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ORIGINAL PAPER

Can sulphur improve the nutrient uptake, partitioning, and seed yield of sesame?

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Abstract

Sulphur (S) is considered to improve the nutrient uptake of plants due to its synergistic relationship with other nutrients. This could ultimately enhance the seed yield of oilseed crops. However, there is limited quantitative information on nutrient uptake, distribution, and its associated impacts on seed yield of sesame under the S application. Thus, a two-year field study (2018 and 2019) was conducted to assess the impacts of different S treatments (S_0 = Control, S_{20} = 20, S_{40} = 40, and S_{60} = 60 kg ha^{-1}) on total dry matter production, nitrogen, phosphorus, potassium, S uptake and distribution at the mid-bloom stage and physiological maturity. Furthermore, treatment impacts were studied on the number of capsules per plant, number of seeds per capsule, thousand seed weight, and seed yield at physiological maturity in sesame. Compared to S_0, over the years, treatment S_{40} significantly increased the total uptake of nitrogen, phosphorus, potassium, and S (by 13, 22, 11% and 16%, respectively) at physiological maturity, while their distribution by 13, 36, 14, and 24% (in leaves), 12, 15, 11, and 15% (in stems), 15, 42, 18, and 10% (in capsules), and 14, 22, 9, and 15% (in seeds), respectively. Enhanced nutrient uptake and distribution in treatment S_{40} improved the total biomass accumulation (by 28%) and distribution in leaves (by 34%), stems (by 27%), capsules (by 26%), and seeds (by 28%), at physiological maturity, as compared to S_0. Treatment S_{40} increased the number of capsules per plant (by 13%), number of seeds per capsule (by 11%), and thousand seed weight (by 6%), compared to S_0. Furthermore, over the years, relative to control, sesame under S_{40} had a higher seed yield by 28% and enhanced the net economic returns by 44%. Thus, our results suggest that optimum S level at the time of sowing improves the nutrient uptake and distribution during the plant lifecycle, which ultimately enhances total dry matter accumulation, seed yield, and net productivity of sesame.

Keywords Sesame · Sulphur · Nutrient uptake · Seed yield · Economics

Introduction

Oilseeds are important crops that play a prominent role in the agriculture industry all over the globe. The oil obtained through these oilseed crops is the major constituent of the human diet and an important source of healthy fatty acids to meet human dietary needs (Zargar et al. 2016; Abiodun 2017). However, the rapidly increasing population of the world,

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clearly indicates that demand for high-quality oilseeds continues to grow (Islam et al. 2016). Likewise, over the past three decades, increased interest in oilseeds led to an 82% expansion in the total cultivated area (Rahman and Dejiménez 2016). Consequently, this continuous intensification and extension in cropping areas are exerting pressure on agricultural land and resulting in overexploitation of the natural resources, which is a major concern in agricultural sustainability (FAO 2017). Thus, to satisfy the growing demands of edible oils, oilseeds production needs to be coupled with efficient agronomic practices to increase the per unit area yield on a sustainable basis.

Sulphur (S) is considered a key element in plant nutrition and oilseed crops may not reach their full potential when it becomes a limiting factor. Because it affects the developmental processes (such as capsule initiation) in plants (Girondé et al. 2014). Hence, high seed yield and quality of oilseeds are possible when they have access to the optimum amount of S (Scherer 2001). It also increases the uptake of major plant nutrients, namely, nitrogen (N), phosphorus (P), and potassium (K), while reducing the uptake of toxic elements such as chlorine and sodium (Zhang et al. 1999; Salvagiotti et al. 2009). Furthermore, studies have documented that S application improves sesame seed yield, oil, and protein contents (Raza et al. 2018a, 2018b). However, these investigations have not quantified the effects of S application on the nutrient uptake and distribution in sesame crop. Therefore, S fertilization can show promising results in improving the nutrient uptake, biomass accumulation, and seed yield of sesame.

N, P, K, and S are the key macronutrients that drive the growth and developmental processes of crops (Scherer 2001; Raza et al. 2019). Adequate availability and uptake of these essential nutrients influence the synthesis and distribution of carbohydrates in plants (Arduini et al. 2006). The optimum quantity of N in crops increases the leaves development and photosynthetic capacity (Muchow and Davis 1988), and also improves the biomass accumulation and distribution towards the reproductive organs of the crop plants (Vouillot and Devienne-Barret 1999; Prystupa et al. 2004). P influences the dry matter accumulation and distribution in vegetative as well as reproductive parts in a different way than N (Batten 1992; Prystupa et al. 2004) and affects the seed yield and yield components of crops (Elliott et al. 1997). Similarly, optimum uptake of K is essential for improving crop production, Iqbal and Hidayat (2016) revealed that adequate K significantly enhances crop growth, dry matter accumulation, and partitioning in economic plant parts such as seeds. Moreover, nutrient uptake depends on the crop type, cultivar, and microenvironment but it is more influenced by the growing conditions (such as nutrient availability) in field rather than any other factor (Raza et al. 2019). Hence, understanding the nutrient uptake of the crop is critical for sustainable agricultural production. However, past investigations neglected the role and importance of nutrient uptake and distribution in sesame productivity. Besides, studies have not focused on the effects of S application on nutrient accumulation and distribution of sesame.

The S deficiency in oilseeds adversely impacts the seed yield and quality because it reduces the carbohydrates translocation to the reproductive parts and utilization for oil synthesis (Rani et al. 2009; Sahoo et al. 2018). In recent decades, reports on S deficiency have increased due to reduction in soil fertility status and organic matter content as a result of intensive agriculture and low S containing fertilizers as a result of strict sulphur dioxide emissions control (Eriksen 2009; Steinke et al. 2015; Carciochi et al. 2016). However, S application has been reported to enhance nutrient uptake and seed yield. Previously, it has been confirmed that S application contributes towards better nutrients uptake and carbohydrate synthesis in the crop plants due to synergistic effects with other nutrients such as N, P, and K (Haneklaus et al. 2007; Carciochi et al. 2020). Furthermore, past improvements in crop yields were associated with enhanced nutrients accumulation and distribution because these nutrients are essential seed components (Sinclair et al. 2019), whereas, the effects of S application on N, P, K, and S uptake and distribution were not studied before in sesame. Hence, adequate S availability is a key factor in sesame production and there is insufficient knowledge about the potential benefits of S application on nutrient uptake and distribution in sesame plants.

Therefore, in this study, we investigated the effects of S application on major plant nutrients uptake (at the mid-bloom and physiological maturity stages) and seed yield (at physiological maturity) of sesame under the rainfed conditions. The key objectives of this field study were to (1) assess the impact of S application on dry matter production, N, P, K, and S uptake, and their distribution in sesame plants (at the mid-bloom and physiological maturity); (2) study the influence of S application on yield components and seed yield of sesame (at physiological maturity), and (3) evaluate the effects of S application on economic returns of sesame.

