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Cotton Yield Response to Sulfur as Influenced by Source and Rate in the Çukurova Region, Turkey

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Abstract: Rapid expansion in nitrogen and phosphorus usage occurring over the past two decades in Turkey without an accompanying increase in the addition of sulfur (S) and decreased atmospheric SO_2 emissions has possibly created a major plant nutrient S deficit. Attention needs to be paid to S requirement of cotton producing environments where S deficiencies may become somewhat more common due to increased use of S free fertilizers, adoption of high yielding cultivars and more intensive cropping systems, and lower atmospheric S deposits. The effectiveness of sulfur fertilization for cotton grown in the region is not known. This study evaluated the effect of sulfur fertilizers on the yield and fiber quality of cotton (*Gossypium hirsutum* L). Four S rates, (0, 15, 30 and 45 kg ha^{-1}) were applied to the plots as elemental and gypsum at planting. The most beneficial effect on the yield of cotton was produced by the rate of 30 kg S ha^{-1}. Significant effects on the number of harvestable bolls plant^{-1} coupled with significant effects on boll weight, resulted in seed cotton yield being significantly higher with 30 kg ha^{-1} as compared to other rates. All S rates, except 45 kg S ha^{-1} produced significantly higher fiber length uniformity. Applications of 30 and 15 kg S ha^{-1} resulted in 4.0 to 2.0% increase in micronaire. The results suggest that 30 kg ha^{-1} gypsum supplied sufficient sulfur optimum yield under semiarid conditions. Cotton yield increase due to sulfur fertilizer indicates producers have the flexibility to apply sulfur fertilizer.

Key words: Boll weight, dry matter accumulation, *Gossypium hirsutum* L., sulfur rate, yield

Çukurova Bölgesinde Kükürt Kaynak ve Dozlarının Pamuk Verimine Etkisi

Özet: Türkiye'de son 20 yılda kükürt eklemesinde artış olmaksızın azot ve fosfor kullanımındaki hızlı büyümeler ve atmosferik SO_2 emisyonları kükürt noksanlığını oluşturmuştur. Kükürt noksanlıklarının kükürtsüz gübrelerin artan kullanımı, yüksek verimli çeşitlerin benimsenişi, daha yoğun üretim sistemleri ve daha düşük atmosferik kükürt depozitleri sonucunda daha yaygın duruma gelebildiği pamuk üretim çevrelerinde bitkinin kükürt gereksinimine yeterli özenin gösterilmesi gereklidir. Bölgede yetiştirilen pamukta kükürtlü gübrelemenin etkinliği bilinmemektedir. Çalışmada pamuk verimi ve kalitesi üzerine kükürt gübrelerinin etkisi değerlendirilmiştir. Ekimle birlikte dört kükürt dozu (0, 15, 30 and 45 kg ha^{-1}) elemental ve jips olarak uygulanmıştır. Pamuk verimi üzerine en yararlı etki 30 kg S ha^{-1} dozu ile oluşmuştur. Koza ağırlığı yanısıra bitkideki hasat edilebilir koza sayısı üzerine önemli etkileri, diğer dozlarla karşılaştırıldığında, 30 kg ha^{-1} uygulamasında önemli düzeyde yüksek kütlü pamuk verimini sonuçlamıştır. 45 kg S ha^{-1} dozu dışında tüm kükürt dozları önemli düzeyde yüksek lif yeknesaklığı oluşturmuştur. 30 ve 15 kg S ha^{-1} uygulamaları mikronerde % 4.0 ile % 2.0 artışa yol açmıştır. Sonuçlar 30 kg ha^{-1} jips uygulamasının yarı kurak koşullar altında optimum verim sağlanmasında yeterli olduğunu ortaya koymuştur. Kükürtlü gübre uygulaması ile oluşan pamuk verim artışı üreticilere kükürtlü gübre uygulayabilme esnekliğini göstermiştir.

