Response of Sunflower to Sources and Levels of Sulfur under Rainfed Semiarid Tropical Conditions

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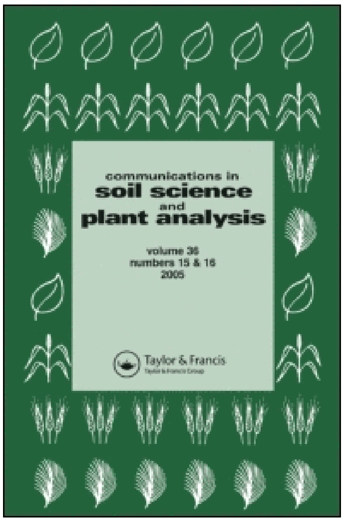

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Response of Sunflower to Sources and Levels of Sulfur under Rainfed Semi-arid Tropical Conditions

K. Usha Rani, K. L. Sharma, K. Nagasri, K. Srinivas, T. Vishnu Murthy, G. R. Maruthi Shankar, G. R. Korwar, K. Sridevi Sankar, M. Madhavi, and J. Kusuma Grace

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Abstract: Sulfur (S) is one of the severely limited nutrients in rainfed semi-arid tropical Alfisols. Its application plays an important role in improving the yield and quality of oilseed crops. To identify the optimum level of sulfur for greater yield and oil content in the sunflower crop (MSFH-8) through suitable sources, a field experiment involving varying levels of S through two sources (gypsum and elemental S) in combination with standard levels of nitrogen (N) and phosphorus (P) was conducted on a sandy loam soil (Typic Haplustalf) at Hayathnagar Research Farm of Central Research Institute for Dryland Agriculture, Hyderabad, situated at an altitude of 515 m above mean sea level and on 78° 36′ E longitude and 17° 18′ N latitude. The response to S application in sunflower crop in terms of growth parameters, yield components, nutrient uptake, and seed oil content was conspicuous. The application of graded levels of sulfur at rates of 20, 40, and 60 kg ha^{-1} applied through elemental S significantly increased the seed yield of the sunflower crop over the control by 5.4, 10.7, and 18.1% respectively, whereas the corresponding increases in case of gypsum ($CaSO_4 \cdot 2H_2O$) were 25.1, 28.8, and 33.9% respectively. The greatest seed yield of sunflower (1175 kg ha^{-1}) and percentage oil content (39.7%) was obtained with 60 kg S ha^{-1} through gypsum under rainfed conditions. Our study clearly indicated that the application of S at relatively high levels significantly increased the uptake of N, P, and S. The percentage oil content in seed recorded a positive and highly significant relationship with the uptake of N ($r = 0.958^{**}$), P ($r = 0.967^{**}$), and S ($r = 0.951^{**}$), signifying the importance of balanced nutrition in influencing the oil

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content of seed in sunflower. The application of S through gypsum at rate of 60 kg S ha^{-1} along with 40 kg N and 30 kg P_2O_5 ha^{-1} was most superior in enhancing the seed yield and percentage oil content in seed.

Keywords: Alfisol, S application, S sources, seed oil content N/S and P/S ratio, sunflower

INTRODUCTION

Sulfur (S) is one of the essential elements needed by plants. It plays an important role in crop production. Plant nutrient S (PNS) is required by the plants in amounts similar to phosphorus (P) and is important to the plants for protein formation and other functions. Functionally, S significantly influences yield and quality of crops, improves odor and flavors, and imparts resistance to cold, and hence it is generally considered a "quality nutrient." Sulfur-deficient soils are widely distributed around the world. Sulfur-deficiency symptoms are more often observed in crops at early stages of growth, because S can be easily leached from the surface soil (Hitsuda, Yamada, and Dirceu 2005). Sulfur is deficient in rainfed semi-arid tropical (SAT) Alfisols because of low organic-matter content in soil, coarse texture of the soils, more removal of S than its application, and use of fertilizers without any S content. The native plant-available S [0.15% calcium chloride ($CaCl_2$)–extractable S] in rainfed Alfisols in the SAT regions rarely exceeds 10–20 kg ha^{-1}, and the soils are mostly categorized as low to medium in S (Takkar 1988; Morris 1987). Consequently, the yield of oilseed crops, especially sunflower, is severely affected due to S deficiency. Response of crops to other nutrients also becomes less and less because of the marginally low level of S in these soils. In addition, the disproportionately greater use of nitrogen (N) and P in comparison to S has widened the N–S and P–S ratios (Manickam and Vijayachandran 1985). This imbalance affects the efficiency of fertilizers and impairs the quality of produce besides reducing yield According to Tandon (1985), each unit of S applied on S-deficient soils can augment the supply of edible oils considerably. Sunflower is a newly introduced oilseed crop in India in general and in SAT regions under rainfed conditions in particular, but it has gained good popularity among the growers because of its attractive price and demand for its oil. Because it is an energy-rich oilseed crop, its P and S nutrition assumes greater importance in comparison to other nutrients. In the absence of S, carbohydrates are not fully utilized for the formation of oil (Yadav and Singh 1970). Because information on the effect of sources and levels of S on the yield attributes and yield of sunflower and plant nutrient uptake in rainfed SAT Alfisols is lacking, the present study was undertaken to study the response of rainfed sunflower to S application and to recommend the optimum levels of S, to evaluate inexpensive sources of S fertilizer for their suitability for sunflower crop, and to monitor the internal response in terms of S uptake and improvement in oil content.