Material and methods

Site description

This field experiment was conducted during the growing seasons of 2018 and 2019 at the research farm (33°11′62″ N, 73°00′99″ E, 520 m elevation) of PMAS-Arid Agriculture University Rawalpindi in Punjab Province, Pakistan (Fig. 1). The climate of the research site falls under the dry sub-humid region with monsoon-influenced high summer rainfall (mainly in July and August). Monthly rainfall, average maximum,

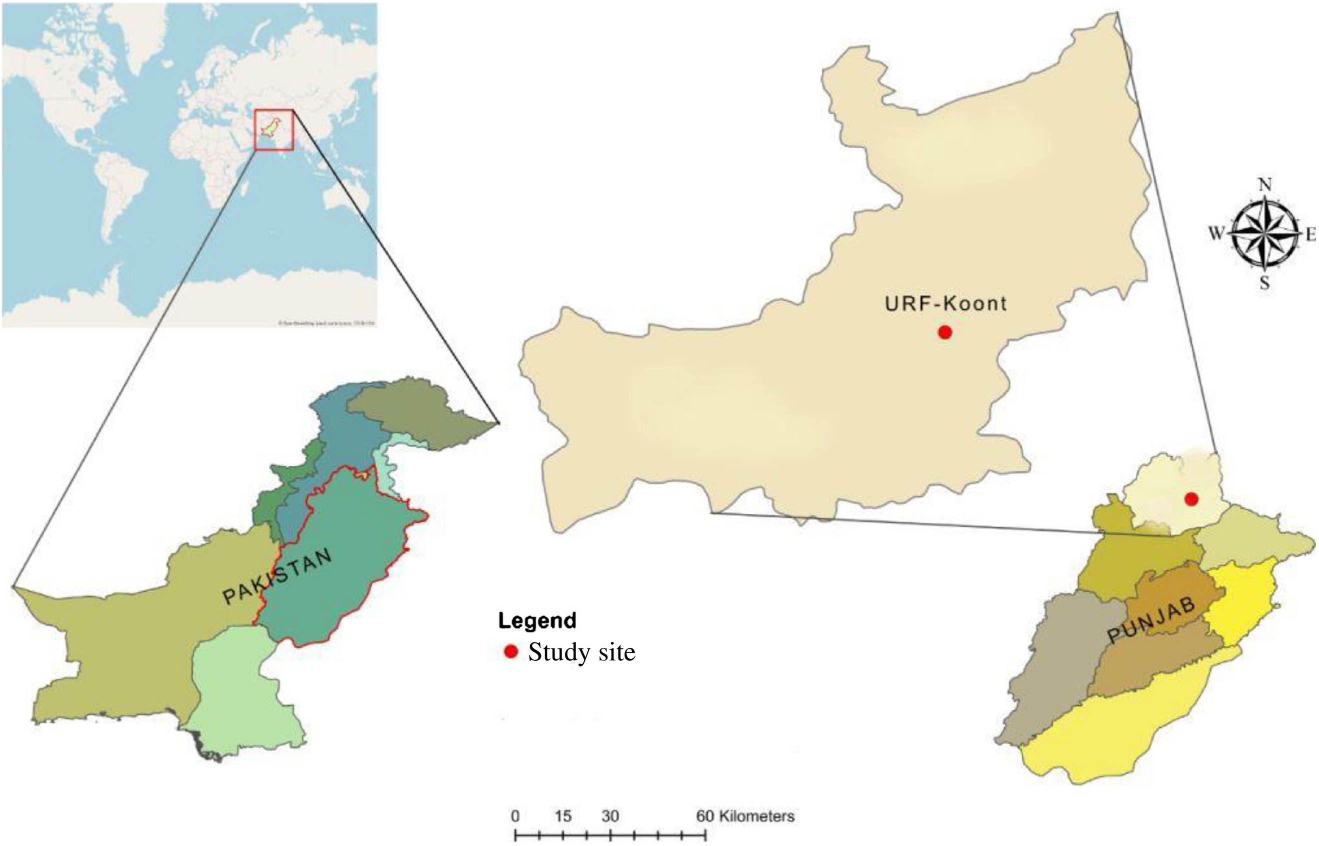

Fig. 1 Location of the study site

and minimum temperature during growing seasons in 2018 and 2019 are given in Fig. 2. For soil testing and analysis, procedures of ICARDA Manual "Soil Plant and Water Analysis" were followed (Estefan et al. 2013), i.e., pH meter for soil pH, EC meter for soil electrical conductivity, Kjeldahl Method for soil available N, Olsen's method for soil available P, Flame Atomic Absorption Spectrophotometry Method for soil available K, Turbidimetric method for soil available S, Walkley-Black method for soil organic matter, saturation paste percentage method for soil saturation, and excavation method of distributed soil samples for soil bulk density. According to the soil tests at the time of sowing, the top soil layer of 20 cm had loam texture with pH (7.2), electrical conductivity (1.02 dSm^{-1}), available N (0.28 g kg^{-1}), available P (2.5 g kg^{-1}), available K (95 g kg^{-1}), available S (4.3 g kg^{-1}), organic matter (0.57%), saturation (34%), and bulk density (1.23 g cm^{-3}).

Experimental design and details

The experiment was executed in RCBD-factorial design with three replicates. This field study had two sesame cultivars (TS-5 and TS-3) and four S levels (S_0 = Control, S_{20} = 20, S_{40} = 40, and S_{60} = 60 kg ha^{-1}) as treatments. Seed of sesame cultivars was collected from Ayub Agriculture Research Institute (AARI), Faisalabad. Both cultivars, namely, TS-5 and TS-3 were high yielding and branched with the genetic potential of 2346 kg ha^{-1} and 2214 kg ha^{-1} (AARI). While S was applied as a basal dose at the time of sowing and ammonium sulphate was used as a source of S. The size of each plot was 5 m wide and 6 m long (30 m^2), and the total area was 720 m^2 (30 m^2 × 24 plots). Sesame was sown during the first week of July in 2018 and 2019 while harvested during the second week of November in 2018 and 2019. The sesame seeds were sown manually with a hand-operated seed drill at the seeding depth of 2 cm. The distance between the plants and rows was maintained at 10 and 45 cm, respectively, which resulted in a plant population of 200,000 plants ha^{-1}. The fertilizers were applied as basal dose at the time of sowing, at the rate of N 50 kg ha^{-1}, P 60 kg ha^{-1}, K was not applied because the soil at the study site had adequate K-content and S was applied as per treatment. Urea and diammonium phosphate were used as sources of N and P. No supplemental irrigation was given during the growing period of the crop and it was completely dependent on rainfall. All other recommended practices were kept uniform in all experimental units.

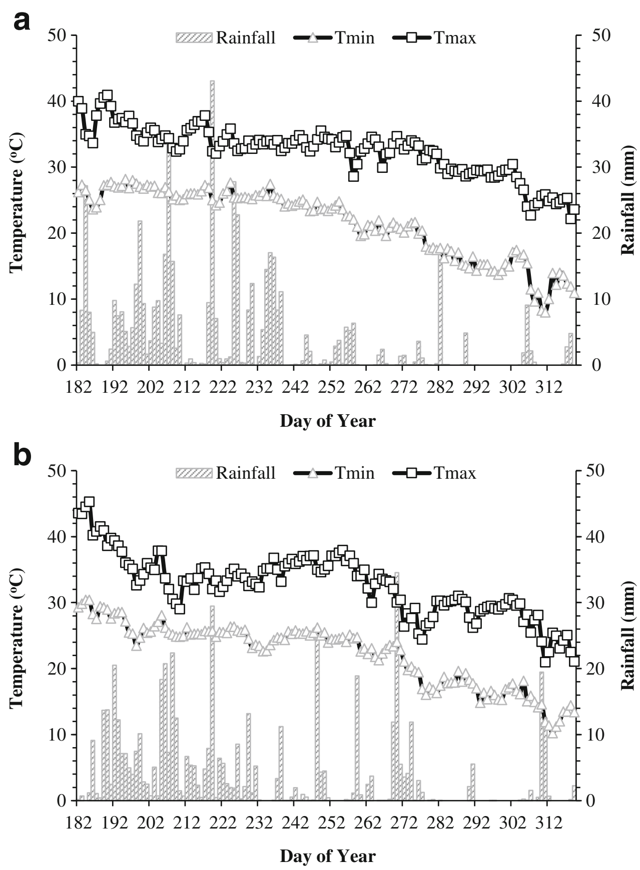

Fig. 2 Mean maximum and minimum temperature, and rainfall during the growing season of sesame in 2018 and 2019

Measurements

For sampling, measurements, and analysis of dry matter production and distribution, nutrient uptake and distribution, and seed yield, two sesame growth stages (mid bloom (MB) (65 days after sowing) and physiological maturity (PM) (125 days after sowing)) were selected following the previously published phenological scale (Langham 2007).

