcareous nature, high exchangeable calcium and magnesium levels and low sesquioxide content. The Langmuir adsorption isotherm effectively described the sulphur adsorption behaviour, emphasizing the soil's capacity to retain sulphur under specific conditions. These findings highlighted the importance of considering soil properties, particularly in calcareous soils, to optimize sulphur fertilization strategies and enhance nutrient availability for crops.

Effect of sulphur fertilization on total dry matter production (DMP) of sesame

The data presented in Table 4 highlighted the significant influence of sulphur fertilization combined with N, P_2O_5 and K_2O on the dry matter production (DMP) of sesame at three critical growth stages. The mean DMP ranged from 351 to 798 kg ha^{-1} at 30 DAS, 820 to 1465 kg ha^{-1} at 60 DAS and 838 to 2780 kg ha^{-1} at harvest. The highest DMP was recorded in the treatment (T_{13})

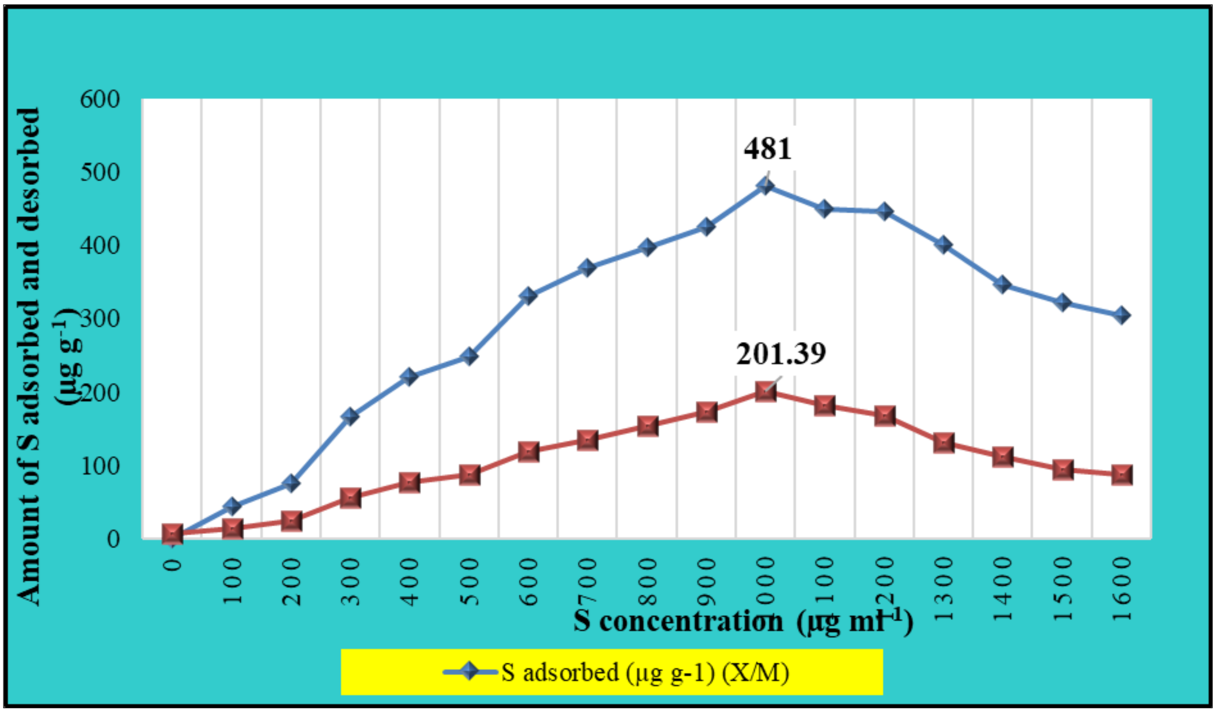

Fig. 1. Adsorption and desorption behaviour of sulphur in Typic Chromustert.

Table 2. Sorption behaviour of sulphur in Peelamedu soil series

S added ($\mu g\ ml^{-1}$)	Initial concentration ($\mu g\ ml^{-1}$)	Equilibrium concentration ($\mu g\ ml^{-1}$) (C)	S adsorbed ($\mu g\ g^{-1}$) (X/M)	% adsorbed	C/X/M	S desorbed ($\mu g\ g^{-1}$)	% desorbed
0	0	0.00	0.00	0	0.0000	6.91	0
100	2	1.03	44.00	44.00	0.0234	13.85	31.48
200	4	2.38	75.50	37.75	0.0315	24.56	32.53
300	6	2.59	166.50	55.50	0.0156	55.24	33.18
400	8	3.53	220.00	54.75	0.0160	76.91	34.96
500	10	4.97	248.00	49.60	0.0200	87.56	35.31
600	12	5.00	331.50	55.17	0.0151	118.19	35.65
700	14	6.52	370.00	52.86	0.0176	135.46	36.61
800	16	7.98	396.50	49.56	0.0201	153.22	38.64
900	18	9.42	424.50	47.17	0.0222	173.39	40.85
1000	20	10.29	481.00	48.10	0.0214	201.39	41.87
1100	22	12.91	449.00	40.82	0.0288	182.24	40.59
1200	24	14.99	446.50	37.21	0.0336	167.14	37.43
1300	26	17.88	401.50	30.88	0.0445	130.35	32.47
1400	28	20.08	346.50	24.75	0.0580	112.33	32.42
1500	30	23.50	322.50	21.50	0.0729	94.67	29.36
1600	32	25.83	304.50	19.03	0.0848	86.72	28.48

Table 3. Langmuir and Freundlich constants for sulphur adsorption

A. Langmuir constants

Langmuir constants		Maximum bufferingcapacity ($mg\ kg^{-1}$)	Regression equation	R2
Sorption maximum ($mg\ kg^{-1}$)	Bonding energy (K)			
182.6	2.32	395	Y= 0.0054+ 0.0027x	0.86**