MATERIALS AND METHODS

Description of the Field Experiment

To achieve the objectives, a field experiment was conducted at the Hayathnagar Research Farm of Central Research Institute for Dryland Agriculture, Hyderabad, situated at 78° 36′ E longitude and 17° 18′ N latitude at an altitude of 515 m above the mean sea level (msl). The soil of the experimental field is an Alfisol (Typic-Haplustalf), sandy loam in texture; slightly acidic to neutral in reaction; low in organic C, available N, and available S; and medium in available P and potassium K. The climate of the region is semi-arid tropical with hot summers and mild winters. The mean annual rainfall of this region is generally 750 mm and accounts for approximately 42% of annual potential evapotranspiration (1754 mm). Before seeding, the experimental field was plowed twice using a tractor-drawn disc and was harrowed. The field was leveled with a bullock-drawn leveler after complete removal of stubbles of previous crop to provide suitable tilth for the crop. The experimental treatments consisted of four levels of S (0, 20, 40, and 60 kg S ha^{-1}) through two sources [viz., elemental S (ES) (85% S) and gypsum (Gyp) (18.6% S)]; two levels of phosphorus (0 and 30 kg P_2O_5 ha^{-1}); and two levels of N (0 and 40 kg N ha^{-1}). Because the soils were adequate in available potassium (K), it was not applied. These treatments were labeled as 0 kg N + 0 kg P_2O_5 + 0 kg S (T1), 40 kg N + 30 kg P_2O_5 + 0 kg S (T2), 40 kg N + 30 kg P_2O_5 + 20 kg S (ES) (T3), 40 kg N + 30 kg P_2O_5 + 40 kg S (ES) (T4), 40 kg N + 30 kg P_2O_5 + 60 kg S (ES) (T5), 40 kg N + 30 kg P_2O_5 + 20 kg S (Gyp) (T6), 40 kg N + 30 kg P_2O_5 + 40 kg S(Gyp) (T7), and 40 kg N + 30 kg P_2O_5 + 60 kg S(Gyp) (T8). These treatments were applied in a randomized block design (RBD) with four replications. Hybrid sunflower (MSFH-8) was seeded at a row-to-row spacing of 60 cm and plant-to-plant spacing of 25 cm in plots of 3.6 m × 8 m. A total rainfall of 419.0 mm was received during the cropping season (July–October) in 21 rainy days. The N and P were applied through di-ammonium phosphate (DAP), and the balance amount of N was supplemented through urea. One third of the N and whole of the S and P were applied basally at the time of sowing of sunflower crop. The remaining two-thirds dose of N was top-dressed at 30 days after sowing (DAS). All standard crop production practices were followed. After harvest of the crop, the weights of the heads and stalks were recorded after thorough drying. The seeds from the harvested dried heads were separated after threshing. Seed was air dried, and plot-wise seed yields were recorded. Samples of air-dried seed were dried to constant weight in an oven at 60 °C, and the moisture content of the seed was taken into account while calculating the uptake of different nutrients.

Methods for Field Observations

To measure the external response, growth observation were taken at 30 and 60 DAS and at harvest from five randomly selected and previously tagged plants in each plot. Observations recorded on the five plants were averaged and expressed on per plant basis. In addition to this, five plants from each plot were removed in a specific order from the field at 30 DAS, 60 DAS, and at harvest for destructive sampling. The important plant growth observations recorded/calculated were plant height (m), leaf area (cm^2), leaf area index (LAI), dry matter accumulation/plant, seed yield, and yield components [i.e., head diameter (m), total number of seeds per head, filled seeds per head, and test weight].

Methods for Laboratory Analysis

Oil content in the seed was estimated by using the nuclear magnetic resonance (NMR) technique. Nitrogen content in the plant samples was estimated using the modified Kjeldahl method (Jackson 1973). Phosphorus content in the plant samples was estimated by vanadomolybdophosphoric yellow color method as suggested by Jackson (1973). Sulfur content in the sampled plants in each treatment was estimated at each stage after digesting the samples in di-acid mixture [nitric acid (HNO_3)–perchloric acid ($HClO_4$) 9:4] followed by colorimetric estimation using the barium chromate method (Palaskar and Ghosh 1981).

Statistical Analysis

The data obtained from the study were analyzed statistically using analysis of variance (ANOVA) for RBD as per the procedures given by Snedecor and Cochran (1967). The significance of the treatment effect was judged by calculating the variance ratio. Critical difference for examining treatment means for their significance was seen at P = 0.05. For calculating the effect of graded S rates on seed yield, a linear relationship was assumed.