Dry matter production and distribution

For dry matter production (kg ha^{-1}) and distribution in leaves, stem, capsule, and seeds (g m^{-2}) analysis, fifteen consecutive plants of sesame, from central rows of each plot were manually harvested with sickles at MB and PM stages. Then, all the collected plant samples were separated into leaves, stem, and capsules (at MB), and leaves, stem, capsules, and seed (at PM). At each stage, all the plant organ samples were oven-dried at 70°C to attain a constant dry weight and then the dry matter for each plant organ was presented as grams per meter square. The total dry matter (TDM) production was calculated as the product of dry matter per meter square and the number of meter squares per hectare.

Nutrient uptake and distribution

At MB and PM, after the determination of the dry matter production, the same samples (leaves, stem, capsules, and seeds) were utilized for the measurement of N, P, K, and S contents in the plant organs. For the preparation of samples to determine the nutrient contents, each plant organ sample was ground by using a Wiley Mill, passed through a 0.5 mm sieve, and then sample digestion was carried out using Nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). Then N-content (g plant^{-1}) of each organ sample was measured using the Kjeldahl procedure (Li et al. 2001), P-content (g plant^{-1}) of each organ sample was determined using the Vanadomolybdate method (Xia et al. 2013), K-content (g plant^{-1}) of each organ sample was estimated using the Flame Atomic Absorption Spectrophotometry Method and S-content (g plant^{-1}) of each organ sample was measured using the Turbidimetric method (Verma et al. 1977). The N, P, K, and S accumulation was determined as the product of dry matter in each plant organ and N, P, K, and S concentration in each plant organ, and presented as kilograms per hectare. The total N, P, K, and S uptake was calculated by the summation of N, P, K, and S contents in all the plant organs.

Seed yield

For seed yield and yield components, twenty sesame plants from central rows of each plot were manually harvested using shears, at physiological maturity. Harvested samples were then sun-dried in the form of bundles for one week by keeping the plants in a vertical direction. After drying, plants were threshed manually to determine the seed yield (kg ha^{-1}) and yield components including the number of capsules (plant^{-1}), number of seeds (capsule^{-1}), and thousand seed weight (g).

Economic analysis

The economic analysis, using partial budgeting was performed to determine the economic viability of S application for sesame production. The total cost of production included all the expenses from sowing to harvesting of the crop were estimated depending on the local rates, while the gross income was estimated based on the local market prices of sesame, and net income was calculated from the subtraction of total cost from the obtained gross income (Raza et al. 2018b).

Statistical analysis

Statistical analysis of the data was performed using Statistix 8.1 software. Significant differences among the studied cultivars and S levels were computed through the Analysis of Variance (ANOVA) technique in combination with the Least Significant Difference (LSD) test. The significance of the computed differences between means was evaluated at a 5% probability level ($p < 0.05$). Graphical representation of the data was made using the Microsoft Excel program.

Results

Dry matter production and distribution

The dry matter production and distribution within sesame plants under different S treatments at MB and PM are shown in Table 1. Across the different S treatments and sampling stages, on average over the years, sesame plants produced dry matter of 4357.8 kg ha^{-1} and 6440.1 kg ha^{-1} in S_0, 4613.0 kg ha^{-1} and 7011.1 kg ha^{-1} in S_{20}, 5654.1 kg ha^{-1} and 8239.8 kg ha^{-1} in S_{40}, and 4887.8 kg ha^{-1} and 7660.8 kg ha^{-1} in S_{60}, at MB and PM, respectively. Different S levels not only influenced the dry matter production but also altered the distribution patterns in the plant part of the sesame (Table 1). For example, across the years, compared to S_0, treatment S_{40} improved the biomass in leaves, stem, and capsules by 27, 29, and 35%, respectively, at MB. Moreover, optimum S level in S_{40} significantly increased the dry matter by 28%, and dry matter contents in leaves by 34%, stem by 27%, capsules by 26%, and seeds by 28% at PM in comparison with S_0, indicating that S application significantly enhanced the source size which improved the biomass accumulation and distribution in economic parts (capsules and seeds).

N-uptake

Table 2 shows the total N-uptake and N-contents in different plant organs of sesame in different S treatments. On average, the highest nitrogen uptake (58.4 and 94.4 kg ha^{-1}, at MB and PM, respectively) was observed in S_{40} while the lowest N-uptake (51.2 and 83.6 kg ha^{-1}, at MB and PM, respectively) was found in S_0. We also measured the nitrogen contents in leaves, stems, capsules, and seeds of sesame understudied S treatments. Our results suggested that the N-contents of sesame leaves, stem, capsules, and seeds were highest at MB and PM in S_{40} among all the treatments. On average, at MB, the maximum N-content in leaves, stems, and capsules (28.2, 14.0, and 16.4 kg ha^{-1}, respectively) were obtained in S_{40} whereas the minimum N-content in leaves, stems, and capsules (24.7, 12.2, and 14.3 kg ha^{-1}, respectively) were noted in S_0. Similarly, at PM, the average highest N-content in leaves (11.8 kg ha^{-1}), stem (33.3 kg ha^{-1}), capsules (6.6 kg ha^{-1}), and seeds (42.8 kg ha^{-1}) were observed in S_{40} while the lowest N-content in leaves (10.4 kg ha^{-1}), stem (29.8 kg ha^{-1}), capsules (5.8 kg ha^{-1}), and seeds (37.7 kg ha^{-1}) were obtained in S_0. Moreover, N and S dynamics during this study suggested that their uptake in sesame was closely related to the amount of S applied, and the maximum uptake was recorded for S_{40} treatment (Fig. 3).

P-uptake

Table 3 presents the total P-uptake and P-contents under the studied S treatments. At MB and PM, the average highest P-uptake of 12.1 kg ha^{-1} and 24.3 kg ha^{-1} were measured in S_{40}, whereas the average lowest P-uptake of 9.7 kg ha^{-1} and 19.9 kg ha^{-1} were obtained in S_0 treatment. Overall, S_{40} treatment increased the P-uptake (by 24%) at MB and (by 22%) at PM, over the years, as compared to S_0. In this experiment, different S treatments also influenced the P-contents in different plant organs of sesame at MB and PM. On average, at MB, the average maximum P-contents of leaves (4.6 kg ha^{-1}), stem (6.2 kg ha^{-1}), and capsules (1.4 kg ha^{-1}) were measured in S_{40}. Similarly, at PM, the average maximum P-contents in leaves (2.9 kg ha^{-1}), stem (7.6 kg ha^{-1}), capsules (1.7 kg ha^{-1}), and seeds (12.2 kg ha^{-1}) were also found in S_{40}. However, the average minimum P-contents in all plant organs, at MB and PM, were observed in treatment S_0. Overall, treatment S_{40} enhanced the P-content in leaves (by 32%), stem (by 17%), capsules (by 46%), and seeds (by 22%), as compared to S_0 treatment.

K-uptake

Table 4 shows the total K-uptake and K-contents in various plant parts of sesame under different S treatments. Different S treatments significantly affected the K-uptake, and K-contents of sesame. The highest K-uptake at both MB and PM was obtained in treatment S_{40} while the lowest in K-uptake in treatment S_0. On average, across the years, S_{40} improved the K-uptake (by 13% at MB and 11% at PM) compared to S_0, (by 6% at MB and 4% at PM) compared to S_{20}, and (by 3% at MB and 2% at PM) compared to S_{60}. S treatments also influenced the K-contents at the plant organ level in sesame at both stages, while S_{40} showed the highest K-contents in different plant organs of sesame. Averaged across the years, S_{40} increased the K-contents in leaves, stem, capsules, and seeds by (11% at MB and 14% at PM), (12% at MB and 11% at PM), (21% at MB and 18% at PM), and (9% at PM), respectively.