B. Freundlich constants

Freundlich constants		Regression equation	R2
K	1/n		
25.86	1.184	Y= 3.174+ 1.086x	0.52*

Table 4. Effect of sulphur fertilization on total dry matter production of sesame

Treatments	Total dry matter production (kg ha^{-1})		
	30 DAS	60 DAS	At Harvest
T_1- Absolute control	351	820	838
T_2- RDF N, P_2O_5, K_2O	548	936	1042
T_3- N, P_2O_5, K_2O on STCR basis	577	1098	1212
T_4- T_3 + sulphur @20kg ha^{-1} as gypsum	614	1151	1637
T_5- T_3 + sulphur @40kg ha^{-1} as gypsum	698	1275	2074
T_6- T_3 + sulphur @60kg ha^{-1} as gypsum	724	1344	2191
T_7- T_4 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	621	1164	1686
T_8- T_5 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	733	1350	2236
T_9- T_3 + sulphur @20kg ha^{-1} as $FeSO_4$	650	1212	1957
T_{10}- T_3 + sulphur @40kg ha^{-1} as $FeSO_4$	757	1398	2539
T_{11}- T_3 + sulphur @60kg ha^{-1} as $FeSO_4$	781	1459	2766
T_{12}- T_9 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	664	1227	1973
T_{13}- T_{10} + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	798	1465	2780
SEd	**14.2**	**23.8**	**30.1**
CD (*p*=0.05)	**29.4**	**47.6**	**60.2**

that included N, P_2O_5 and K_2O based on soil test crop response (STCR) values, along with soil application of sulphur at 40 kg ha^{-1} as $FeSO_4$ and foliar application of K_2SO_4 at 0.5 % at 20 and 40 DAS. This treatment resulted in DMP of 798, 1465 and 2780 kg ha^{-1} at vegetative, flowering and harvest stages respectively. Treatment T_{11}, which involved N, P_2O_5 and K_2O on an STCR basis and soil application of sulphur at 60 kg ha^{-1} as $FeSO_4$, showed comparable results with DMP values of 781, 1459 and 2766 kg ha^{-1} at the corresponding stages. Treatment T_{10}, where sulphur was applied at 40 kg ha^{-1} as $FeSO_4$ along with N, P_2O_5 and K_2O on an STCR basis, ranked next with a total DMP of 2539 kg ha^{-1} at harvest. A consistent increase in DMP was observed with increasing levels of sulphur application. The lowest DMP was recorded in the control treatment, which did not receive any fertilizer, with a value of 838 kg ha^{-1} at harvest stage. The superior performance of $FeSO_4$ as a sulphur source was attributed to its high solubility (260 g L^{-1}), which facilitated the rapid release of sulphate ions into the soil solution, enhancing sulphur availability and uptake.

The increased DMP in treatments receiving balanced nutrient application could also have been linked to improved plant growth parameters, such as plant height, number of branches and leaf area index (LAI). These factors collectively contributed to enhanced biomass accumulation (17). Notably, the total dry biomass in T_{13} showed a 54.3 % increase at harvest compared to the treatment that received only N, P_2O_5 and K_2O on an STCR basis alone. These findings aligned with earlier reports (18), which suggested that balanced nutrient application enhanced dry matter translocation and partitioning.

At the vegetative stage, when reproductive structures were weak sinks, the majority of dry biomass was translocated to stems, followed by leaves. However, by 60 DAS, biomass partitioning shifted, with the reproductive parts (capsules and seeds) becoming the primary sinks (19). This transition underscored the importance of sulphur application in supporting reproductive growth. Applying sulphur at 60 kg ha^{-1} resulted in the highest DMP (46.2 q ha^{-1}) in maize, while the control recorded the lowest (36.7 q ha^{-1}), highlighting the vital role of sulphur in enhancing crop productivity through improved nutrient availability and biomass partitioning (20).

Effect of sulphur fertilization on yield attributes of sesame

Number of capsules per plant

The data on yield attributes, as presented in Table 5, indicated that the number of capsules per plant varied significantly depending on the sulphur source and application levels. The average number of capsules ranged from 75.1 to 118.1. The highest number of capsules (118.1) was recorded in the treatment (T_{13}), which received N, P_2O_5 and K_2O applied on STCR basis, along with soil application of sulphur at 40 kg ha^{-1} as $FeSO_4$ and foliar application of K_2SO_4 at 0.5 % at 20 and 40 DAS. This result was statistically on par with the treatment T_{11}- N, P_2O_5 and K_2O on an STCR basis, supplemented with soil-applied sulphur at 60 kg ha^{-1} as $FeSO_4$. In contrast, the treatment (T_3) with N, P_2O_5 and K_2O applied on STCR basis without sulphur recorded a significantly lower number of capsules (85.4). The absolute control plot, which did not receive any fertilizers, had the lowest number of capsules per plant (75.1).

Table 5. Effect of sulphur fertilization on yield attributes of sesame

Treatments	No. of capsules /plant	No. of seeds capsule
T_1- Absolute control	75.1	35.8
T_2- RDF N, P_2O_5, K_2O	80.2	38.3
T_3- N, P_2O_5, K_2O on STCR basis	85.4	40.8
T_4- T_3 + sulphur @ 20kg ha^{-1} as gypsum	91.1	42.8
T_5- T_3 + sulphur @ 40kg ha^{-1} as gypsum	101.7	48.8
T_6- T_3 + sulphur @ 60kg ha^{-1} as gypsum	106.8	51.2
T_7- T_4 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	90.6	43.4
T_8- T_5 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	107.3	51.6
T_9- T_3 + sulphur @ 20kg ha^{-1} as $FeSO_4$	96.7	46.3
T_{10}- T_3 + sulphur @ 40kg ha^{-1} as $FeSO_4$	112.3	54.1
T_{11}- T_3 + sulphur @ 60kg ha^{-1} as $FeSO_4$	117.6	56.8
T_{12}- T_9 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	96.1	47.1
T_{13}- T_{10} + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	118.1	57.1
SEd	**2.2**	**0.76**
CD (*p*=0.05)	**4.6**	**1.56**

The enhanced number of capsules in sulphur-treated plots was attributed to sulphur's critical role in reproductive development. Sulphur regulated metabolic and enzymatic activities, particularly through its role in chlorophyll synthesis via increased activity of the heme-containing enzyme, which enhanced photosynthetic efficiency and promoted nutrient translocation to sink sites. These findings were consistent with earlier reports (21, 22).