Anahtar kelimeler: Koza ağırlığı, kuru madde birikimi, *Gossypium hirsutum* L., kükürt dozu, verim

Introduction

The availability of sulfur needed for profitable crop production continues to decline. Sulfur deficiencies are attributed to improved fertilizers that contain little to no S impurities, intensive cropping systems that leave behind little organic matter, increased yield that results in more S removal, less deposition of S from the atmosphere, and less use of S-containing pesticides. Sulfur fertilization of crops needs to be an integral component of balanced nutrition for producing optimum yields and quality of crops. Crops like cotton, which have high-protein in seed, need larger quantities of sulfur. For normal yields, the crops with high sulfur requirements need 20 to 45 kg S ha^{-1} (Aulakh et al., 1985). Hence, fertilizer recommendations for sulfur in cotton production are quite high. The amount of sulfur needed by the cotton plant is directly proportional to seed cotton yield. Significant yield increases of cotton in response to S additions have been reported elsewhere. Makhdum et al. (2001) reported that seedcotton yield, number of bolls per plant and boll weight showed a significant response to sulfur fertilization. Deficiency symptoms occur when soils have available SO_4-S less than 10-15 mg kg^{-1} of soil (Hearn, 1981). Unfortunately, many producers are loosing crop yield because they unaware of the importance of S in crop production and unable to recognize mild to moderate S deficiency symptoms in their crops. While consumption of S containing N fertilizers, such as ammonium sulfate decreased 37.5%, single superphosphate was completely replaced by both triple superphosphate, and diammonium phosphate for the last decade in Turkey (Anonymous, 1999). Rapid expansion in N and P usage occurring over the past two decades in Turkey without an accompanying increase in the addition of S and decreased atmospheric SO_2 emissions has possibly created a major plant nutrient S deficit. Furthermore, hardly any attention is given to nutrients other than NPK in the crop response investigations carried out in this region. The S status of Turkey's soils is not well defined, and S effects on the growth of Turkey crops have not been extensively researched. Although the responses of crop growth and yield to the addition of S fertilizers have been reported from most of the agricultural areas of the world (Rasmussen and Kresge, 1986; Pasricha and Fox, 1993), this type of investigations from the regions under study is completely nonexistent. Substantial information on S nutrition of plants is available, but the data related to S application in cotton is insufficient in soils of Southern Turkey. Based on these observations, sufficient supply of S is required to maintain the optimum growth and nutrient uptake ability of plants. Therefore, the present study was undertaken to investigate the impact of S fertilization on growth, yield and quality of cotton grown in Southern Turkey.

Materials and Methods

Field experiments comprised four amounts of S (0, 15, 30 and 45 kg S ha^{-1}) applied from two sources (gypsum or elemental sulfur), arranged in a completely randomized block with split plot arrangement and replicated three times. Main plots consisted of S sources and rates were assigned as sub-plots. Field experiments were conducted to evaluate the response of cotton to S rates and sources in 2010 and 2011 on a deep soil classified as a Vertisol at the Faculty of Agricultural Experimental Farm, University of Çukurova in Adana (37°00′02″N lat and 35°18′00″E long; 161 m a.s.l.). Prior to the application of any soil amendment a composite soil sample was collected from the 0 to 30 cm depth. The soil characteristics were as follows: (pH: 7.7, 17.9 % sand, 39.4 % silt, 42.8 % clay, with a cation exchange capacity of 23.9 meq 100 g^{-1}, organic matter, 1.47%, available N 41.5 ppm, available P 21.6 ppm available K 156 ppm). The soil of the experimental plots, developed from alluvial deposits of river terraces, is typical for the Çukurova region, and is classified as a Vertisol (chromoxeret), and the relatively high clay content with predominant clay minerals smectite and kaolinite is typical for the soils of the Çukurova region. Wetaher data (precipitation, mean, maximum and minimum air temperatures) were recorded daily and are reported as mean monthly data for site (Table 1). Six rows of seed, 70 cm apart, were sown down each plot of 12 m length. Cotton cv. SG-125 (*Gossypium hirsutum* L.) seed was sown at 25 kg per hectare on 7 May 2010 and 12 May 2011. Fertilizer, control of insects and weeds and furrow irrigation were given as needed during the growth season according to the local recommendations. For elemental S powder, finely ground powder elemental sulfur (90% S) was used. The fertilizers were surface-broadcast and incorporated into the soil before planting. During the first week of bloom stage twenty leaf tissues from the uppermost fully expanded leaves on the vegetative stem were collected from the two center rows of each plot for nutrient analysis. Soil samples were analyzed for sulfate-S by the monocalcium phosphate sulfate-S soil test method. Soil test levels of S at 30 cm depth was ≤ 7 mg kg^{-1} for our experiment, and rated as "low" according to Ankerman and Large (2001). Response to S fertilization was likely for cotton production as soil test S was 7 mg/kg of extractable S. Plant tissue analysis for the total concentration of sulfur was determined by ICP-AES method. Plant dry matter determinations were made at 65 and 96 days after planting (DAP). Plants from 0.6 m of the second row of the four row plots were cut at the soil line. The plants were separated into leaves, stems, squares, immature bolls and mature bolls. All samples were dried in an oven at 70ºC for at least 48 hours and dry weight recorded. Vegetative dry weight was the sum of stem and leaf dry weights. Reproductive dry weight was the sum of the dry weights of squares, immature bolls, and mature bolls. The variables were recorded from 10 randomly selected plants per plot at the time of picking as follows: number of sympodial branches and harvestable bolls per plant. Average boll weight was calculated by dividing the total seed cotton picked from 20 boll samples with the respective number of balls. The center four rows of each plot were hand picked. Lint yield was determined by hand picking four center rows of the plot and multiplying the seedcotton weight by the gin turnout. Earliness was determined by percent first harvest. A subsample of seed cotton was retained from each plot and ginned on a laboratory gin to determine gin turnout and fiber quality. Fiber properties of the lint were analyzed by HVI 900A. All quality testing of fibers was carried out in the temperature-humidity-controlled laboratory. The air in the laboratory was maintained at a temperature of 21°C plus or minus 1/2°C and a relative humidity of 65 percent plus or minus 2 percent, which are the standard conditions used in the testing of textile materials. Fiber samples were conditioned to bring the moisture content into equilibrium with the approved atmospheric conditions. Conditioned samples will have a moisture content between 6.75 and 8.25 percent (on a dry-weight basis). The samples must be exposed to the approved atmosphere until the specified moisture level is reached, which usually takes at least forty-eight hours.