S-uptake

Table 5 presents the total S-uptake and S-content under different S treatments. Total S-uptake was significantly influenced by the different S treatments. Overall, across all the treatments, treatment S_{40} showed the average highest S-uptake (32.7 kg ha^{-1} at MB and 45.6 kg ha^{-1} at PM) at both sampling intervals and years. On average, treatments S_{40} increased the total S-uptake by 21% at MB and 16% at PM,

Table 1 Effects of sulphur application on the total dry matter (TDM) accumulation and distribution of sesame at mid-bloom and physiological maturity in 2018 and 2019

Years	Treatments		Mid bloom stage (MB)				Physiological maturity stage (PM)				
			Leaves ($g\ m^{-2}$)	Stem ($g\ m^{-2}$)	Capsules ($g\ m^{-2}$)	TDM ($kg\ ha^{-1}$)	Leaves ($g\ m^{-2}$)	Stem ($g\ m^{-2}$)	Capsules ($g\ m^{-2}$)	Seeds ($g\ m^{-2}$)	TDM ($kg\ ha^{-1}$)
2018	Cultivar	TS-5	214.3 ± 7.7a	163.7 ± 8.3a	134.9 ± 6.4a	5128.8 ± 184.6a	142.6 ± 7.4a	246.0 ± 6.8a	230.9 ± 8.4a	129.1 ± 4.4a	7485.8 ± 233.3a
		TS-3	188.8 ± 10.0b	139.4 ± 7.1b	114.9 ± 4.8b	4430.7 ± 198.2b	119.5 ± 6.0b	228.9 ± 8.5b	206.6 ± 4.8b	118.4 ± 3.8b	6733.2 ± 199.9b
	LSD		24.0	19.2	15.5	442.8	15.5	16.3	14.8	9.3	351.8
	Sulphur	S_0	181.1 ± 7.1b	136.2 ± 10.2b	112.6 ± 7.7b	4298.3 ± 203.0b	108.3 ± 8.4c	209.7 ± 7.8c	197.6 ± 7.9c	108.6 ± 4.8c	6242.0 ± 206.5d
		S_{20}	189.3 ± 10.8b	143.5 ± 8.3b	116.4 ± 8.6b	4491.6 ± 231.7b	122.0 ± 6.5bc	230.8 ± 8.1bc	210.5 ± 9.4bc	120.5 ± 4.8bc	6838.5 ± 219.9c
		S_{40}	232.5 ± 7.9a	175.5 ± 6.6a	144.3 ± 4.5a	5523.2 ± 158.8a	151.8 ± 6.8a	266.0 ± 7.9a	242.6 ± 6.2a	138.1 ± 3.9a	7984.0 ± 147.0a
		S_{60}	203.3 ± 16.2ab	150.9 ± 10.9ab	126.5 ± 6.4ab	4805.9 ± 290.2b	142.0 ± 6.0ab	243.4 ± 9.0ab	224.1 ± 5.3ab	127.9 ± 4.0ab	7373.5 ± 205.1b
	LSD		33.8	27.1	21.9	626.2	22.0	23.1	20.9	13.1	497.6
2019	Cultivar	TS-5	226.0 ± 9.8a	169.1 ± 6.0a	132.0 ± 5.9a	5271.0 ± 198.6a	154.3 ± 6.8a	269.6 ± 10.3a	230.5 ± 7.4a	137.1 ± 5.0a	7914.5 ± 250.3a
		TS-3	198.9 ± 7.5b	149.0 ± 8.2b	120.3 ± 5.8b	4682.1 ± 201.3b	138.2 ± 6.1b	240.5 ± 8.3b	218.2 ± 7.5b	124.9 ± 4.6b	7218.2 ± 218.8b
	LSD		23.5	18.9	9.8	440.9	13.9	22.7	11.6	10.6	360.5
	Sulphur	S_0	192.1 ± 8.5b	143.2 ± 4.7b	106.5 ± 4.6a	4417.3 ± 140.2b	127.4 ± 2.8b	226.2 ± 10.4c	196.1 ± 7.2d	114.2 ± 5.9c	6638.1 ± 167.2d
		S_{20}	204.0 ± 16.5b	150.7 ± 9.8b	118.8 ± 7.4b	4734.4 ± 311.5b	132.3 ± 8.8b	243.6 ± 13.7bc	213.7 ± 5.6c	128.8 ± 5.3bc	7183.7 ± 237.6c
		S_{40}	242.1 ± 8.5a	185.6 ± 5.0a	150.9 ± 4.0c	5785.0 ± 165.7a	163.9 ± 6.4a	285.4 ± 9.0a	254.3 ± 7.8a	146.0 ± 6.4a	8495.5 ± 164.2a
		S_{60}	211.6 ± 9.3ab	156.8 ± 13.9b	128.6 ± 7.7bc	4969.6 ± 280.8b	161.5 ± 5.1a	264.9 ± 8.4ab	233.4 ± 6.6b	135.0 ± 5.0ab	7948.1 ± 173.8b
	LSD		33.3	26.7	13.9	623.6	19.7	32.1	16.4	15.0	509.8

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1} , respectively. Means with a different letter in the column varied significantly at $p < 0.05$

Table 2 Effects of sulphur application on total N-uptake and distribution of sesame at mid-bloom and physiological maturity in 2018 and 2019.

Years	Treatments		Mid bloom stage (MB)				Physiological maturity stage (PM)				
			Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Total N-uptake (kg ha^{-1})	Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Seeds (kg ha^{-1})	Total N-uptake (kg ha^{-1})
2018	Cultivar	TS-5	27.4 ± 0.43a	12.9 ± 0.29a	16.0 ± 0.36a	56.3 ± 0.96a	11.2 ± 0.19a	31.7 ± 0.58a	6.3 ± 0.12a	41.1 ± 0.56a	90.4 ± 1.28a
		TS-3	26.0 ± 0.57b	12.2 ± 0.27b	14.9 ± 0.40b	53.1 ± 1.08b	10.6 ± 0.17b	30.4 ± 0.61b	5.9 ± 0.11b	38.5 ± 0.91b	85.4 ± 1.52b
	LSD		0.9	0.4	1.0	1.3	0.4	1.3	0.3	2.1	2.8
	Sulphur	S_0	24.5 ± 0.45c	11.2 ± 0.31c	14.1 ± 0.51b	49.7 ± 1.06c	10.1 ± 0.23c	29.4 ± 0.41b	5.7 ± 0.13b	37.2 ± 0.75b	82.4 ± 1.12c
		S_{20}	26.7 ± 0.46b	12.6 ± 0.32b	15.8 ± 0.30a	55.1 ± 0.82b	10.9 ± 0.17b	29.9 ± 0.78b	6.1 ± 0.16ab	39.6 ± 0.37ab	86.5 ± 1.32b
		S_{40}	28.0 ± 0.73a	13.3 ± 0.38a	16.3 ± 0.67a	57.3 ± 1.60a	11.4 ± 0.21a	32.7 ± 0.67a	6.4 ± 0.18a	41.5 ± 1.33a	92.0 ± 1.85a
		S_{60}	27.6 ± 0.58ab	13.1 ± 0.15ab	15.8 ± 0.42a	56.6 ± 0.80ab	11.3 ± 0.10ab	32.2 ± 0.56a	6.2 ± 0.10a	40.8 ± 1.03a	90.6 ± 1.28a
	LSD		1.2	0.6	1.3	1.9	0.5	1.8	0.4	2.3	4.0
2019	Cultivar	TS-5	27.8 ± 0.44a	14.7 ± 0.19a	16.5 ± 0.35a	59.0 ± 0.77a	11.9 ± 0.21a	33.2 ± 0.68a	6.5 ± 0.14a	42.6 ± 0.98a	94.2 ± 1.61a
		TS-3	26.2 ± 0.54b	13.4 ± 0.25b	15.1 ± 0.29b	54.7 ± 0.91b	11.0 ± 0.17b	31.1 ± 0.59b	6.1 ± 0.17b	40.0 ± 0.92b	88.9 ± 1.54b
	LSD		1.0	0.4	0.9	1.1	0.4	1.2	0.3	2.4	2.8
	Sulphur	S_0	24.9 ± 0.41c	13.2 ± 0.23c	14.6 ± 0.59b	52.7 ± 0.97c	10.7 ± 0.26c	30.1 ± 0.70b	5.8 ± 0.19c	38.1 ± 1.09c	84.7 ± 1.73c
		S_{20}	26.8 ± 0.56b	14.1 ± 0.25b	15.9 ± 0.28a	56.8 ± 0.56b	11.5 ± 0.21b	32.3 ± 0.99a	6.3 ± 0.11b	40.6 ± 1.38bc	90.7 ± 1.81b
		S_{40}	28.3 ± 0.66a	14.7 ± 0.29a	16.5 ± 0.45a	59.4 ± 1.11a	12.1 ± 0.17a	33.8 ± 0.67a	6.8 ± 0.13a	44.1 ± 1.19a	96.8 ± 1.66a
		S_{60}	28.0 ± 0.37ab	14.2 ± 0.31ab	16.2 ± 0.25a	58.5 ± 0.52a	11.6 ± 0.24ab	33.5 ± 0.66a	6.5 ± 0.18ab	42.4 ± 0.57ab	93.9 ± 1.00ab
	LSD		1.4	0.6	1.3	1.6	0.5	1.7	0.4	3.4	3.9