Number of seeds per capsule

The response of sulphur application on the number of seeds per capsule exhibited a significant increase compared to treatments without sulphur application. The highest number of seeds per capsule (57.1) was observed in the treatment (T_{13}), where sulphur was applied at 40 kg ha^{-1} as $FeSO_4$ along with foliar application of potassium sulphate at 0.5 % at 20 and 40 DAS, in addition to N, P_2O_5 and K_2O applied on an STCR basis. This was statistically on par with treatment T_{11}, which recorded 56.8 seeds per capsule. The second-highest number of seeds per capsule (54.1) was obtained in the treatment involving soil application of sulphur at 40 kg ha^{-1} as $FeSO_4$ along with STCR-based N, P_2O_5 and K_2O. The synergistic effect of split application of nitrogen and potassium at reproductive stages with sulphur application contributed to these positive results.

Sulphur played a pivotal role in enhancing nitrogen metabolism and the activity of nitrate reductase and sulphate reductase enzymes, leading to increased chloroplast production and improved seed formation. Additionally, sulphur stimulated the plant's metabolic energy, positively impacting seed development. These findings aligned with earlier studies (23, 24), which reported increased seed production with sulphur application. The lowest number of seeds per capsule (40.8) was recorded in the treatment (T_3) receiving STCR-based N, P_2O_5 and K_2O without sulphur, followed by the treatment (T_2) with recommended doses of N, P_2O_5 and K_2O but no sulphur. These results corroborate earlier findings that reported similar increases in seed production with sulphur application in linseed (25).

Effect of sulphur fertilization on nutrient uptake of sesame

The data pertained to nutrient uptake of sesame showed a significant influence due to the application of sulphur irrespective of its sources and levels (Table 6).

Nitrogen uptake

Nitrogen (N) uptake by sesame varied significantly across treatments, ranging from 10.53 to 27.42 kg ha^{-1} in grain and 11.73 to 36.47 kg ha^{-1} in stalk at the reproductive stages. The highest N uptake values of 27.42 kg ha^{-1} in grain and 36.47 kg ha^{-1} in stalk at harvest were recorded in treatment T_{13}, which included STCR-based application of N, P_2O_5 and K_2O along with soil-applied sulphur at 40 kg ha^{-1} as $FeSO_4$ and foliar application of potassium sulphate (K_2SO_4) at 0.5 % at 20 and 40 DAS. This was statistically on par with treatment T_{11}. The enhanced N content and uptake in sesame under these treatments could be attributed to the higher solubility of $FeSO_4$ compared to gypsum, leading to increased sulphur availability.

Adequate sulphur supply likely promoted N uptake during the reproductive phase, boosting seed production. This improvement can be explained by the synergistic interaction between N and S, as sulphur acts as a cofactor for the nitrogenase enzyme involved in nitrogen fixation, enhancing nitrogen accessibility to the crop. Additionally, the application of sulphur may have enabled the retention of nitrate (NO_3^-) in the labile pool by reducing competition for adsorption sites with sulphate (SO_4^{2-}), thereby increasing nitrogen absorption (26-29). The lowest N uptake values of 15.89 kg ha^{-1} in grain and 19.28 kg ha^{-1} in stalk were observed in treatment T_3, where only STCR-based N, P_2O_5 and K_2O were practical without sulphur.

Phosphorous uptake

The highest phosphorus (P) uptake of 2.68 kg ha^{-1} in grain and 4.59 kg ha^{-1} in stalk was achieved with the application of N, P_2O_5 and K_2O based on the STCR approach, combined with 40 kg S ha^{-1} as $FeSO_4$ and a foliar spray of 0.5 % potassium sulphate (K_2SO_4) at 20 and 40 DAS. This result was statistically comparable to treatment T_{11}, which involved STCR-based N, P_2O_5 and K_2O application along with 60 kg S ha^{-1} as $FeSO_4$. In treatment T_{10},

Table 6. Effect of sulphur fertilization on nutrient uptake of sesame

Treatments	N uptake (kg ha^{-1})		P uptake (kg ha^{-1})		K uptake (kg ha^{-1})		Ca uptake (kg ha^{-1})	
	Grain	Stalk	Grain	Stalk	Grain	Stalk	Grain	Stalk
T_1- Absolute control	10.53	11.73	0.73	0.80	5.36	10.24	1.10	1.89
T_2- RDF N, P_2O_5, K_2O	13.85	15.68	1.03	1.17	6.92	13.74	1.37	2.72
T_3- N, P_2O_5, K_2O on STCR basis	15.89	19.28	1.15	1.52	7.75	16.55	1.64	3.19
T_4- T_3 + sulphur @ 20kg ha^{-1} as gypsum	17.63	21.48	1.35	1.83	8.32	18.79	2.18	4.20
T_5- T_3 + sulphur @ 40kg ha^{-1} as gypsum	22.24	27.31	1.95	2.85	10.36	24.25	2.92	6.89
T_6- T_3 + sulphur @ 60kg ha^{-1} as gypsum	23.81	30.00	2.18	3.46	11.13	26.69	3.21	7.25
T_7- T_4 + foliar spray of K_2SO_4@ 0.5 % at 20 and 40 DAS	18.08	21.67	1.41	1.86	8.48	18.96	2.24	4.23
T_8- T_5 + foliar spray of K_2SO_4@ 0.5 % at 20 and 40 DAS	24.20	30.11	2.24	3.52	11.35	26.60	3.24	7.28
T_9- T_3 + sulphur @ 20kg ha^{-1} as $FeSO_4$	20.10	24.09	1.70	2.39	9.34	21.31	1.98	4.26
T_{10}- T_3 + sulphur @ 40kg ha^{-1} as $FeSO_4$	25.40	33.12	2.41	4.02	12.07	28.87	2.49	6.15
T_{11}- T_3 + sulphur @ 60kg ha^{-1} as $FeSO_4$	26.85	35.87	2.63	4.55	12.81	31.32	2.71	6.46
T_{12}- T_9 + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	20.63	24.60	1.76	2.44	9.60	21.78	2.02	4.51
T_{13}- T_{10} + foliar spray of K_2SO_4@ 0.5 per cent at 20 and 40 DAS	27.42	36.47	2.68	4.59	13.13	31.62	2.76	6.54
SEd	**0.5**	**0.52**	**0.04**	**0.07**	**0.23**	**0.41**	**0.04**	**0.13**
CD (p=0.05)	**1.02**	**1.07**	**0.09**	**0.14**	**0.46**	**0.83**	**0.08**	**0.22**

