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Effect of Sulphur Application on Photosynthesis and Biomass Accumulation of Sesame Varieties under Rainfed Conditions

Muhammad Ali Raza [1,†], Ling Yang Feng [1,†], Nasir Iqbal [1,†], Abdul Manaf [2], Muhammad Hayder Bin Khalid [1,3], Sana ur Rehman [2], Allah Wasaya [4], Muhammad Ansar [2], Masum Billah [1,3], Feng Yang [1,*] and Wenyu Yang [1,*]

1 College of Agronomy, Sichuan Agricultural University, Chengdu 611130, China; razaali0784@yahoo.com (M.A.R.); fgazelle@126.com (L.Y.F.); nasir.iqbal54@gmail.com (N.I.)
2 Department of Agronomy, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi 46000, Pakistan; munafawan@yahoo.com (A.M.); sana07139@gmail.com (S.u.R.); muhammad.ansar@uaar.edu.pk (M.A.)
3 Maize Research Institute, Sichuan Agricultural University, Chengdu 611130, China; haider2323@gmail.com (M.H.B.K.); kazimasum.agpstu20@gmail.com (M.B.)
4 College of Agriculture, Bahadur Sub Campus, Bahauddin Zakariya University, Multan, Layyah 31200, Pakistan; wasayauaf@gmail.com
* Correspondence: f.yang@sicau.edu.cn (F.Y.); mssiyangwy@sicau.edu.cn (W.Y.); Tel.: +86-28-8629-0960 (W.Y.); Fax: +86-28-8629-0870 (W.Y.)
† These authors contributed equally to this work.

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Abstract: Oilseeds yield response to sulphur (S) has been well investigated but the dynamics of total biomass accumulation (TBA) and partitioning by sesame plants in response to S are not well understood. This study was initiated to investigate the effects of S on sesame, in which four sesame varieties V_1, SG-27; V_2, SG-30; V_3, SG-36; V_4, SG-51 and four S treatments T_1, 20; T_2, 30; T_3, 40; T_4, 50 kg ha^{-1} were used. Results revealed that the leaf area index and photosynthetic rate of sesame varieties were significantly higher under T_3 with V_3. Similarly, S fertilization considerably increased the TBA and maximum TBA was reached at late-flowering with V_3 in T_3. Relative to T_1, plants in T_3 had 33 and 23% higher capsule and seed biomass, respectively. Furthermore, total S accumulation and distribution in different plant organs changed with growth stage, at pre-flowering and mid-flowering stage maximum S was found in the stem, whereas at late-flowering and full-maturity stage highest S was recorded in reproductive parts. These results implied that S fertilizers should be applied to agricultural fields to improve oilseed production and by selecting the appropriate and area-specific genotype we can increase sesame seed yield under rainfed conditions.

Keywords: sulphur accumulation; sesame; biomass; photosynthetic rate; leaf area index; seed yield

1. Introduction

Sulphur (S) is considered as the fourth main plant nutrient after nitrogen (N), phosphorus (P) and potassium (K) and its low availability in various soils causes the innate S deficiency. High yield and quality of oilseed crops are possible only when crops have access to the optimum amount of Sulphur [1]. Sufficient application of S fertilizer has been documented to improve sesame seed yield and yield related traits [2–5], as well as oil [6] and protein content [2] in sesame. Moreover, our recent results demonstrated that sesame crop can accumulate 40 kg S ha^{-1} under rainfed conditions [7]. Sulphur application increased the availability of other major nutrients N, P and K [5] and enhanced sesame growth under drought conditions [6]. Its deficiency negatively affects the crop growth phases, crop maturity [8,9] and oil quality of oilseed crops [10,11]. Moreover, application of low S or S free fertilizers has decreased the S inputs to agriculture fields during the last 20 years [12]. The higher seed yield production has increased the rate of sulphur removal from soil [6,13]. Oilseed crops need more S than cereal crops because it promotes pod initiation, whereas a deficiency of S aborts pods [10]. Overall, an optimum amount of S application considerably enhances the sesame growth [2] and seed quality by increasing the oleic acid content in oilseeds [11]. Sesame is a conventional oilseed crop and generally grows in rainfed areas [14]. Compared to other oilseeds, sesame contains maximum protein (25%) and oil (55%) contents [2,15] and it also has sesamol and sesamolin (antioxidant), which inhibit the oil rancidity [16]. For optimum sesame seed yield, it requires an adequate amount of S at vegetative stages [7]. Typically, sesame is planted in arid to semi-arid areas, where the amount and pattern of rainfall changes from sowing to harvesting. The severe environmental conditions especially drought may affect the crop during the reproductive phase which ultimately reduces the crop yield and seed quality Presently, drought resistant varieties are replacing drought prone varieties with the purpose of increasing seed yield. The severe environmental conditions at the reproductive phase reduces the crop yields [17].