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1} , respectively. Means with a different letter in the column varied significantly at $p < 0.05$

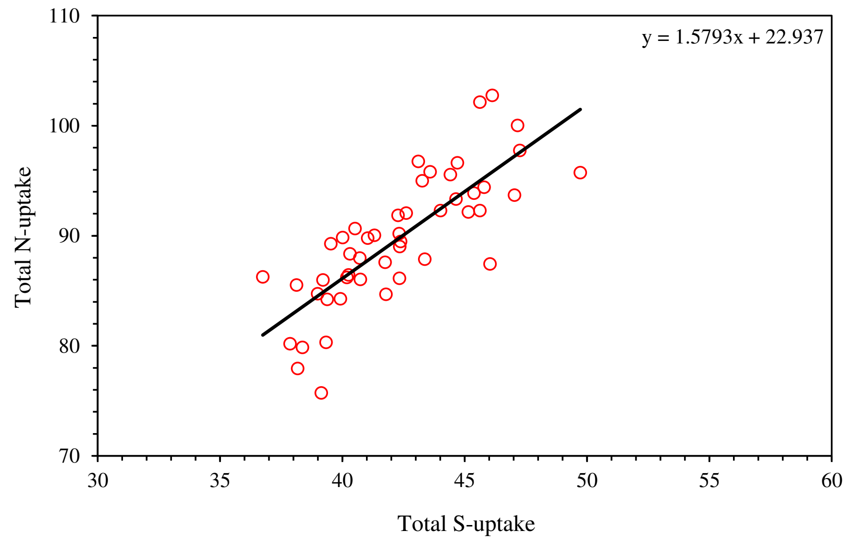

Fig. 3 Total Nitrogen and Sulphur uptake (kg ha^{-1}) in sesame

compared to control. Different S treatments had also affected the S-content in different plant parts of sesame. However, treatment S_{40} showed the highest S-content in leaves, stem, capsules, and seeds at both MB and PM stages under-studied treatments. Overall, compared to control, treatment S_{40} increased the S-content in leaves (by 26%), stem (by 15%), and capsules (by 20%) at MB, while in leaves (by 24%), stem (by 15%), capsules (by 10%), and seeds (by 14%) at PM.

Seed yield and yield components

Figure 4 presents the influence of different S treatments on seed yield and yield components of sesame. The sesame yield components including the number of capsules (plant^{-1}), number of seeds (capsule^{-1}), and thousand seed weight are given in Fig. 4. During both years of this study, S treatments exhibited a significant influence on yield components of sesame plants. The average highest number of capsules plant^{-1} (29.5), number of seeds capsule^{-1} (70.9), and thousand seed weight (3.58 g) were noted in S_{40} treatment, whereas the average lowest number of capsules plant^{-1} (26.2), number of seeds capsule^{-1} (63.9), and thousand seed weight (3.37 g) were recorded in S_0. On average, across the years, compared to S_0, treatment S_{40} increased the number of capsules plant^{-1} (by 13%), the number of seeds capsule^{-1} (by 11%), and thousand seed weight (by 6%). Moreover, the seed yield of sesame was also significantly influenced by different S treatments (Fig. 4). The highest seed yield (1396.1 kg ha^{-1} in 2018, and 1425.7 kg ha^{-1} in 2019) was recorded in S_{40}, while the lowest (1086.3 kg ha^{-1} in 2018, and 1135.8 kg ha^{-1} in 2019) seed yield was recorded in S_0 treatment. Overall, across the years, relative to S_0, treatment S_{40} enhanced the sesame seed yield by 28%, however, relative to S_{40}, excessive S application in S_{60} decreased the sesame yield by 8%.

Economic analysis

The economic analysis under different S treatments for sesame production is given in Table 6. In this study, the average maximum total income of sesame was observed in treatment S_{40}, and the average minimum total income of sesame was recorded in S_0. On average, over the years, compared to S_0, the net income was increased by 21% under S_{20} treatment, 44% in S_{40} treatment, and 29% in S_{60} treatment.

Discussion

The improvements in resource utilization efficiency of plants require a multifaceted approach and could enhance the dry matter and nutrient accumulation as well as translocation towards the economic plant parts. This experiment showed that different S levels at the mid-bloom and physiological maturity had significant impacts on dry matter production and partitioning, nutrient uptake and partitioning, and seed yield of sesame. Overall, optimum S availability at 40 kg ha^{-1} for sesame in S_{40}, as compared with S_0, increased the total dry matter (+29%), seed yield (+28%), and enhanced the N-uptake (+13%), P-uptake (+22%), K-uptake (+11%) and S-uptake (+16%) in sesame. This study demonstrated that an optimum dose of S allowed better S availability to sesame plants which improved the nutrients uptake, total dry matter production, and ultimately enhanced the seed yield of sesame.