where sulphur was applied at 40 kg ha^{-1} as $FeSO_4$, phosphorus uptake varied across harvest stage, with values of 2.41 kg ha^{-1} at grain and 4.02 kg ha^{-1} at stalk.

This variation in phosphorus uptake was attributed to the enhanced availability of P in the soil, facilitated by the anion exchange mechanism between sulphate (SO_4^{2-}) and phosphate ($H_2PO_4^-$) ions. The release of $H_2PO_4^-$ from adsorption sites due to sulphur application likely increased phosphorus content in the labile pool, thereby promoting higher uptake. The experimental soil's calcium carbonate content (7.5 %) may have further contributed by forming $CaSO_4$ complexes with SO_4^{2-}, releasing $H_2PO_4^-$ into the soil solution. These findings are consistent with earlier studies that reported increased phosphorus uptake with sulphur fertilization, while the lowest uptake was observed in the absolute control (T1) (30).

Potassium uptake

At the harvest stage, the highest potassium (K) uptake in grain and stalk was observed in the treatment where N, P_2O_5 and K_2O were applied on STCR basis, along with soil application of sulphur at 40 kg ha^{-1} as $FeSO_4$ and foliar application of K_2SO_4 at 0.5 % at 20 and 40 DAS. The K uptake values were 13.13 kg ha^{-1} for grain and 31.62 kg ha^{-1} for stalk. The dissociation of $FeSO_4$ into Fe^{2+} and SO_4^{2-} ions likely facilitated the formation of K_2SO_4, a highly soluble compound, enhancing the availability of both sulphur and potassium to the plant. This synergy between sulphur and potassium availability may have contributed to the increased K accumulation. Sulphur fertilization also improved the polarization of potassium ions relative to calcium ions, which enhanced potassium (K) availability (27, 28).

The experimental soil, which contained a high exchangeable calcium content (12.80 C mol (p$^+$) kg^{-1}), likely contributed to this effect by promoting the release of K^+ from the soil colloidal complex into the labile pool. These findings align with results showing higher K acquisition in wheat with sulphur application (31). The lowest potassium absorption (7.75 kg ha^{-1} for grain and 16.55 kg ha^{-1} for stalk) was observed in the treatment with N, P_2O_5 and K_2O applied on STCR basis (T_3), followed by the treatment with recommended dose application (T_2), which recorded 6.92 kg ha^{-1} for grain and 13.74 kg ha^{-1} for stalk.

Calcium uptake

Calcium (Ca) accumulation was higher in treatments where sulphur was applied as gypsum, irrespective of the application levels, compared to other treatment combinations. The highest Ca content of 3.24 kg ha^{-1} in grain and 7.25 kg ha^{-1} in stalk at harvest was observed in the treatment where N, P_2O_5 and K_2O were applied on STCR basis, combined with soil application of 40 kg sulphur ha^{-1} as gypsum and foliar application of K_2SO_4 at 0.5 % at 20 and 40 DAS (T_8). This treatment was statistically comparable to T_6, which also showed a positive impact on Ca accumulation.

The data revealed a consistent relationship between sulphur levels and Ca accumulation at all growth stages of sesame. The treatment T_5, which included STCR-based N, P_2O_5 and K_2O along with 40 kg sulphur ha^{-1} as gypsum, recorded a Ca content of 2.92 kg ha^{-1} in grain and 6.89 kg ha^{-1} in stalk at harvest. Gypsum, containing 23.3 % calcium and 18.6 % sulphur, likely provided an adequate supply of both nutrients, facilitating enhanced Ca absorption by the plants. Calcium, being immobile in plants, accumulates primarily in leaves once translocated (32). Similar findings were reported, with gypsum application resulting in increased Ca accumulation in groundnut (33). The lowest Ca content (1.10 kg ha^{-1} in grain and 1.89 kg ha^{-1} in stalk stages) was noted in the absolute control treatment (T_1).

Sulphur uptake

The application of various sulphur levels significantly influenced sulphur (S) absorption by the sesame crop. The highest S uptake of 4.77 kg ha^{-1} in grain and 8.67 kg ha^{-1} in stalk at harvest was noticed in the treatment (T_{13}), where N, P_2O_5 and K_2O were supplied on STCR basis, along with 40 kg S ha^{-1} as $FeSO_4$ and foliar spray of potassium sulphate (0.5 %) at 20 and 40 DAS. This treatment showed similar results comparable to the one where N, P_2O_5 and K_2O were applied on STCR basis with a higher dose of soil-applied sulphur (60 kg ha^{-1}) as $FeSO_4$. Treatment T_{10} exhibited the second-highest S accumulation, with values of 4.28 kg ha^{-1} at 30 DAS, 7.57 kg ha^{-1} at 60 DAS and higher content at harvest (grain and stalk). The increased S absorption in these treatments could be attributed to the enhanced solubility of $FeSO_4$ (260 g L^{-1}), which dissociates into Fe^{2+} and SO_4^{2-} ions, thereby increasing the concentration of SO_4^{2-} in the labile pool and making it more available for plant absorption (34).