RESULTS AND DISCUSSION

Effect on Growth Parameters, Yield Attributes, and Dry Matter

Application of N and P (T2) gave significantly higher plant height (PH) at all growth stages over control (T1). Increasing S levels from 0 to 60 kg S ha^{-1} in the form of elemental S significantly increased the PH at all growth stages. Each additional level of S applied as gypsum also significantly increased the PH at all growth stages. However, 60 kg S ha^{-1} gave the maximum PH over all lower levels tested. Both sources of S (elemental S and gypsum) had significant influence on plant height, but gypsum had a more pronounced effect at all levels at all growth stages (Table 1).

Leaf area index (LAI) was recorded from day 30 after sowing at 30-day intervals, and the mean values are presented in Table 1. Application of N and P (T2) significantly increased the LAI at 90 DAS but there was no significant difference at 30 and 60 DAS over control. The three levels of elemental S showed significant increase in LAI over no S (T2) at all crop growth stages, but this parameter was significantly greater at 60 kg ha^{-1} over other levels. Application of gypsum significantly increased LAI over its control at all growth stages of crop. At 30 days, both 40 and 60 kg S ha^{-1} were on par but superior to 20 kg S ha^{-1} in influencing LAI. At 60 days and at maturity, 60 kg S ha^{-1} was significantly superior to the other two lower levels. Among the two sources of S, gypsum performed well at all levels and at all growth stages over elemental S.

The data on dry matter (DM) production plant^{-1} at 30-day intervals was recorded and are presented in Table 1. Dry-matter accumulation was significantly influenced by N and P (T2) at all growth stages over control (T1). The increases in DM production due to N and P application (T2) over control (T1) at 30 DAS, 60 DAS, and at maturity were 1.3, 2.9, and 3.3%, respectively. Different levels of elemental S showed increased DM accumulation at all levels and at all growth stages except at 60 DAS, where the response at 40 kg S ha^{-1} was on par with 60 kg S ha^{-1}. In the case of gypsum, the DM accumulation was influenced significantly at all levels and at all growth stages, but 60 kg S ha^{-1} (T8) at 30 and 60 DAS and 40 kg S ha^{-1} (T7) at harvest were found to be advantageous. Both sources of S gave greater DM over no sulfur (T2). Among the two sources, gypsum gave significantly more DM yield over elemental S at all corresponding levels. At maturity of crop, 20, 40, and 60 kg S ha^{-1} in the form of gypsum gave 8.3, 12.6, and 9.8% more DM over corresponding levels of elemental S. The effect of N and P on girth of stem was nonsignificant at all growth stages. The stem diameter increased significantly only up to the first incremental dose (20 kg ha^{-1}) of elemental S over control (T2) at all growth stages. In the case of gypsum also, a similar trend was observed as was in case of elemental S except

Table 1. Growth parameters as influenced by levels and sources of sulfur in sunflower at different growth stages

$N–P_2O_5–S$ treatments	30 DAS				60 DAS				Harvest			
	PH (m)	LAI	DM (kg ha^{-1})	Girth (cm)	PH (m)	LAI	DM (kg ha^{-1})	Girth (cm)	PH (m)	LAI	DM (kg ha^{-1})	**Girth (cm)**
T1 0–0–0	0.162	0.34	161.05	2.68	0.794	2.05	2157.86	4.13	0.910	2.63	3415.43	5.13
T2 40–30–0	0.185	0.36	163.18	2.78	0.889	2.09	2220.44	4.23	0.925	2.71	3526.90	5.25
T3 40–30–20[a]	0.196	0.43	164.71	3.23	0.944	2.13	2273.92	4.58	0.943	2.79	3627.83	5.40
T4 40–30–40[a]	0.205	0.47	167.49	3.38	1.000	2.17	2349.27	4.75	0.962	2.84	3726.95	5.60
T5 40–30–60[a]	0.212	0.51	170.07	3.58	1.021	2.23	2436.08	5.00	0.993	2.92	3812.55	5.73
T6 40–30–20[b]	0.225	0.53	171.22	3.68	1.047	2.28	2505.08	5.38	1.064	3.01	3929.27	5.95
T7 40–30–40[b]	0.238	0.59	172.94	3.95	1.077	2.36	2604.77	5.60	1.091	3.11	4196.74	6.13
T8 40–30–60[b]	0.246	0.60	177.05	4.08	1.090	2.55	2724.71	5.75	1.122	3.18	4186.78	6.28
LSD ($P = 0.05$)	0.002	0.02	1.43	0.36	0.004	0.04	87.30	0.29	0.001	0.03	184.49	0.17

[a] Elemental S.

[b] Gypsum.

that gypsum responded up to 40 kg S ha^{-1}. Irrespective of treatments, stem diameter increased markedly up to 60 days (age of the crop).