Dry matter production and distribution in plant parts of sesame were enhanced under various S treatments (S_0, S_{20}, S_{40}, and S_{60}), consistently with previously reported trends in

Table 3 Effects of sulphur application on total P-uptake and distribution of sesame at mid-bloom and physiological maturity in 2018 and 2019

Years	Treatments		Mid bloom stage (MB)				Physiological maturity stage (PM)				
			Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Total P-uptake (kg ha^{-1})	Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Seeds (kg ha^{-1})	Total P-uptake (kg ha^{-1})
2018	Cultivar	TS-5	4.4 ± 0.14a	5.9 ± 0.16a	1.3 ± 0.05a	11.5 ± 0.33a	2.5 ± 0.10a	7.3 ± 0.14a	1.5 ± 0.07a	11.2 ± 0.31a	22.4 ± 0.55a
		TS-3	3.8 ± 0.12b	5.4 ± 0.13b	0.9 ± 0.06b	10.1 ± 0.27b	2.3 ± 0.09b	6.9 ± 0.18b	1.4 ± 0.06b	10.6 ± 0.27b	21.2 ± 0.53b
	LSD		0.2	0.3	0.1	0.3	0.1	0.3	0.1	0.4	0.6
	Sulphur	S_0	3.5 ± 0.13c	5.1 ± 0.18c	0.8 ± 0.05d	09.4 ± 0.30c	1.9 ± 0.12c	6.4 ± 0.21c	1.1 ± 0.07c	09.7 ± 0.26c	19.1 ± 0.57c
		S_{20}	3.9 ± 0.10b	5.6 ± 0.15b	1.0 ± 0.04c	10.5 ± 0.23b	2.4 ± 0.06b	7.1 ± 0.12b	1.4 ± 0.05b	10.7 ± 0.34b	21.6 ± 0.42b
		S_{40}	4.5 ± 0.09a	6.1 ± 0.16a	1.3 ± 0.05a	11.8 ± 0.27a	2.7 ± 0.11a	7.5 ± 0.18a	1.6 ± 0.07a	11.7 ± 0.31a	23.5 ± 0.61a
		S_{60}	4.4 ± 0.06a	5.9 ± 0.15ab	1.1 ± 0.05b	11.4 ± 0.17a	2.5 ± 0.07b	7.4 ± 0.17ab	1.5 ± 0.04b	11.5 ± 0.23a	22.9 ± 0.27a
	LSD		0.2	0.4	0.1	0.5	0.2	0.4	0.1	0.6	0.8
2019	Cultivar	TS-5	4.6 ± 0.13a	6.0 ± 0.16a	1.3 ± 0.07a	11.9 ± 0.28a	2.8 ± 0.13a	7.5 ± 0.17a	1.6 ± 0.08a	12.2 ± 0.38a	24.1 ± 0.65a
		TS-3	4.0 ± 0.12b	5.5 ± 0.15b	1.0 ± 0.05b	10.5 ± 0.30b	2.6 ± 0.11b	7.1 ± 0.13b	1.5 ± 0.05b	10.8 ± 0.29b	22.0 ± 0.49b
	LSD		3.8	0.3	0.1	0.4	0.1	0.4	0.1	0.6	0.9
	Sulphur	S_0	3.7 ± 0.12c	5.2 ± 0.14b	1.0 ± 0.04c	10.0 ± 0.18d	2.3 ± 0.09c	6.7 ± 0.23b	1.3 ± 0.06c	10.3 ± 0.25b	20.7 ± 0.47c
		S_{20}	4.2 ± 0.14b	5.5 ± 0.17b	1.1 ± 0.09bc	10.8 ± 0.29c	2.6 ± 0.06b	7.3 ± 0.17a	1.5 ± 0.07b	10.9 ± 0.44b	22.3 ± 0.69b
		S_{40}	4.7 ± 0.16a	6.2 ± 0.14a	1.4 ± 0.03a	12.3 ± 0.30a	3.0 ± 0.08a	7.6 ± 0.18a	1.8 ± 0.07a	12.6 ± 0.25a	25.0 ± 0.49a
		S_{60}	4.5 ± 0.09ab	6.1 ± 0.10a	1.1 ± 0.06b	11.7 ± 0.18b	2.9 ± 0.04a	7.6 ± 0.12a	1.6 ± 0.06b	12.1 ± 0.23a	24.2 ± 0.21a
	LSD		0.4	0.4	0.1	0.6	0.2	0.5	0.1	0.8	1.3

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1} , respectively. Means with a different letter in the column varied significantly at $p < 0.05$

Table 4 Effects of sulphur application on total K-uptake and distribution of sesame at mid-bloom and physiological maturity in 2018 and 2019

Years	Treatments		Mid bloom stage (MB)				Physiological maturity stage (PM)				
			Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Total K-uptake (kg ha^{-1})	Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Seeds (kg ha^{-1})	Total K-uptake (kg ha^{-1})
2018	Cultivar	TS-5	25.2 ± 0.46a	29.2 ± 0.58a	8.2 ± 0.21a	62.6 ± 1.01a	18.0 ± 0.37a	38.8 ± 0.80a	5.5 ± 0.13a	20.2 ± 0.28a	82.4 ± 1.19a
		TS-3	23.3 ± 0.39b	27.8 ± 0.45b	7.0 ± 0.12b	58.2 ± 0.75b	16.8 ± 0.39b	35.8 ± 0.78b	4.9 ± 0.11b	18.9 ± 0.25b	76.4 ± 1.24b
	LSD		1.0	1.3	0.3	1.6	0.9	1.9	0.2	0.7	2.2
	Sulphur	S_0	23.2 ± 0.66b	26.7 ± 0.72b	6.8 ± 0.31c	56.7 ± 0.44c	15.9 ± 0.44b	34.8 ± 0.71b	4.7 ± 0.15c	18.8 ± 0.32b	74.2 ± 0.86c
		S_{20}	23.9 ± 0.52b	28.3 ± 0.73ab	7.7 ± 0.17b	59.9 ± 0.43b	17.5 ± 0.43a	37.1 ± 1.29ab	5.1 ± 0.12b	19.4 ± 0.31ab	79.1 ± 1.44b
		S_{40}	25.4 ± 0.43a	30.1 ± 0.50a	8.2 ± 0.66a	63.7 ± 0.53a	18.2 ± 0.53a	39.0 ± 1.18a	5.5 ± 0.14a	20.3 ± 0.33a	83.0 ± 1.82a
		S_{60}	24.5 ± 0.57ab	28.9 ± 0.52a	7.8 ± 0.78ab	61.2 ± 0.47b	18.0 ± 0.47a	38.2 ± 0.75a	5.4 ± 0.09ab	19.9 ± 0.29a	81.4 ± 0.80ab
	LSD		1.4	1.9	0.4	2.3	1.2	2.7	0.3	1.0	3.1
2019	Cultivar	TS-5	26.2 ± 0.56a	30.8 ± 0.42a	8.6 ± 0.24a	65.6 ± 0.94a	18.5 ± 0.32a	39.4 ± 0.55a	5.7 ± 0.15a	20.8 ± 0.30a	84.3 ± 1.09a
		TS-3	24.3 ± 0.52b	28.6 ± 0.44b	7.3 ± 0.14b	60.1 ± 0.96b	17.5 ± 0.26b	37.3 ± 0.71b	5.2 ± 0.14b	19.1 ± 0.25b	79.1 ± 1.15b
	LSD		1.3	0.9	0.3	1.1	0.5	1.6	0.4	0.6	2.0
	Sulphur	S_0	23.1 ± 0.65b	28.1 ± 0.27b	7.0 ± 0.30c	58.2 ± 1.06c	16.6 ± 0.36c	36.1 ± 0.66b	4.9 ± 0.20b	18.9 ± 0.35c	76.5 ± 1.26c
		S_{20}	25.6 ± 0.79a	29.1 ± 0.56b	8.1 ± 0.13b	62.8 ± 0.47b	18.0 ± 0.33b	38.3 ± 0.77ab	5.5 ± 0.17a	19.9 ± 0.29b	81.7 ± 1.00b
		S_{40}	26.2 ± 0.83a	31.1 ± 0.38a	8.5 ± 0.22a	65.8 ± 1.25a	18.8 ± 0.32a	39.5 ± 0.94a	5.8 ± 0.21a	20.8 ± 0.36a	84.8 ± 1.53a
		S_{60}	25.9 ± 0.52a	30.5 ± 0.39a	8.2 ± 0.14ab	64.6 ± 0.73a	18.5 ± 0.21ab	39.5 ± 0.77a	5.6 ± 0.13a	20.1 ± 0.29ab	83.7 ± 0.89ab
	LSD		1.9	1.3	0.4	1.6	0.8	2.3	0.5	0.9	2.8