In contrast, the application of gypsum, although containing SO_4^{2-} ions, showed reduced S absorption compared to $FeSO_4$. The presence of free Ca^{2+} ions in the soil solution, due to the common ion effect, reduced the solubility of gypsum and delayed the availability of sulphur to plants (35). This resulted in lower S accumulation in gypsum-treated plots. The lowest S content of 2.29 kg ha^{-1} in grain and 3.64 kg ha^{-1} in stalk at harvest was observed in the treatment where only N, P_2O_5 and K_2O were applied on STCR basis without any sulphur source (T_3). The absolute control treatment (T_1), also exhibited the lowest S content as shown in Fig. 2. The increased S application led to improved vegetative and root growth, which likely enhanced sulphur absorption by the crop (36). These results were consistent with studies conducted on safflower (37), rice (38), soybean (39) and mustard (40).

Effect of sulphur fertilization on grain and stalk yield of sesame

Grain yield

A detailed analysis of the data on grain and stalk yield of sesame was presented in Fig. 3. The results revealed a substantial increase in grain yield due to sulphur fertilization. The grain yield ranged from 383 to 836 kg ha^{-1}, with the highest yield of 836 kg ha^{-1} recorded in the treatment where N, P_2O_5 and K_2O were applied on STCR basis, along with 40 kg S ha^{-1} as $FeSO_4$ and a 0.5 % foliar spray of potassium sulphate at 20 and 40 DAS (T_{13}). This treatment was statistically at par with T_{11}, which also produced a high yield. Following T_{11}, the treatment in which N, P_2O_5 and K_2O were supplied on STCR basis with 40 kg S ha^{-1} as $FeSO_4$ recorded a grain yield of 779 kg ha^{-1}. Additionally, treatments incorporating gypsum as a sulphur source also had a positive impact on grain yield.

The treatment T_8, where N, P_2O_5 and K_2O were applied on STCR basis with 40 kg S ha^{-1} as gypsum and a 0.5 % foliar spray of potassium sulphate at 20 and 40 DAS, recorded a grain yield of 747 kg ha^{-1}. This was found to be statistically on par with treatment T_6, where N, P_2O_5 and K_2O were applied on STCR basis along with 60 kg S ha^{-1} as gypsum. The lowest grain yield of 383 kg ha^{-1} was observed in the control treatment (T_1). The positive

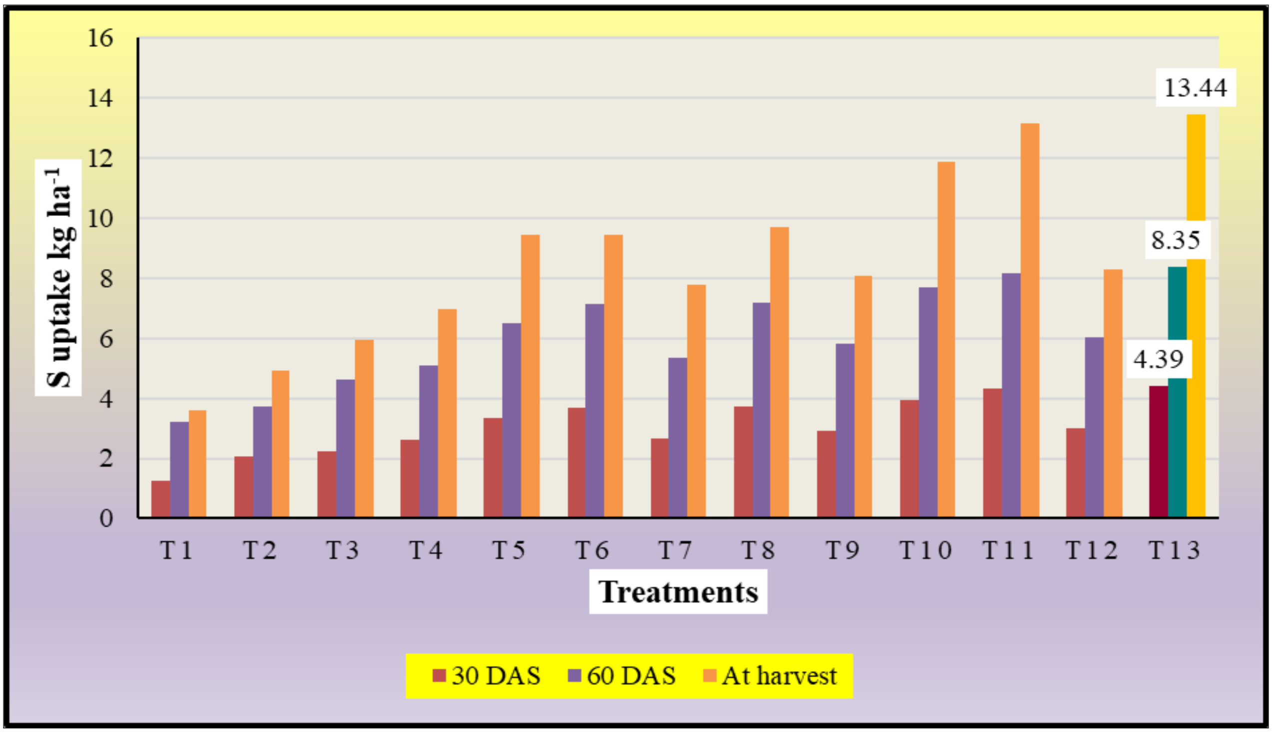

Fig. 2. Effect of sulphur fertilization on S uptake (kg ha^{-1}) at different growth stages of sesame.