However, suitable crop varieties under prevailing environmental conditions can reduce weather risks [18]. Previous studies revealed that drought is the major factor that had affected the seed yield under rainfed conditions [19–21] while, S application considerably increased the biomass accumulation in crops by increasing their ability to cope drought conditions [22]. Recently, a study revealed that under drought conditions S application has increased the root biomass accumulation in maize to find water at the cost of leaf biomass [23]. In addition to environmental variations, nutrient availability is an important factor for crop growth and development. Although crops uptake only small portions of S during their first 2 to 3 weeks of early growth, this initial accumulation of S is extremely critical. Furthermore, partitioning of biomass towards seed at the reproductive stage was increased by early S fertilization in sesame [2]. Crop growth phases are crucial in determining the total biomass accumulation, many previous studies reported the biomass accumulation of corn and wheat in response to N and P [24–26] but the effects of sulphur fertilization on biomass accumulation and partitioning under rainfed conditions have not been investigated. A comprehensive study of sesame biomass in response to sulphur fertilization was needed for appropriate sulphur fertilization decisions, which can improve sesame seed yield and quality parameters. Although S is a major nutrient for oilseeds, its effect has not investigated thoroughly, especially under rainfed areas, whereas deficiency of S has been documented with increasing frequency during the past decades in the world [27]. Previous field studies have revealed that the different varieties double low genotypes (low in erucic acid and glucosinolates) of rapeseed are more prone to sulphur deficiency than single low genotypes (low in erucic acid) exhibited different response to S application [28,29]. However, the role of S application on biomass accumulation and partitioning towards economic parts in sesame under rainfed conditions has never been investigated. Therefore, this study was conducted to understand the effects of S application on biomass accumulation and partitioning in sesame varieties to improve the sesame cultivation management and maintain sustainable oilseed production in rainfed areas.

The objectives of this two-year field experiment were (i) to investigate the impact of sulphur treatments on the leaf area index and photosynthetic rate of sesame varieties; (ii) to investigate the effect of sulphur on total biomass accumulation and partitioning in different plant parts of sesame varieties under rainfed conditions; (iii) to characterize total sulphur accumulation and distribution in different plant parts of sesame varieties under rainfed conditions and (iv) to find out an economical and appropriate level of sulphur for higher sesame yield under rainfed conditions.

2. Materials and Methods

2.1. Ethics Statement

No specific permissions were needed for the field studies. All the experiments were conducted according to institutional guidelines of Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan.

2.2. Research Site and Planting Material

Two-year field experiment was carried out at the Koont research station (Chakwal, 32°56′ North, 72°52′ East, 513-m elevation) of Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Punjab Province of Pakistan during the summer (locally known Kharif) season in 2012 and 2013. Before the start of the present study, wheat was planted in this research area. From the pool of twenty-five sesame varieties recognized on the basis of drought resistance in 2009–2011, seeds of two moderately drought tolerant and two drought tolerant sesame varieties were collected from National Agricultural Research Centre (NARC), Islamabad, Pakistan: V_1 and V_2 (SG-27 and SG-30, moderately drought tolerant); V_3 and V_4 (SG-36 and SG-51, drought tolerant) for this experiment.

2.3. Weather Description and Soil Characteristics

The research station has dry sub humid climatic conditions and falls in medium rainfall region with an annual evapotranspiration of about 1585 mm. Weather data of 2012 and 2013 including average minimum and maximum temperature, humidity and monthly rainfall during the crop growth period from sowing to harvesting is shown in Figure 1. During the crop growing season, the total amount of precipitation was 315 mm in 2012 and 499 mm in 2013. Soil samples at the start of the present experiment were analyzed. The experimental soil has organic matter = 0.67 (%), pH = 7.6, bulk density = 1.27 (g cm^{-3}), EC = 0.26 (dSm^{-1}), available S = 6.1 (mg kg^{-1}), available P = 6.7 (g kg^{-1}), available K = 120 (g kg^{-1}), saturation = 38 (%) and soil texture = loam in the 0–15 cm soil layer.