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1} , respectively. Means with a different letter in the column varied significantly at $p < 0.05$

Table 5 Effects of sulphur application on total S-uptake and distribution of sesame at mid-bloom and physiological maturity in 2018 and 2019

Years	Treatments		Mid bloom stage (MB)				Physiological maturity stage (PM)				
			Leaves (kg ha^{-1})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Total S-uptake (kg ha^{-1})	Leaves (kg ha^{-})	Stem (kg ha^{-1})	Capsules (kg ha^{-1})	Seeds (kg ha^{-1})	Total S-uptake (kg ha^{-1})
2018	Cultivar	TS-5	14.4 ± 0.52a	10.2 ± 0.18a	5.6 ± 0.17a	30.3 ± 0.74a	09.8 ± 0.30a	16.1 ± 0.38a	09.5 ± 0.15 NS	7.2 ± 0.18a	42.5 ± 0.81a
		TS-3	13.4 ± 0.43b	09.8 ± 0.17b	5.0 ± 0.19b	28.1 ± 0.66b	09.3 ± 0.34b	15.4 ± 0.34b	09.2 ± 0.17	6.7 ± 0.13b	40.5 ± 0.79b
	LSD		0.9	0.5	0.5	1.1	0.4	0.7	0.4	0.4	1.0
	Sulphur	S_0	11.8 ± 0.74c	09.5 ± 0.21b	4.7 ± 0.23b	25.9 ± 1.00c	08.4 ± 0.22c	14.9 ± 0.34b	09.1 ± 0.17b	6.4 ± 0.18b	38.8 ± 0.40c
		S_{20}	14.1 ± 0.48b	09.9 ± 0.25ab	5.2 ± 0.22ab	29.2 ± 0.65b	08.8 ± 0.26c	15.3 ± 0.46b	09.2 ± 0.23b	6.9 ± 0.22ab	40.1 ± 0.83c
		S_{40}	15.3 ± 0.55a	10.5 ± 0.27a	5.9 ± 0.20a	31.7 ± 0.67a	10.9 ± 0.15a	17.1 ± 0.43a	09.9 ± 0.10a	7.3 ± 0.21a	45.2 ± 04.9a
		S_{60}	14.6 ± 0.35ab	10.1 ± 0.11a	5.4 ± 0.26ab	30.0 ± 0.54b	10.1 ± 0.22b	15.6 ± 0.50b	09.3 ± 0.24b	7.2 ± 0.11a	42.2 ± 0.93b
	LSD		1.2	0.6	0.7	1.5	0.6	1.0	0.6	0.6	1.5
2019	Cultivar	TS-5	15.0 ± 0.38a	11.5 ± 0.31a	6.1 ± 0.16a	32.5 ± 0.70a	10.0 ± 0.21a	16.6 ± 0.36a	10.1 ± 0.25 NS	7.6 ± 0.16a	44.4 ± 0.82a
		TS-3	13.9 ± 0.40b	10.6 ± 0.25b	5.4 ± 0.18b	29.9 ± 0.66b	09.3 ± 0.25b	15.9 ± 0.33b	09.6 ± 0.17	6.9 ± 0.15b	41.7 ± 0.73b
	LSD		0.7	0.7	0.4	0.7	0.5	0.6	0.6	0.4	1.2
	Sulphur	S_0	12.7 ± 0.46c	10.1 ± 0.41c	5.3 ± 0.19c	28.0 ± 0.86d	08.8 ± 0.18c	14.9 ± 0.43c	09.4 ± 0.20b	6.8 ± 0.15c	39.9 ± 0.67c
		S_{20}	14.3 ± 0.35b	11.0 ± 0.35b	5.6 ± 0.22bc	30.9 ± 0.43c	09.4 ± 0.24bc	15.9 ± 0.33b	09.5 ± 0.33b	7.2 ± 0.21bc	41.9 ± 0.68b
		S_{40}	15.6 ± 0.48a	12.0 ± 0.33a	6.1 ± 0.16a	33.7 ± 0.48a	10.5 ± 0.27a	17.2 ± 0.32a	10.5 ± 0.27a	7.8 ± 0.20a	45.9 ± 0.55a
		S_{60}	15.3 ± 0.12a	11.1 ± 0.32ab	6.0 ± 0.18ab	32.4 ± 0.55b	10.1 ± 0.21ab	17.1 ± 0.23a	09.9 ± 0.19ab	7.4 ± 0.15ab	44.4 ± 0.61a
	LSD		0.9	0.9	0.5	0.9	0.7	0.9	0.8	0.5	1.7

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1} , respectively. Means with a different letter in the column varied significantly at $p < 0.05$

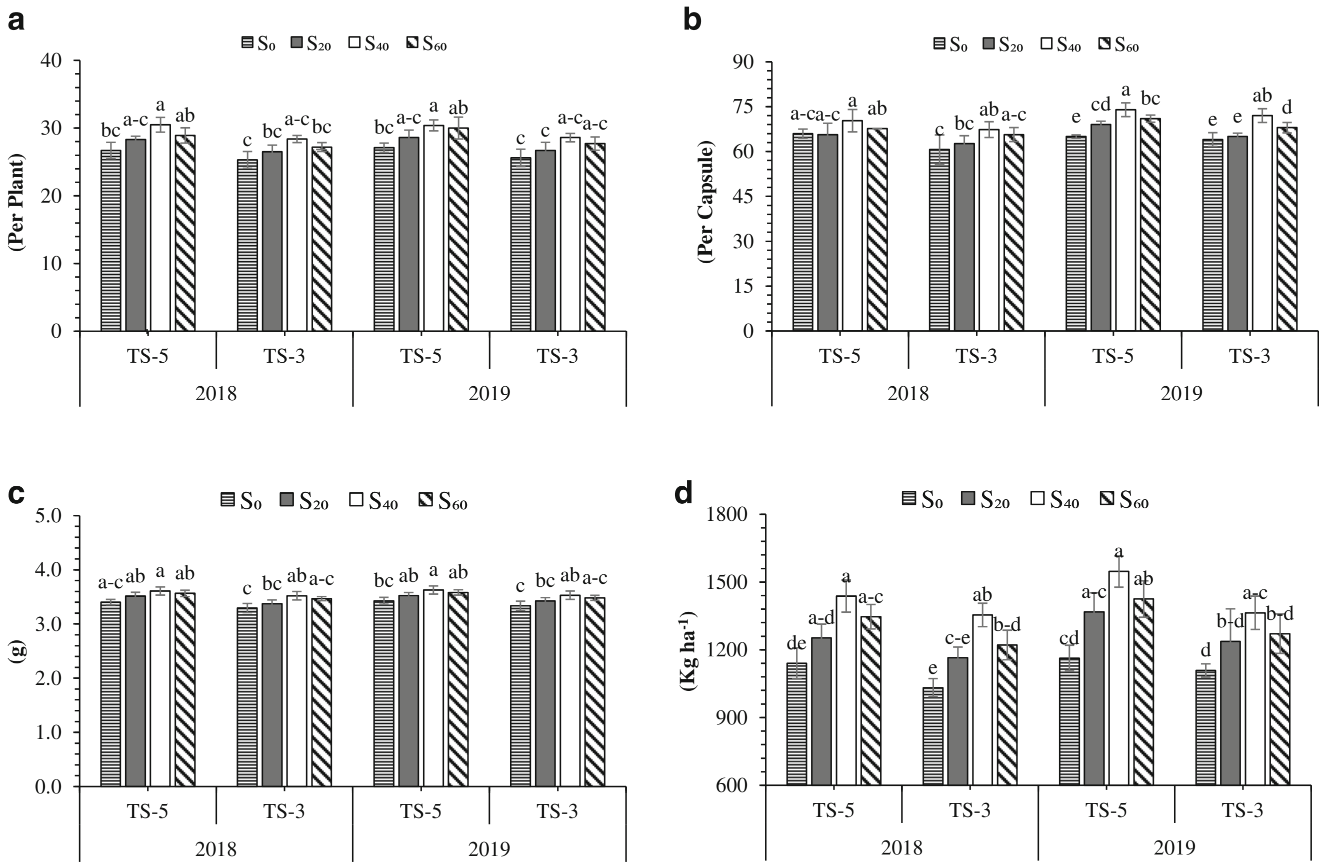

Fig. 4 Number of capsules per plant (**a**), number of seeds per capsule (**b**), thousand seed weight (**c**), and seed yield (**d**) of sesame in 2018 and 2019. The S0, S20, S40, and S60 represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1}, respectively