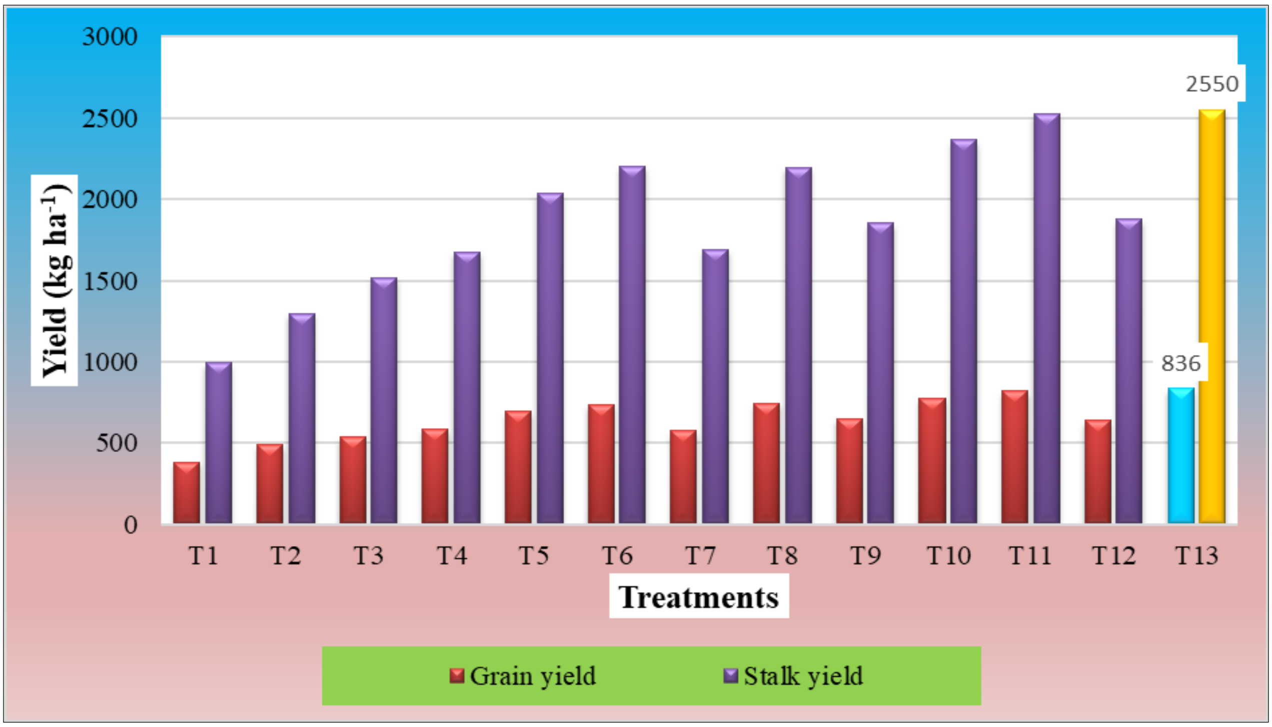

Fig. 3. Effect of sulphur fertilization on grain and stalk yield (kg ha^{-1}) of sesame.

impact of sulphur fertilization on yield attributes and overall yield could be attributed to the balanced nutritional environment created by sulphur application. This, in turn, promoted active metabolite partitioning and optimal nutrient translocation to the reproductive parts of the plant. The stimulation of protein synthesis due to sulphur application likely contributed to increased grain and stalk production. Furthermore, sulphur may have accelerated the photosynthetic rate, enhanced key yield-contributing traits and leading to significantly higher grain and stalk yields (41). Adequate sulphur availability during the seed-filling period may have improved the accumulation and distribution of dry matter and nutrients, ultimately boosting sesame seed yield (29). This resulted in a favourable source-sink relationship, which is crucial for higher seed yield.

Stalk yield

The stalk yield of sesame demonstrated a significant improvement with sulphur application. The highest yield, 2550 kg ha^{-1}, was achieved in the treatment (T13) where N, P_2O_5 and K_2O were applied based on the STCR approach, supplemented with a soil application of 40 kg S ha^{-1} as $FeSO_4$ and a foliar spray of 0.5 % potassium sulphate at 20 and 40 DAS. This treatment resulted in a 40 % increase in stalk yield compared to the treatment where N, P_2O_5 and K_2O were applied on STCR basis alone (T_3). These findings align with those reporting a 20-42 % increase in sesame yield with sulphur fertilization (42). When comparing the two sources of sulphur, $FeSO_4$ and gypsum, the application of $FeSO_4$ resulted in higher stalk yield. This was likely due to the greater solubility of $FeSO_4$ (260 g L^{-1}), which released SO_4^{2-} more rapidly, maintaining higher concentrations of sulphate in the labile pool and promoting its absorption. This is consistent with previous studies that also found sulphur application enhanced both the growth and yield of sesame (43-46).

Conclusion

From the laboratory study it was concluded that the adsorption and desorption behaviour of sulphur in calcareous soil revealed that the maximum sulphur adsorption occurred at 1000 µg mL^{-1}, beyond which it deteriorated. The data were best fitted into the Langmuir adsorption isotherm, indicating a strong adsorption capacity. The desorption studies also showed maximum sulphur desorption at 1000 µg mL^{-1}, after which the desorption reduced. The field experiment also exposed that the integrated application of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) based on Soil Test Crop Response (STCR) recommendations, combined with soil application of 40 kg S ha^{-1} as $FeSO_4$ and foliar application of K_2SO_4 at 0.5 % at 20 and 40 DAS, significantly enhanced yield attributes, nutrient uptake (N, P, K and S) and overall sesame yield.