Table 1. Monthly minimum, maximum and mean temperatures and precipitation at Adana,

Month	2010				2011			
	Mean (°C)	Max. (°C)	Min. (°C)	Precipitation (mm)	Mean (°C)	Max. (°C)	Min. (°C)	Precipitation (mm)
April	29.3	19.3	23.8	58.7	27.0	18.2	22.1	55.1
May	32.7	23.9	27.6	0.8	31.7	22.7	26.7	50.0
June	36.1	27.4	31.1	1.5	35.3	27.8	30.9	33.0
July	38.3	30.8	33.7	6.9	38.8	31.3	34.0	0.0
August	41.6	32.6	36.1	0.0	40.0	31.2	34.7	0.0
September	38.8	29.2	33.2	0.0	38.1	28.2	32.8	2.8
October	32.4	23.3	27.5	33.0	33.1	22.5	27.4	2.3

The temperature at the experimental site during the growing seasons was favorable for cotton growth and development. In 2011, mid-May was wet due to a period of plentiful rain (50 mm). There was an extended dry and hot period during June and early August in both years, and surprisingly 33 mm to 6.9 mm of precipitation occurred on June 2011 and on July 2010. Higher than normal (but not excessively hot) temperatures through mid-June promoted growth, squaring and boll setting. A warm fall occurred, resulting in good conditions to mature the crop. August and September continued hot.

Data recorded were analyzed statistically, using analysis of variance techniques appropriate for randomized complete block design. Main and interaction effects were compared using Least Significant Difference (LSD) test at the 5 % level of probability, when the F-values were significant.