The data on "days taken for 50% flowering" under different treatments are presented in Table 2. Application of N and P (T2) did not show significant difference on days taken for 50% flowering over control (T1). Among the levels of elemental S, 20 and 40 kg S ha^{-1} were on par but 60 kg S ha^{-1} significantly advanced 50% flowering over no S treatment (T2). In the case of gypsum, the increased level of S from 40 kg S ha^{-1} caused significant decrease in days to 50% flowering. Among the two sources of S, advanced flowering was observed with gypsum over elemental S at all corresponding levels of S. Nitrogen in combination with P (T2) significantly increased the sunflower head diameter over control (T1) by 6.8%. Each successive increment of S applied as elemental S significantly improved the head diameter over its lower level. The increases in head diameter due to application of elemental S at rate of 20, 40, and 60 kg S ha^{-1} were 7.8, 14.3, and 20.4%, respectively, over control (T2). In the case of gypsum, 60 kg S ha^{-1} showed significant increase in head diameter over 20 kg S ha^{-1} and its control (T2) but was on par with 40 kg S ha^{-1}. Among the two sources of S, gypsum gave significantly greater head diameter over the corresponding levels of elemental S.

Application of N and P (T2) significantly increased the number of filled seeds per head over no N and P (T1). There was significant increase in the number of filled seeds per head with every graded dose of S irrespective of the source of S. Among the levels of elemental S, the increase in seed number in 60, 40, and 20 kg S ha^{-1} over no S (T2) was 20.2, 10.8, and 7.2%, respectively. Gypsum at 60, 40, and 20 kg S ha^{-1} increased the seed number per head by 36.2, 32.6, and 25.9%, respectively, over no S (T2). Among the two sources of S, gypsum was significantly superior to elemental S at all levels in recording more filled seeds per head. Application of N and P significantly enhanced the test weight over control (T1) by 4.5%. Application of different levels of elemental S (viz., 20, 40, and 60 kg S ha^{-1}) recorded greater test weight by 7.0, 12.8, and 16.8% compared to no S treatments (T2). Among the levels of S applied through gypsum, 40 and 60 kg S ha^{-1} levels were on par and significantly superior to 20 kg S ha^{-1} and no S treatment (T2). The increase in test weight at 40 kg S ha^{-1} over 20 kg S ha^{-1} and no S were 1.9 and 25.1% respectively. Each level of gypsum significantly enhanced the test weight over the corresponding levels of elemental S.

Effect on Seed Yield

Application of N and P significantly increased the seed yield over control (Table 2) (T1) by 9.8%. Among the levels of elemental S, greater seed

Table 2. Yield attributes as influenced by levels and sources of sulfur in sunflower

$N–P_2O_5–S$ treatments	Days to 50% flowering	Head diameter (m)	Filled seeds per head	Test weight (Kg)	Seed yield ($kg\,ha^{-1}$)	Harvest index (%)	Oil content (%)	Oil yield ($kg\,ha^{-1}$)
T1 0–0–0	58.25	0.132	284.00	0.037	798.94	23.39	34.15	272.84
T2 40–30–0	57.83	0.141	305.75	0.039	877.08	24.87	34.60	303.47
T3 40–30–20^a	57.49	0.153	328.00	0.041	925.32	25.51	34.89	322.84
T4 40–30–40^a	57.36	0.162	338.75	0.043	971.46	26.07	35.35	343.41
T5 40–30–60^a	56.87	0.170	367.50	0.045	1036.57	27.18	36.00	373.17
T6 40–30–20^b	56.43	0.179	385.00	0.047	1097.92	27.94	36.68	402.72
T7 40–30–40^b	55.84	0.182	405.50	0.048	1130.49	26.93	37.80	427.33
T8 40–30–60^b	54.74	0.186	416.50	0.049	1175.49	28.07	39.68	466.43
LSD (P = 0.05)	0.51	0.70	9.36	0.87	40.85	1.87	0.47	13.00

[a] Elemental S.
[b] Gypsum.

yield of 1036.57 kg ha^{-1} was recorded with 60 kg S ha^{-1} (T5). The yield in T5 was significantly more than T4 (971.46), T3 (925.32), and T2 (877.08). The yield increases in T5 over T4, T3, and T2 were 6.7, 12.0, and 18.2%, respectively. This trend indicated that the response in seed yield was linear with the increasing level of S.

In the case of gypsum, 20 kg S ha^{-1} was significantly superior to control (T2), but 60 kg S ha^{-1} was significantly greater than all the lower levels of S in terms of seed yield. Increases in seed yield at 60 kg S ha^{-1} over the lower levels of gypsum (viz., 40, 20, and 0 kg S ha^{-1}) were 3.9, 7.1, and 34.0%, respectively. Among the two sources of S, gypsum at all levels showed significantly greater seed yield over the corresponding levels of elemental S. Irrespective of sources, 60 kg S ha^{-1} gave the greatest seed yield (26%) over no S treatment. This could be attributed to better development of the vegetative parts of the plant (source) reflected by increased PH, LAI, and DM accumulation and proportionate increase in reproductive parts (sink) of the plant as evidenced by larger disc diameter and number of seeds per head, resulting in a balanced source–sink relationship. This in turn was reflected by seed yield. Data on seed yield per hectare revealed significant response to levels of S irrespective of source.

Data on harvest index (%) of sunflower influenced by different treatments are given in Table 2. Harvest index of sunflower was significantly increased with the application of N and P over control (T1). Increased levels of both the sources of S under test did not show significant differences in harvest index over the lower level. However, greater levels of S (60 kg S ha^{-1}) in both the sources showed significant differences in harvest index over T2 (no S). Among the sources of S, gypsum recorded significantly better harvest index at corresponding S levels.