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Authors' contributions

The study was conceptualized by PN and PSP, who also developed the methodology. Resources were provided by PSP, RI and KK. Data collection was managed by PSP, while the investigation was conducted collaboratively by PSP and RI. Formal analysis was performed by PN and PS. The original draft of the manuscript was written by PN and PSP under the supervision of RI and KK. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflicts of interest.

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References

1. FAO. Sustainable food systems: Concept and framework-Guiding principles. Rome: FAO; 2021.
2. Pathak N, Rai AK, Kumari R, Bhat KV. Value addition in sesame: A perspective on bioactive components for enhancing utility and profitability. Pharmacogn Rev. 2014;8(16):147. https://doi.org/10.4103/0973-7847.134249
3. Kamal-Eldin A, Yousif G, Iskander GM, Appelqvist LA. Seed lipids of *Sesamum indicum L.* and related wild species in Sudan I: Fatty acids and triacylglycerols. Lipid/Fett. 1992;94(7):254-9. https://doi.org/10.1002/lipi.19920940705
4. Dobermann A. Rice: Nutrient disorders & nutrient management. 1st ed. Los Baños: International Rice Research Institute; 2000. https://doi.org/10.1007/978-94-011-5078-1_1
5. Jamal A, Moon YS, Abdin MZ. Sulphura general overview and interaction with nitrogen. Aust J Crop Sci. 2010;4(7):523-9. https://search.informit.org/doi/10.3316/informit.536574654936406
6. De Kok LJ, Castro A, Durenkamp M, Koralewska A, Posthumus FS, Stuiver CEE, et al. Pathways of plant sulfur uptake and metabolism-an overview. Landbauforsch Völkenrode, Special Issue. 2005;283:5-13.
7. Ali R, Khan MJ, Khattak RA. Response of rice to different sources of sulfur (S) at various levels and its residual effect on wheat in rice-wheat cropping system. Soil Environ. 2008;27(1):131-7.
8. Raja A, Hattab KO, Gurusamy L, Vembu G, Suganya S. Sulphur application on growth and yield and quality of sesame varieties. Int J Agric Res. 2007;2(1):599-606. https://doi.org/10.3923/ijar.2007.599.606
9. Bohn HL, Barrow NJ, Rajan SSS, Parfitt RL. Reactions of inorganic sulfur in soils. Sulfur Agric. 1986;27:233-49. https://doi.org/10.2134/agronmonogr27.c7
10. Chesnin L, Yien CH. Turbidimetric determination of available sulfates. Soil Sci Soc Am J. 1951;15(C):149-51. https://doi.org/10.2136/sssaj1951.036159950015000C0032x
11. Dolui AK, Nandi S. Adsorption and desorption of sulfate in some soils of West Bengal (India). Health Environ Res Online. 1989;55(5-6).
12. Bolan NS, Syers JK, Sumner ME. Calcium-induced sulfate adsorption by soils. Soil Sci Soc Am J. 1993;57(3):691-6. https://doi.org/10.2136/sssaj1993.03615995005700030011x
13. Gayathri P, Saravana Pandian P. Evaluation of various levels of phosphorus and sulphur on yield and economics of blackgram (*Phaseolus mungo L.*) in Vylogam soil series of Madurai district. Int J Farm Sci. 2019;9(1):85-8. https://doi.org/10.5958/2250-0499.2019.00011.9
14. Ghosh A, Das P. Optimization of copper adsorption by soil of polluted wasteland using response surface methodology. Indian Chem Eng. 2014;56(1):29-42. https://doi.org/10.1080/00194506.2014.883728
15. Das I, Datta A, Ghosh K, Chatterjee S, Chakraborty A. Sulphate sorption/desorption behavior vis-à-vis thermodynamic characteristics of some sulphur deficient soils of West Bengal. Arch Agron Soil Sci. 2009;55(1):35-50. https://doi.org/10.1080/03650340802342250
16. Pandian PS. Long-term manure fertilizer addition on adsorption and desorption of sulphur in typic haplustalf under rice monoculture. Madras Agric J. 2010;97(7-9):254-60. https://doi.org/10.29321/MAJ.10.100499
17. Meshram D, Pagar PC, Kuchanwar OD, Moharkar R, Raut V. Effect of sulphur and boron on quality, nutrient content. J Soils Crops. 2015;27(1):158-61. https://doi.org/10.22271/chemi.2020.v8.i4u.9923
18. Das SK. Effect of phosphorus and sulphur on yield attributes, yield, nodulation and nutrient uptake of green gram (*Vigna radiate* L. Wilczek). Legume Res. 2017;40(1):138-43. https://doi.org/10.18805/lr.v0iOF.9385

19. Couch A, Jani A, Mulvaney M, Hochmuth G, Bennett J, Gloaguen R, et al. Nitrogen accumulation, partitioning and remobilization by diverse sesame cultivars in the humid southeastern USA. Field Crops Res. 2017;203:55-64. https://doi.org/10.1016/j.fcr.2016.12.012

20. Sakal R, Singh AR, Singh KDN. Effect of sulphur on yield, nutrient uptake and quality of sugarcane grown on Calciorthents. Ann Pl Soil Res. 2002;4(1):7-14.

21. Duhoon SS, Deshmukh MR, Jyotishi A, Jain HC. Effect of sources and levels of sulphur on seed and oil yield of sesame (*Sesamum indicum L.*) under different agro-climatic situations of India. J Oilseeds Res. 2005;22(1):199-200.

22. Singh R, Rai RK. Yield attributes, yield and quality of soybean (*Glycine max*) as influenced by integrated nutrient management. Indian J Agron. 2004;49(4):271-4. https://doi.org/10.59797/ija.v49i4.5217

23. Abdin MZ, Ahmad A, Khan N, Khan I, Jamal A, Iqbal M. Sulphur interaction with other nutrients. In: Abdin MZ, Ahmad A, editors. Sulphur in plants. Springer. 2003; p. 359-74. https://doi.org/10.1007/978-94-017-0289-8_20

24. Paul SK, Khatun MM, Sarkar MAR. Effect of sulphur on the seed yield and oil content of sesame (*Sesamum indicum* L.): Seed yield and oil content of sesame. J Bangladesh Agric Univ. 2019;17(1):33-8. https://doi.org/10.3329/jbau.v17i1.40660

25. Nandanwar SB, Chaphale SD, Badole WP, Badole RB. Effect of sulphur and zinc on growth and yield of linseed. J Soils Crops. 2000;10(2):301-2.