Results

A significant yearxS-sourcexS-rate interaction occurred for a number of sympodial branches per plant, seed cotton yield, lint yield and fiber length uniformity. The S-source of S-rate interaction was significant for a number of sympodial branches plant^{-1}, number of harvestable bolls plant^{-1}, lint yield, earliness, and gin turnout. The main effects of S-source and S-rate were significant for a number of sympodial branches and harvestable bolls plant^{-1}, seed cotton yield, lint yield, gin turnout, boll weight, fiber length uniformity, fiber strength and leaf tissue S concentration. YearxS-source interactions were significant for boll weight and leaf tissue S concentration. YearxS-rate interactions were significant for a number of harvestable bolls plant^{-1}, seed cotton yield yield and lint yield. Therefore, the data for these variables are presented by year. Data for all other variables were combined over the years. Sulfur treatments had no impact on the accumulation of vegetative (VDW) and reproductive (RDW) dry weights during the early bloom stage (65 DAP) in both years (data not shown). Although not statistically significant, cotton plants applied gypsum at a rate of 30 kg S ha^{-1} produced numerically more VDW and RDW by early bloom. By the boll filling period (96 DAP), treatments had an insignificant effect on the accumulation of vegetative dry weight. The growth of reproductive structures was mostly affected by S fertilization at 96 DAP. S rate effect on the accumulation of reproductive dry weight was significant. When sulfur was applied to the plants at the 30 kg ha^{-1} or 45 kg ha^{-1} rate, a significant RDW increase was observed, relative to all other S treatments. Seedcotton yield and boll number were strongly related to biomass at 96 DAP. Since S deficiency decreased yield and biomass at 96 DAP, but did not affected biomass at 65 DAP, it could be concluded that biomass accumulation increased from 65 DAP and continued till 96 DAP. It's reported that an adequate amount of S during growth stages improved the photosynthetic rate of leaves due to an increase in protein synthesis and maintenance of high chlorophyll content and a Rubisco/soluble protein ratio because of the improved N-utilization efficiency of the plant (Ahmad and Abdin, 2000). Thus, the improvement in photosynthesis higher biomass accumulation due to production of more photosynthates. Significant response in a number of sympodial branches plant^{-1} and gin turnout weas evident between the two sources of S fertilizer applied. Data in Table 2 and Table 3 revealed that the different yield attributing characters of cotton like number of sympodial branches and harvestable bolls per plant and boll weight were significantly influenced by different source and rates of sulfur. Plants receiving 30 kg S ha^{-1} had highest the number of sympodial branch plant^{-1}. Increase in number of sympodial branch plant^{-1} was (21%, 26.5% and 17.5% at S rates of 15, 30 and 45 kg ha^{-1}, respectively) compared to the control further increase in sulfur fertilizer tended to decrease the number of sympodial branches plant^{-1}. Gypsum was more effective than elemental sulfur for a number of sympodial branches per plant (Table 2). Also, interaction between S source and application rate was significant, as significantly higher number of sympodial branches plant^{-1} were recorded in the treatments receiving applications of sulfur as gypsum at 15 and 30 kg ha^{-1} and elemental sulfur at 30 kg ha^{-1}. These results are consistent with those of Singh (1997) and Prasad (2000) who showed increases in the number of sympodial branches plant^{-1} with added sulfur.

Table 2. Effect of source and rate of sulfur on number of sympodial branches per plant

	S rate kg ha^{-1}				
Treatments	Number of sympodial branches plant^{-1}				Mean
S source	0	15	30	45	
Elemental	8.9 c	11.5 b	12.6 a	11.4 b	11.1 b
Gypsum	9.9 c	12.3 a	12.9 a	11.3 b	11.9 a
Mean	9.4 c	11.9 ab	12.8 a	11.4 b	
LSD(0.05)	0.57				0.41

Mean values with the same letters are not statistically different from each other according to the LSD test at P≤0.05.

Applications of S had significant effect on the number of harvestable bolls plant^{-1} and boll weight. The gypsum was about 18.5% more effective than elemental sulfur for number of harvestable bolls plant^{-1} over two years. Application of sulfur at 30 kg ha^{-1} gave the boll number advantages of 28.2% and 40.9 % higher over the control in 2010 and 2011, respectively (Table 3). The low S treatment significantly reduced the total number of harvestable bolls plant^{-1}in both years.

Table 3. Effect of source and rate of sulfur on number of bolls per plant and boll weight

	Number of bolls plant^{-1}			Boll weight (g)		
Treatments	2010	2011	Mean	2010	2011	Mean
S source						
Elemental	11.1* b	12.8 b	11.9 b	6.7 b	6.9 b	6.8 b
Gypsum	13.4 a	14.7 a	14.1 a	7.5 a	7.3 a	7.4 a
LSD(0.05)	0.76	0.77	0.51	0.24	0.20	0.15
S rate (kg ha^{-1})						
0	10.4 d	10.4 d	10.4 d	6.4 c	6.4 c	6.4 c
15	12.1 c	12.1 c	12.1 c	6.9 b	7.2 b	7.1 b
30	14.5 a	17.6 a	16.0 a	7.8 a	7.7 a	7.8 a
45	13.1 b	15.0 b	13.6 b	7.2 b	7.1 b	7.1 b
LSD(0.05)	1.08	1.09	0.71	0.34	0.28	0.21

Mean values with the same letters are not statistically different from each other according to the LSD test at P≤0.05.