In the present study, the application of graded levels of S in rainfed SAT Alfisol significantly influenced the plant growth parameters and crop yield. Further, gypsum as S source maintained its superiority over elemental S. A similar response pattern in terms of plant growth parameters such as LAI, PH, head diameter, filled seeds per head, seed test weight, and seed yield with the application of S in addition to other nutrients has been reported earlier by Ramu and Reddy (2003) and Nabi, Salim, and Gill (1995). Similarly, Giri et al. (2003) observed that in the intercropping system, LAI, total DM (TDM), and pod/seed weight increased significantly due to the application of P and S. The studies of Ozer, Polat, and Ozturk (2004) revealed that all plant parameters were significantly influenced by S applications in combination with required levels of N. In an S response study conducted with sunflower crop, Sajjan and Pawar (2005) reported that application of 20 kg S ha^{-1} along with limiting micronutrient, zinc, helped in maintaining desirable yield levels. While studying the superiority of S sources in sunflower crop, Vaiyapuri et al. (2004) reported the better performance of gypsum over pyrite in terms of plant growth, yield, quality, and nutrient uptake.

Crop response to S application generally depends upon the initial S status of the soil. Hence, in the present investigation, the response to added doses of S was attributed to low soil S level (14 kg S ha^{-1}). Increased levels of S irrespective of the source significantly increased the three growth characters studied (viz. PH, LAI, and DM accumulation), and the maximum were found at 60 kg S ha^{-1}. The response of sunflower crop to S application might be due to more synthesis of chlorophyll (Chatterjee, Chosh, and Chakrabarty 1985). Among the two sources of S, gypsum showed significantly greater seed yield over the corresponding levels of elemental S, and this was amply supported by increased values of growth characters (PH, LAI, and DM production) as well as yield contributing characteristics (diameter of head, filled seeds per head, and test weight) obtained by gypsum application. Similarly, the harvest index was also greater in the case of gypsum, indicating the faster rate of conversion of biological yield into economic yield, and thus gypsum proved its superiority over corresponding levels of elemental S.

Effect on Oil Content and Oil Yield

Data on seed oil content under different treatments are presented in Table 2. Nitrogen and P application did not have any significant effect in increasing the seed oil content over the control (T2). The difference in seed oil contents among different levels of elemental S showed that 40 kg S ha^{-1} recorded significantly greater seed oil content over control (T2), and it was on par with 20 kg S ha^{-1}. Similarly, 60 kg S ha^{-1} was significantly superior over other lower levels of elemental S. In the case of gypsum, increased levels of S significantly increased the seed oil content. Greater oil percentage was recorded at 60 kg S ha^{-1} (39.7%), whereas the corresponding oil content with no S application was 34.6%. Among the two sources of S, gypsum resulted in greater percentage of oil content in seed at all the levels tested over the corresponding levels of elemental S.

Application of N and P showed significant increase in oil yield over control (T1) by 11.2%. Each level of elemental S showed significant increase in the oil yield over its lower level, and the greatest oil yield (373.2 kg ha^{-1}) was registered with 60 kg S ha^{-1}. The increases in oil yield at 60, 40, and 20 kg S ha^{-1} were 23.0, 13.2, and 6.4% respectively over no S (T2). Increased levels of S fertilization through gypsum resulted in significant increase in oil yield of sunflower. Gypsum application at rates of 60, 40, and 20 kg S ha^{-1} gave 53.7, 40.8, and 32.7% increased oil yields over no S (T2). Among the two sources of S, gypsum was found superior over elemental S in recording significantly greater oil yields at all corresponding levels of S. While studying the impact on oil content in sunflower, Poonia (2003) observed a significant increase in oil content in sunflower up to 25 kg S ha^{-1}, whereas oil yield ha^{-1} increased significantly up to 50 kg S ha^{-1}. Further, he reported that an optimum combination of N and S is a must for maintaining greater oil content, oil yield, and nutrient uptake. The present findings are on par with those earlier reported for groundnut by Sukhija et al. (1987), indicating that the supplementation of limiting nutrients such as S helps in increasing the oil content in the matured kernels. It was interesting to observe that in the present study, the application of S through gypsum exhibited greater percentage of oil in seed as well as greater oil yield over elemental S at all levels. These findings clearly indicated the superiority of gypsum over elemental S in not only obtaining greater seed yield but also greater oil yield. Further, in this study, we clearly observed that oil content and oil yield of sunflower were significantly increased with progressive levels of S application. The increase in oil content of sunflower seed with S application was of the order of 5.0, 7.1, and 10.8% at 20, 40, and 60 kg S ha^{-1} over no S irrespective of the sources of S. This increase in oil content is probably due to efficient fatty acid synthesis with increasing levels of S application. In fatty acid synthesis, acetyl Co-A is converted into malonyl Co-A. In this conversion, an enzyme (thiokinase) is involved. The activity of thiokinase enzyme depends upon S supply. Moreover, acetyl Co-A itself contains S and S hydroxyl group. This may be the reason for the increase in oil content of seed. Further, the increase in oil yield due to S application was due to increase of both seed yield and its oil content. These results of our study lend support to earlier findings of Verma, Thakur, and Rai (1973), Barhanbure (1976), Patil, Shinde, and Zende (1981), and Karle (1982), who have also reported increased oil content in different oilseed crops due to S application.