sesame (Raza et al. 2018b; Couch et al. 2017). It was confirmed in previous studies that low S availability significantly abate the biomass accumulation in sesame plants (Shah et al. 2013; Raza et al. 2018b). However, our study showed that the S application to the sesame plants at the rate of 40 kg ha^{-1} greatly enhanced the biomass production and distribution as compared to other treatments. This increase might be associated with optimum S availability to sesame plants (Raza et al. 2018b), which increases the photosynthesis ability of sesame due to the enhanced chlorophyll biosynthesis and Rubisco activity (Resurreccion et al. 2001; Singh et al. 2018), and improves the nutrient uptake due to increased water flow from the rhizosphere, (Muchow and Davis 1988; Elliott et al. 1997). Moreover, the biomass partitioning also followed the previously reported trend, where the vegetative parts had the maximum proportion of biomass at the start of the seed filling phase (MB) while at the end of the seed filling phase (PM), reproductive parts showed a significant increase in the proportion of accumulated biomass (Narayanan and Reddy 1982; Atta and Van Cleemput 1988; Couch et al. 2017; Mehmood et al. 2021). The possible reason for this improvement in reproductive biomass was the increased assimilate production by sesame stems and capsules which retained longer than leaves, and remobilization of assimilates from senescing leaves towards the capsules and developing seed tissues. Such trends of assimilate production by capsules and remobilization from leaves were reported earlier in filed pea and soybean (Flinn and Pate 1970; Andrews and Svec 1975, 1976). Hence, it is convincible that photosynthesis by sesame stems and capsules, and remobilization from senescing leaves contributed to increasing the reproductive biomass at

Table 6 Economic analysis for different sesame cultivars and Sulphur treatments in 2018 and 2019

Treatments		Net income (US $ ha^{-1})		
		2018	2019	Average
Cultivar	TS-5	584.3	575.0	579.7
	TS-3	511.7	491.1	501.4
Sulphur	S_0	434.7	420.7	427.7
	S_{20}	512.1	518.3	515.2
	S_{40}	631.8	603.2	617.5
	S_{60}	560.5	542.8	551.6

The S_0, S_{20}, S_{40}, and S_{60} represent the sulphur treatments, Control, 20, 40, and 60 kg ha^{-1}, respectively. The exchange rate for the US dollar was 138.9 and 155.3 Pakistani Rupee (PKR) in 2018 and 2019, respectively maturity. However, the photosynthetic ability of sesame stems and capsules is still unknown and warrants detailed investigation. Hence, our results indicate that from MB to PM, sesame plants had the chance to enhance the biomass accumulation and partitioning to plant organs, if the conditions are favorable during growing period, such as improved nutrient availability and uptake, which can be maintained through an optimum level of S application, as observed during this study.

We determined that all the treatments significantly altered the total N, P, K, and S accumulation and distribution into different plant parts (leaves, stem, capsules, and seeds) of sesame at MB and PM, depending on the nutrient requirements (low and high) in various parts. In the past, researchers have inferred and regarded seeds as the most active and vital sink for photoassimilate and nutrients during the reproductive phase (Couch et al. 2017; Kitonyo et al. 2018). Likewise, N, P, K, and S uptake in leaves and capsules reduced from MB to PM, suggesting that uptake and remobilization of these nutrients to other plant parts of sesame, possibly in seeds and stems were increased. Additionally, partitioning of N, P, K, and S in leaves is critical in maintaining the higher rate of photoassimilate production, and accumulation of these nutrients depends on the photosynthetic capacity of plants, which governs the nutrient allocation patterns in various plant organs (Raza et al. 2020). In past studies, scientists have reported that low S availability can reduce the total uptake of nutrients especially N, P, K, and S in plants (Abdallah et al. 2010; Motior et al. 2011; Girondé et al. 2014). Correspondingly, treatment S_{40} enhanced the S availability, which might improve the biomass partitioning and carbohydrates translocation in roots as well and ultimately enhance the nutrients uptake (Henry and Raper Jr 1991; Abdallah et al. 2010). Previously, scientists have reported that increased S availability due to an adequate supply of S could improve the N-uptake during the reproductive growth, which ultimately increases the seed yield of crops (Abdallah et al. 2010; Motior et al. 2011), as noted in this study. Compared with N-uptake, P-uptake occurs throughout the growing period of crops (Batten 1992), whereas a substantial amount of P accumulation was documented during seed filling (Papakosta 1994), as observed in our experiment. Similarly, an increase in K-uptake and S-uptake in response to S fertilization is also reported in several investigations (Motior et al. 2011; Raza et al. 2018a, 2018b). Thus, enhanced S availability through optimum S fertilization could enhance the nutrients accumulation, distribution, and uptake in various plant organs by maintaining a high supply of assimilates and improving the microenvironment of crop plants.

Application of S fertilizer at the rate of 40 kg ha^{-1} (S_{40}) produced the highest seed yield, with an increment of 28%, as compared to control (S_0). Furthermore, we also observed that different S levels significantly increased the number of capsules per plant, number of seeds per capsule, and thousand seed weight, while maximum values for these yield components were observed under S_{40} treatment during both years. Therefore, the highest sesame yield was ascribed to heavier sesame seeds and greater capsules number per plant and seeds per capsule. Another reason for these increments might be the availability of supplementary carbohydrates and photoassimilate due to enhanced photosynthetic capacity of sesame under optimum S availability which increased the biomass and nutrient accumulation that ultimately lead to improvements in seed yield and yield components of sesame (Raza et al. 2018b). Our results were consistent with earlier reported findings where an optimum S application (40–50 kg ha^{-1}) enhanced the seed yield of sesame (Shah et al. 2013; Raza et al. 2018a, 2018b). Hence, adequate S availability during seed filling could improve the seed yield of sesame by improved accumulation and distribution of dry matter and nutrients in plant organs.

The economic analysis of the current study revealed that in comparison with control, higher net returns by 44% were achieved under the S_{40} treatment. Farming communities only adopt strategies that can provide greater yield and net economic returns for the farmers (Raza et al. 2018b). Hence, treatment S_{40} increased the dry matter accumulation, nutrient uptake of N, P, K, and S, which ultimately improved the sesame productivity and provided higher net returns for farmers.

Conclusion

This research provided evidence for different patterns of biomass accumulation and nutrient uptake (N, P, K, and S), and their partitioning in plant organs of sesame at the mid-bloom and physiological maturity under different S treatments. Based on our research, results revealed that greater dry matter production, nutrient uptake, and seed yield is possible in sesame with an optimum (S_{40} = 40 kg ha^{-1}) amount of S application, which could also improve the net economic returns for the farmers. To the best of our knowledge, this research is the first to report the effects of S application on nutrient uptake and partitioning in sesame. However, further research is warranted to completely understand the mechanisms regulating the increased nutrient uptake, specifically during the seed filling phase of sesame.

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Data availability All data is available in this article.

Code availability No codes are used.

Declarations

This research work does not involve humans or animals as research material.

Conflict of interest The authors declare that they have no competing interests.

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