Sulfur fertilizer had a significant positive influence on the boll weight up to certain level. Boll weight was the highest in plants treated with 30 kg S ha^{-1}. Further increase in sulfur fertilizer tended to decrease the boll weight irrespective of years. The addition of 30 kg S ha^{-1} increased boll weight by an average of 21.1% over two years compared to the control treatment (Table 3). Application of sulfur in the form of gypsum gave the weight advantage of 11.9% and 5.8% higher over control in 2010 and 2011, respectively.

In addition, source by rate interaction for number of harvestable bolls plant^{-1} was significant in 2010 (Table 3). Application of sulfur as elemental at 30 kg ha^{-1} produced 1.4 more boll over the 45 kg ha^{-1}. Rates from 15 to 45 kg ha^{-1} produced about the same number of harvestable bolls plant^{-1}. The addition of sulfur fertilizer at 30 kg ha^{-1} as gypsum caused a significant increase in the number of harvestable bolls plant^{-1}. 30 kg ha^{-1} rate of gypsum produced a 19.7 percent, or 3.3 boll increase over 45 kg ha^{-1} (Table 4).

Table 4. Effect of interaction between source and rate on number of bolls per plant

	S rate (kg ha^{-1})			
Source	0	15	30	45
Elemental	10.4*d	11.3 cd	12.2 bc	10.8 cd
Gypsum	10.7 d	12.8 b	16.7 a	13.4 b
LSD (0.05)	1.53			

Mean values with the same letters are not statistically different from each other according to the LSD test at P≤0.05.

There was a trend for higher gin turnout when gypsum was the S source. Earliness was not affected by S source. Sulfur rates showed statistically significant differences for gin turnout and earliness. The application of 30 kg S/ha produced 4.1% greater percentage of lint than the control and 45 kg S ha^{-1}. A strong S-sourcexS-rate interaction was observed for gin turnout across the two year (Table 5). Application of gypsum at 30 kg ha^{-1} gave the higher gin turnout over the other S-source and rate of applications. 30 and 45 kg ha^{-1} caused a highly significant increase in earliness, whereas control and 15 kg ha^{-1} gave the lowest. Addition of sulfur had a significant effect on earliness, showing a delay in maturity at 15 kg S ha^{-1}, 77.4% compared with 82.3% at the highest rate applied.

Table 5. Effect of source and rate of sulfur on gin turnout and earliness (averaged across years)

Treatments	S rate kg ha^{-1}				Mean
	Gin turnout (%)				
S source	0	15	30	45	
Elemental	41.2* cd	41.4 c	42.1 b	40.3 e	41.3 b
Gypsum	40.6 e	42.0 b	43.0 a	40.7 de	41.6 a
Mean	40.9 c	41.7 b	42.6 a	40.5 d	
LSD(0.05)	0.32				0.23
	Earliness (%)				Mean
	0	15	30	45	
Elemental	79.8 bc	77.9 cd	80.9 b	84.3 a	80.7
Gypsum	80.3 bc	76.9 d	84.6 a	80.4 bc	80.5
Mean	80.0 bc	77.4 cd	82.7 a	82.3 a	
LSD(0.05)	1.98				NS

Mean values with the same letters are not statistically different from each other according to the LSD test at P≤0.05.

Sulfur sources and rates interacted significantly in earliness. Significantly enhance in earliness with 45 kg ha^{-1} in the form of elemental sulfur and 30 kg ha^{-1} in the form of gypsum was observed. There was statistically significant difference in leaf tissue S for source or rate in both years. Leaf tissue S showed a statistical increase with increasing rate of S. Averaged over two years, gypsum gave a greater leaf tissue S concentration than that of elemental sulfur. The 30 and 45 kg S ha^{-1} rates had higher leaf S concentrations than zero S each year. On average, leaf S concentrations were statistically differed among the four S rates with 45 kg S ha^{-1} having the highest leaf concentration (Table 6). The leaf tissue S of the higher rate of S ha^{-1} was on the below side of the reported sufficiency range of 0.25 to 0.8 %.