Effect on Nutrient Content and Uptake

Nitrogen Content and Uptake.

There was no significant difference in N content of the plant between control (T1) and in the treatment (T2) where N and P were applied at all growth stages of the crop shown (Table 3). At 30 DAS, 60 kg S ha^{-1} in the form of elemental S showed significant increase in N content of the plant over all the lower levels of S. At 60 and 90 DAS, 20, 40, and 60 kg S ha^{-1} were on par, but the higher level of S tested (60 kg S ha^{-1}) was significantly superior over no S treatment (T2). At 30 DAS, the N content recorded in plants was more than that at 60 and 90 DAS. There was a

Table 3. Nitrogen, phosphorus, and sulfur content of plant ($g\,kg^{-1}$) as influenced by levels and sources of sulfur in sunflower at different growth stages

$N–P_2O_5–S$ treatments	30 DAS			60 DAS			At harvest		
	N	P	S	N	P	S	N	P	S
T1 0–0–0	24.3	2.0	2.00	16.8	2.90	2.50	18.5	3.10	2.70
T2 40–30–0	25.8	2.20	2.10	17.7	3.30	2.70	19.2	3.30	3.00
T3 40–30–20[a]	26.1	2.50	2.30	18.5	3.50	2.90	20.0	3.50	3.30
T4 40–30–40[a]	26.2	2.70	2.30	18.8	3.70	3.10	20.4	3.60	3.50
T5 40–30–60[a]	35.2	2.90	2.40	19.6	3.90	3.20	21.0	3.80	3.70
T6 40–30–20[b]	35.4	3.10	2.60	20.1	4.10	3.50	21.6	3.90	4.10
T7 40–30–40[b]	34.5	3.50	2.70	20.4	4.40	3.50	22.6	4.10	4.20
T8 40–30–60[b]	36.1	3.90	2.80	20.7	4.60	3.60	23.1	4.20	4.30
LSD (P = 0.05)	0.39	0.03	0.008	0.11	0.02	0.02	0.11	0.02	0.02

[a] Elemental S.
[b] Gypsum.

decline in N content with the advancement of plant age, which may be attributed to a dilution effect. Similar observations were recorded earlier by Hilton and Zubriski (1985) in sunflower crop. In the case of gypsum, at all the crop growth stages, 20, 40, and 60 kg S ha^{-1} levels were on par, but all these levels were significantly superior over control (T2) in terms of N content of the plant. Among the two sources of S tested, gypsum proved its superiority in improving the N content of plant over elemental S at comparable S levels. Similarly, there was no significant difference in N uptake between N and P treatment (T_2) and its control (T1) except at 60 DAS (Table 4). While studying the influence of S on N uptake, it was clearly observed that at 60 DAS, each increment of S showed significant increase in N uptake of the crop. However, this effect was not much visible on 30 DAS. At 90 DAS, application of 60 kg S ha^{-1} was significantly superior over all the lower levels tested except 40 kg S ha^{-1}. In the case of gypsum, 60 and 40 kg S ha^{-1} were on par, but both the levels were significantly superior to 20 and 0 kg S ha^{-1} except at 60 DAS. Interestingly, among the two sources of S, in the case of gypsum, irrespective of the levels of application, there was 15.7, 15.2, and 20.0% greater N uptake (removal) by sunflower crop at 30 DAS, 60 DAS, and at harvest respectively compared to elemental S. This greater N uptake (removal) could be attributed to relatively greater yield levels obtained under gypsum application, where S uptake was also greater probably owing to the ready availability of S to the gypsum-treated crop. The synergistic effects of N and S have been well documented because these two nutrients are said to increase the concentration and uptake of each other in the plant (Dev and Kumar 1982). It has been established that the need for S is associated with amounts of N available to crop plants. This

Table 4. Nitrogen, phosphorus, and sulfur uptake (kg ha^{-1}) as influenced by levels and sources of sulfur in sunflower at different growth stages

N–P_2O5–S treatments	30 DAS			60 DAS			At harvest		
	N	P	S	N	P	S	N	P	S
T1 0–0–0	3.92	0.32	0.32	36.14	6.15	5.40	63.67	10.50	9.25
T2 40–30–0	4.22	0.35	0.35	39.20	7.22	5.93	67.57	11.56	10.45
T3 40–30–20[a]	4.31	0.40	0.38	42.03	7.96	6.62	72.65	12.52	11.89
T4 40–30–40[a]	4.38	0.45	0.39	44.27	8.59	7.19	75.84	13.43	13.12
T5 40–30–60[a]	5.98	0.49	0.41	47.80	9.45	7.87	79.83	14.30	14.04
T6 40–30–20[b]	6.05	0.53	0.44	50.28	10.28	8.31	84.91	15.43	15.97
T7 40–30–40[b]	5.90	0.61	0.46	53.02	11.34	9.03	94.08	17.06	17.65
T8 40–30–60[b]	6.30	0.69	0.46	56.32	12.53	9.80	96.70	17.90	18.11
LSD (P = 0.05)	0.66	0.05	0.05	1.83	0.58	0.53	4.68	0.74	1.12

[a] Elemental S.
[b] Gypsum.

relationship is not surprising because both of these elements are components of protein and are associated with chlorophyll formation. Nitrogen and S also are linked because S plays a key role in the activation of the enzyme nitrate reductase, which facilitates the conversion of nitrates to amino acids. Low activity of this enzyme due to S deficiency depresses soluble protein concentration in plant tissues (Lamond 1997).