26. Abdullahi R, Sheriff HH, Lihan S. Combine effect of bio-fertilizer and poultry manure on growth, nutrient uptake and microbial population associated with sesame (*Sesamum indicum L.*) in North-Eastern Nigeria. Sci Toxi Food Tech. 2013;5:60-5. https://doi.org/10.9790/2402-0556065

27. Motior MR, Abdou AS, Al Darwish FH, El-Tarabily KA, Awad MA, Golam F, et al. Influence of elemental sulfur on nutrient uptake, yield and quality of cucumber grown in sandy calcareous soil. Aust J Crop Sci. 2011;5(12):1610-5.

28. Raza MA, Feng LY, Manaf A, Wasaya A, Ansar M, Hussain A, et al. Sulphur application increases seed yield and oil content in sesame seeds under rainfed conditions. Field Crops Res. 2018;218:51-8. https://doi.org/10.1016/j.fcr.2017.12.024

29. Mehmood MZ, Afzal O, Ahmed M, Qadir G, Kheir A, Aslam MA, et al. Can sulphur improve the nutrient uptake, partitioning and seed yield of sesame? Arab J Geosci. 2021;14(10):1-15. https://doi.org/10.1007/s12517-021-07229-6

30. Nayak MP, Vyas MD, Mandloi KS. Efficacy of pendimethalin in soybean (*Glycine max*). Indian J Agron. 2000;45(1):162-5. https://doi.org/10.59797/ija.v45i1.3365

31. Sangwan A, Duhan BS, Sangwan PS. Effect of different sources of sulphur on yield and nutrient uptake by wheat. J Pharmacogn Phytochem. 2018;7(6):2686-91.

32. Aulakh MS, Dev G. Interaction effect of calcium and sulphur on the growth and nutrient composition of alfalfa (*Medicago sativa* L. pers.), using 35S. Plant Soil. 1978;50(1):125-34. https://doi.org/10.1007/BF02107162

33. Singh AL, Joshi YC, Chaudhari V. Effect of different sources of iron and sulphur on nutrient concentration and uptake by groundnut. Fertil Res. 1990;24(2):97-103. https://doi.org/10.1007/BF01073226

34. Pandey M, Ali J. Effect of sources and levels of sulphur on sulphur uptake, yield and quality of linseed (*Linum usitatissimum*). Ann Agric Res. 2014;35(1):44-50.

35. Parmar NN, Patel AP, Choudhary M. Effect of sources and levels of sulphur on growth, yield and quality of summer sesame under South Gujarat condition (*Sesamum indicum* L.). Int J Curr Microbiol Appl Sci. 2018;7(2):2600-5. https://doi.org/10.20546/ijcmas.2018.702.316

36. Patel LR, Patel NR, Patel RH. Effect of nitrogen, phosphorus and sulphur on seed yield and quality of mustard. J Oilseeds Res. 1992;9:333.

37. Baviskar PK, Tapre VV, Jagdale RB, Sune SV, Bhatia NH. Effect of levels of sulphur and its sources on S uptake, growth and yield of safflower. J Soils Crops. 2005;15(2):466-9.

38. Singh AK, Meena MK, Bharati RC, Gade RM. Effect of sulphur and zinc management on yield, nutrient uptake, changes in soil fertility and economics in rice (*Oryza sativa*)-lentil (*Lens culinaris*) cropping system. Indian J Agric Sci. 2013;83(3):344-8.

39. Najar GR, Singh SR, Akhtar F, Hakeem SA. Influence of sulphur level on yield, uptake and quality of soybean (*Glycine max*) under temperate conditions of Kashmir valley. Indian J Agric Sci. 2011;81(4):340-3.

40. Santosh K, Verma SK, Singh TK, Shyambeer S. Effect of nitrogen and sulphur on growth, yield and nutrient uptake by Indian mustard (*Brassica juncea*) under rainfed condition. Indian J Agric Sci. 2011;81(2):145-9.

41. Thentu TL, Nawlakhe SM, Mankar DD, Shrinivasrao M, Bhonde GV. Growth, yield and quality of summer sesame as influenced by the fertilizer and sulphur levels. J Soil Crops. 2014;24(1):143-7.

42. Allam AY. Effect of gypsum, nitrogen fertilization and hill spacing on seed and oil yields of sesame cultivated on sandy soil. Assiut J Agric Sci (Egypt). 2002.

43. Elayaraja D, Singaravel R. Effect of vermicompost and micronutrients fertilization on the growth, yield and nutrients uptake by sesame (*Sesamum indicum* L.) in coastal saline soil. Int J Agric Sci. 2017;13(2):177-83. https://doi.org/10.15740/HAS/IJAS/13.2/177-183

44. Heidari M, Galavi M, Hassani M. Effect of sulfur and iron fertilizers on yield, yield components and nutrient uptake in sesame (*Sesamum indicum L.*) under water stress. Afr J Biotechnol. 2011;10(44):8816-22. https://doi.org/10.5897/AJB11.854

45. Yadav RA, Tripathi AK, Yadav AK. Effect of micronutrients in combinations with organic manures on production and net returns of sesame (*Sesamum indicum*) in Bundelkhand tract of Uttar Pradesh. Ann Agric Res. 2009;30(1&2).

46. Salwa AIE, Abass MM, Behary SS. Amelioration productivity of sandy soil by using amino acids, sulphur and micronutrients for sesame production. J Am Sci. 2010;6(11):250-7.

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