Table 6. Effect of source and rate of sulfur on leaf S concentration

	Leaf S concentration (%)		
Treatments	2010	2011	Mean
S source			
Elemental	0.15	0.16	0.16 b
Gypsum	0.17	0.18	0.18 a
LSD(0.05)	NS	NS	0.019
S rate (kg/ha)			
0	0.09 c	0.11 c	0.10 c
15	0.11 c	0.12 c	0.12 c
30	0.19 b	0.19 b	0.19 b
45	0.25 a	0.25 a	0.25 a
LSD(0.05)	0.038	0.038	0.026

Mean values with the same letters are not statistically different from each other according to the LSD test at P≤0.05.

Sulfur concentrations of cotton leaf applied with S fertilizer at the high rate had increased nearly two times compared to the control treatment. The S sufficiency ranges for cotton are recommended as 2.5 to 8.0 mg kg^{-1} in the youngest mature leaf blade at early bloom (SAAESD, 2009). According to the above standards, leaf blade S concentrations at early bloom were below the sufficiency range in the S treatments in both years. All the rates of sulfur caused a highly significant increase in seed cotton yield as compared to the control (Table 7). As the rate of sulfur increased, the yield-stimulating effect of fertilizer became stronger, but there were no further increase at 45 kg ha^{-1}. The maximum seed cotton yield was observed with 30 kg S ha^{-1} followed by 45 kg S ha^{-1}. Application of sulfur at 30 kg ha^{-1} gave the yield advantage of 26.5.1% and 32.4% higher over the control in 2010 and 2011, respectively. The low S treatment significantly reduced the seed cotton yield and it was significantly affected by S treatment when the 2-year results were combined. Lint yield increased with the application of S fertilizer. Application of 30 kg S ha^{-1} increased lint yields by 29.7 and 34.9% compared to the control in 2010 and 2011, respectively. Averaged over two years, application of 30 kg S ha^{-1} increased lint yield by 32.4%, relative to the control.

Table 7.Effect of source and rate of sulfur on seed cotton and lint yield in 2010 and 2011

	Seed cotton yield(kg/ha)			Lint yield (kg/ha)		
Treatments	2010	2011	Mean	2010	2011	Mean
S source						
Elemental	3434* b	3663	3548 b	1417 b	1516	1466 b
Gypsum	3602 a	3759	3680 a	1489 a	1570	1530 a
LSD(0.05)	120.1	NS	97.5	620.4	NS	423.3
S rate (kg/ha)						
0	2957 d	3040 d	2998 d	1209 c	1245 c	1227 d
15	3373 c	3518 c	3446 c	1406 b	1468 b	1437 c
30	4025 a	4503 a	4264 a	1720 a	1914 a	1817 a
45	3667 b	3783 b	3725 b	1477 b	1544 b	1511 b
LSD(0.05)	209.4	208.5	137.9	877.3	923.6	598.6

Mean values with the same letters are not statistically different from each other according to the LSD test at $P \leq 0.05$.

Gypsum was 4.1 % more effective than elemental sulfur over two years for lint yield. Lint yield was greatest from the 30 kg S ha^{-1} application and were 1720 and 1914 kg ha^{-1} for 2010 and 2011, respectively. Lint yield was 20.9% higher for a high rate than for the low rate over two years. Source x rate interactive effects showed significant response. Highest seed cotton and lint yields were found from the plants treated with gypsum sulfur and with 30 kg ha^{-1} that were significantly different from other treatments (data not shown). Yields increased significantly with successive increases in rates of sulphur applications up to 30 kg S ha^{-1}. Application of gypsum at 30 kg ha^{-1} gave significantly more yields.

Source of S did cause a significant effect on the fiber properties tested in both years, with one exception, for micronaire. Gypsum application increased fiber length, length uniformity and strength by 1.7%, 0.9% and 5.1%, respectively, relative to the elemental sulfur. On average, fiber from the plots treated with gypsum was 0.5 mm longer and 1.6 g/tex stronger (Table 8).