Phosphorus Content and Uptake.

Results also revealed that the N and P application significantly increased P percentage in the plant at 60 DAS, but at 30 and 90 DAS, these effects were not significant (Table 3). Among the levels of elemental S, greater P content was observed in the plant at 60 kg S ha^{-1}, which was on par with 40 kg S ha^{-1} and significantly superior to 20 kg S ha^{-1} and no S treatments at all growth stages. In the case of gypsum, 60 kg S ha^{-1} recorded significantly more P content of plant over other lower levels of S. At 30 DAS, 60 kg S ha^{-1}, and at 60 and 90 DAS, both 60 and 40 kg S ha^{-1} were on par and significantly superior to 20 kg S ha^{-1} and no S treatment (T2). All the three levels of S tested through gypsum resulted in significantly more P content in plants compared to the corresponding levels of elemental S at all growth stages. The increase in the P content of plant with S application indicated the beneficial role of S in mobilizing soil P and its utilization. Similar results were reported by Virmani and Gulati (1971) in mustard crop.

The P uptake by sunflower crop was significantly influenced by N and P application at 60 and 90 DAS (Table 4). The elemental S applied at rate of 60 kg S ha^{-1} was on par with 40 kg S ha^{-1} at 30 DAS but was significantly superior over 20 and 0 kg S ha^{-1}. However, at 60 DAS and at harvest, each increment of S significantly increased the P uptake of crop. Every increase in S level in the form of gypsum resulted in significant increase in P uptake of the crop at all growth stages.

Sulfur Content and Uptake.

The application of N and P significantly influenced the S content of the plant over control (T1) at all growth stages of the crop except at 60 DAS. Application of elemental S at rate of 60 kg S ha^{-1} resulted in the greatest S content of plant over all the lower levels tested at 30 DAS (Table 3). At 60 days and harvest stage, 60 and 40 kg S ha^{-1} were on par in influencing the S content of the plant, but these levels were significantly superior over 20 and 0 kg S ha^{-1}. Increasing levels of S in the form of gypsum resulted in significant increase in S content of the plant at all growth stages. Among the sources of S, gypsum showed significantly more S content of the plant at all comparable levels of elemental S. This trend corroborates with the findings of Kumar, Singh, and Singh (1981). The increased S uptake due to S application can also be attributed to higher demand of S because the crop was grown on an S-deficient soil. The maximum S uptake of 9.45 kg S ha^{-1} was observed with 60 kg S through gypsum (T_8). Application of N and P significantly increased S uptake of crop at 90 DAS (Table 4) but was not significant at 30 and 60 DAS over control (T1). At 30 DAS, 60 kg S ha^{-1} in the form of elemental S was on par with 40 kg S ha^{-1} but was significantly superior to 20 and 0 kg S ha^{-1} in influencing the S uptake by the crop. Every increment of elemental S resulted in significantly more S uptake by the crop at 60 DAS. In the case of gypsum, 20, 40, and 60 kg S ha^{-1} were on par and significantly superior over its control (T2) at 30 DAS. On average, S uptake was greater by 15.3, 25.2, and 32.5% at 30 DAS, 60 DAS, and harvest respectively with gypsum compared to elemental S. The corresponding increase in the S content in sunflower plant was 15.7, 15.2, and 20.0% respectively with gypsum. Boswell (1997) also reported significantly greater S contents in plants raised with gypsum than with elemental S. The decrease in S content due to elemental S might be because the elemental S is regarded as a slow-release fertilizer, because it must be oxidized to sulfate S by soil microorganisms before it is available for plant uptake as sulfate S (Boswell 1997). Moreover, the oxidation of elemental S is favored by optimum soil temperature and adequate soil moisture levels near field capacities, which are limiting factors in these dryland areas. Further, the oxidation of elemental S results in increasing the soil acidity, thus reducing the availability of S to plants. On the other hand, application of gypsum, apart from providing sulfate S, also might have moderated the slightly acidic reaction of these soils by way of contributing calcium.

Interrelationships between Growth Parameters, Yield Attributes, Seed Yield, and Nutrient Uptake.