Discussion

Averaged across all S treatments, significant positive yield responses were obtained in cotton crop. Plants did not lack sulfur during the first stage of growth up to flowering independently of fertilization, but during further developmental stage plants fertilized with sulfur reached better physiological state. As a consequence, reproductive biomass accumulation was higher for plants receiving sulfur at 96 DAP. The marked increase in dry matter yield due

Table 8. Effect of source and rate of sulfur on cotton fiber traits (averaged across years)

Treatment	UHM (mm)	Fiber Length uniformity (%)	Micronaire	Fiber strength (g/tex)
S-Source				
Elemental	29.5* b	82.8 b	4.8	29.8 b
Gypsum	30.0 a	83.6 a	4.8	31.4 a
LSD(0.05)	0.37	0.55	ns	0.65
Rate (kg S ha^{-1})				
0	29.8	82.0 b	4.7 b	30.1 b
15	29.9	83.4 a	4.9 a	30.9 ab
30	29.9	83.7 a	4.8 ab	31.3 a
45	29.4	82.2 b	4.7 b	30.1 b
LSD (0.05)	ns	0.78	0.16	0.92
Interaction	ns	ns	ns	ns

Mean values with the same letters are not statistically different from each other according to the LSD test at $P \leq 0.05$.

to S application could be due to the more soluble sulfur and release of sulfate ions into the soil solution resulting in better absorption of sulfur nutrient.This would have increased the metabolic processes and maintained the process of photosynthesis in the plants, and promoted the meristematic activities causing increased biomass production due to proper partitioning of photosynthates from sources to sink (Legha and Gajendragiri, 1999). Higher rate of reproductive dry matter accumulation at boll filling stage might be due to increased redistribution of dry matter from leaves to bolls, which was influenced by sulfur fertilizer along with other essential elements resulting in higher boll weight. Boll weight increase by application of sulfur could be attributed to the favorable effect of this nutrient on carbohydrate metabolism and accelerated mobility of photosynthates from source to sink (boll). Increase in number of harvestable bolls per plant might be due to enhancement of S containing amino acids, which are an essential component of protein and also prevent shedding of bolls. It can exploit full genetic potential of a crop, when it is grown under favorable conditions and well balanced supply of nutrients to the crop. Further, S has an impact on photosynthesis as well as synthesis of nucleic acids, proteins, amino acids and other essential compounds, which are major constituents affecting boll weight and consequently cottonseed yield. Sulfur is also essential for cell division and development of meristematic tissue, and hence it would have a stimulating effect on increasing the number of flowers and bolls per plant. Improvements in these growths and yield attributes led to a higher seedcotton yield. The increase in yields by gypsum application might be attributed to the contribution of S and Ca in gypsum and it has also had a favorable effect on dry matter production due to proper partitioning of photosynthates from source to sink which lead to increase in yield (Legha and Gajendragiri, 1999). There was a large increase in seed cotton yield due to sulfur fertilizer application suggesting that the soil was deficient in sulfur that resulted in a larger yield difference. Moreover, an increase in the yield might be due to higher availability of applied sulfur and its more adsorption and translocation to bolls and also dilution effect, increased formation of reproductive structures for nutrient absorption and photosynthesis and increased production of assimilates to fill the sinks, resulting in increased yield. Further increase in sulfur rate tended to decrease seed cotton yield. At higher rates of sulfur application availability of sulfur in the soil probably became excess as well as imbalance and thus resulted in decreased utilization. The high response in this site could be accredited to the low $S\text{-}SO_4^{2-}$ available in the soil. Probably a low capacity to provide S from the soil and a low initial S availability could explain these results. Extractable level in the 30 cm depth was lower than the reported 10 ppm critical level (Hoeft et al., 1973). Our experimental location had low soil organic matter content and could possibly generate less S-SO42- available for crops. According to Horowitz and Meurer (2007) the soil organic matter is the most important chemical soil attribute associated with oxidation rates of ES in soils and there are an inverse relationship between soil organic matter and ES oxidation rate. In present study leaf tissue sulfur concentration responded to applied sulfur. Leaf tissue S concentration with control was 0.10 averaged across years and contained insufficient levels of S (Mullins and Burmester, 1993; Cleveland and Cervantes, 2007). Cotton leaf tissue S concentration was significantly increased with increasing S fertilizer rates as compared to the control. Leaf tissue concentration of sulfur treatment fell well below the published critical minimum of 0.25% (Cleveland and Cervantes, 2007) in both years. S source and S rate treatments had a significant effect on the fiber uniformity index, fiber micronaire and fiber strength. In conclusion, results from this study indicate that on marginal site (7 ppm SO_4-S) consistent responses can be achieved with S fertilization. Yield increase might be due to the cumulative favorable effect of higher number of sympodial branches and harvestable bolls per plant. The results observed in field trial are encouraging and hence S must be included in fertilizer recommendations to balance fertilization of cotton.

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