Positive and highly significant correlation was observed between seed yield and growth characters [viz., PH (r = 0.984**), LAI at 60 DAS (r = 0.969**), and DM at harvest (r = 0.965**)] (Table 5). This relationship indicated that the vegetative parts of the plant acted as an efficient source, which helped in filling the sink more efficiently for getting greater seed yield. Seed yield was positively associated with the entire yield-contributing characteristics [viz., head diameter (r = 0.990**), filled seeds per head (r = 0.990**), and test weight (r = 0.985**)], which indicated that the yield-contributing characteristics helped in increasing seed yield in sunflower. Dry-matter production was positively and significantly correlated with N (r = 0.997**), P (r = 0.998**), and S (r = 0.993**) uptake, implying that these characteristics were not completely independent but were interdependent on each other. When the influence of S uptake was studied on N (r = 0.998**) and P (r = 0.998**) uptake, significant correlations were observed. This clearly indicated that S improved the uptakes of other nutrients. It was interesting to observe that the oil percentage in seed recorded positive and highly significant relationships with N (r = 0.958**), P (r = 0.967**), and S (r = 0.951**) uptake, indicating that nutritional status of the plant determined the oil content of seed in sunflower. Significantly negative correlation was observed between the "days to 50% flowering" and all growth characteristics, yield-contributing characteristics as well as seed yield. This finding indicated that the reduction in vegetative growth period due to treatment effects caused increase in growth characteristics (source) and yield-contributing characteristics (sink) and ultimately reflected in seed yield.

CONCLUSIONS

Application of S to sunflower crop is essential in semi-arid tropical Alfisols to ensure good seed yields and oil content. In this study, it was found that PH was significantly increased by the application of N and P at rates of 40 kg N and 30 kg P_2O_5 and similarly with the application of both the sources of S. Highest plant height was observed with 60 kg S ha^{-1} through gypsum. Leaf area index was influenced by the application of N, P, and both the sources of S. Dry-matter production was significantly greater due to application of N and P and both the sources and levels of S; however, greater DM production was seen for gypsum application (4196.7 kg ha^{-1})

Table 5. Interrelationship of plant growth parameters, yield attributes, and nutrient uptake

	Plant height at harvest	LAI at 60 DAS	Dry matter at harvest	Days to 50% flowering	Head diameter	Filled seeds per head	Test weight	Harvest index	Oil percentage of seed	N uptake at harvest	P uptake at harvest	S uptake at harvest	Seed yield
Plant height at harvest	1												
LAI at 60 DAS	0.983**	1											
Dry matter at harvest	0.984**	0.995**	1										
Days to 50% flowering	−0.949**	−0.988**	−0.976**	1									
Head diameter	0.993**	0.968**	0.967**	−0.922**	1								
Filled seeds per head	0.994**	0.983**	0.986**	−0.948**	0.992**	1							
Test weight	0.992**	0.966**	0.967**	−0.917**	0.999**	0.991**	1						
Harvest index	−0.45*	−0.521*	−0.527*	−0.559**	−0.405*	−0.438*	−0.401*	1					
Oil percentage of seed	0.925**	0.978**	0.968**	−0.996**	0.897**	0.927**	0.893**	−0.611*	1				
N uptake at harvest	0.988**	0.995**	0.997**	−0.971**	0.979**	0.993**	0.979**	−0.480*	0.958**	1			
P uptake at harvest	0.990**	0.998**	0.998**	−0.979**	0.976**	0.990**	0.974**	−0.509	0.967**	0.998**	1		
S uptake at harvest	0.995**	0.993**	0.996**	−0.965**	0.986**	0.995**	0.986**	−0.483	0.951**	0.998**	0.998**	1	
Seed yield	0.984**	0.969**	0.965**	−0.931**	0.990**	0.990**	0.984**	−0.437	0.907**	0.976**	0.974**	0.978**	1

*Significant at P=0.05.

**Significant at P=0.01.

at 40 kg S ha^{-1}. Head diameter also significantly increased due to application of N and P and both the sources and levels of S. Highest head diameter (0.186 m) was noticed with application of S at rate of 60 kg S ha^{-1} through gypsum. The filled seeds per head were significantly greater with the application of N and P and both the sources and levels of S. The greatest number of filled seeds (416.5 per head) was recorded with 60 kg S ha^{-1} through gypsum. Heaviest test weights (0.048 kg and 0.049 kg) were associated with application of S at rates of 40 and 60 kg ha^{-1} through gypsum respectively. Days to 50% flowering decreased significantly with the application of N and P and both sources and levels of S. Early flowering (50%) was observed with S at a rate of 60 kg S ha^{-1}. Application of N and P at a rate of 40–30 kg ha^{-1} significantly increased the seed yield (877.08 kg ha^{-1}) over control (798.94 kg ha^{-1}). Seed yield increased with increase in the levels of elemental S while seed yields of sunflower remained on par with the application of 20 and 40 kg S ha^{-1} applied through gypsum. However, significantly greater seed yield (1175.49 kg ha^{-1}) was obtained with S applied at a rate of 60 kg ha^{-1} through gypsum over control and 20 kg ha^{-1} S application. In the case of elemental S, there was a decrease in agronomic efficiency between S_{20} and S_{40}, whereas an increase was observed between S_{40} and S_{60}. A similar trend was observed in the case of agronomic efficiency for each increment. From the study, it can be concluded that application of S at rate of 60 kg S ha^{-1} through gypsum in combination with 40 kg N and 30 kg P_2O_5 is the most desirable option and can be recommended to the farmers growing sunflower crops under rainfed conditions in SAT Alfisols.

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