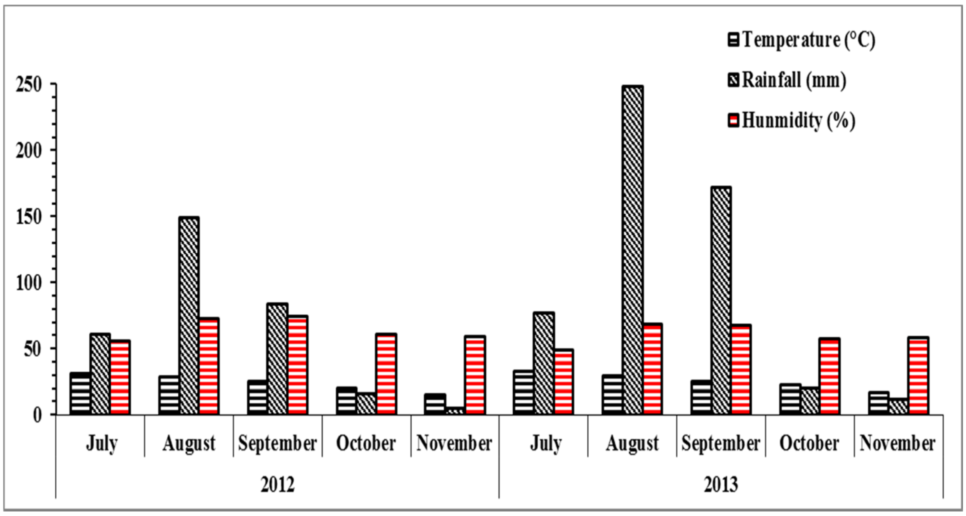

Figure 1. Monthly rainfall, average temperature and humidity from July to November in the crop periods of 2012 and 2013.

2.4. Experimental Details and Treatments

Four sesame varieties were seeded in an RCBD (randomized complete block design) with a split plot arrangement having 4 replications. Each experimental block consisted of one main block with the size of 54 m^2 (10.8 m × 5 m) divided into four sub blocks with a size of 2.7 m × 5 m. The crop seed was used @ 5 kg ha^{-1}, every sub block consisted of 6 sesame rows. Four sesame varieties: V_1 (SG-27);

V_2 (SG-30); V_3 (SG-36); V_4 (SG-51) and four sulphur treatments: T_1 (20 kg ha^{-1}); T_2 (30 kg ha^{-1}); T_3 (40 kg ha^{-1}); T_4 (50 kg ha^{-1}) were used in this experiment. Sesame varieties were maintained in main blocks while sulphur treatments were allocated to the sub-blocks. Sesame was seeded on fourteenth and fifteenth of July 2012 and 2013, respectively at a seeding depth of 2 cm by using the single row hand drill. The crop was planted by maintaining a row to row and plant to plant distance of 45 cm and 10 cm, respectively. Plant density of twenty-two sesame plants m^{-2} was kept by thinning, which was done after the 18 days of sowing. In both study years, nitrogen (N) and phosphorus (P) was applied to all the experimental blocks as a basal dose at the rate of 50 kg ha^{-1} and 60 kg ha^{-1}, respectively and potassium (K) was not used for the experiment because the research site contains the sufficient amount of K. Urea and DAP (di-ammonium phosphate) was used as a source of N and P. The S was applied to all sub blocks as per treatment at the time of sowing. All the remaining agronomic practices were applied uniformly and timely on the basis of crop growth stage and demand. In both years, no irrigation was applied and the crop was grown from sowing to maturity on rainfall water. The crop was harvested by hand on twenty-third and twenty-fifth of November 2012 and 2013, respectively.

2.5. Measurements and Sampling

2.5.1. Changes in Sesame Leaf Area Index

Leaf area index (LAI) under different treatments was measured at the pre-flowering stage (PF), mid-flowering stage (MF), late-flowering stage (LF) and full-maturity stage (FM) of sesame in both years (Table 1). For this purpose, ten sesame plants from the middle rows of every sub block were destructively sampled with at least one meter away from the last sampling. To measure leaf area, we determined the maximum leaf width and length with a ruler, then leaf area of sesame varieties was calculated by multiplying the leaf width and leaf length. LAI of each sub block was calculated as the ratio of plant leaf area to ground area.

Table 1. Sesame physiological stages and periods were recorded in 2012 and 2013 at PMAS AAU, Rawalpindi, Pakistan by following the descriptions given by Langham [30].

Serial No.	Physiological Stage	Growth Period	DAS 2012 *	DAS 2013 *
1	Seed germination	Vegetative	04	03
2	Juvenile	Vegetative	23	21
3	Pre-flowering	Vegetative	35	35
4	Initiation of flowering	Pre-reproductive	37	36
5	Mid-flowering	Reproductive	65	65
6	Late-flowering	Reproductive	95	95
7	Physiological maturity	Reproductive	109	103
8	Full-maturity	Reproductive	125	125

* Plant samples were destructively sampled at 35, 65, 95 and 125 days after sowing (DAS) for biomass accumulation and partitioning analysis.

2.5.2. Photosynthetic Rate

The photosynthetic rate (Pn) of the sesame plants was measured by using a Li-6400 portable photosynthesis system (LI-COR Inc., Lincoln, NE, USA) equipped with an LED leaf chamber. In all treatments, five fully expanded leaves from sesame plants were selected at 35 (PF), 65 (MF) and 95 (LF) days after sowing (DAS) from all experimental blocks to measure photosynthetic rate. All the measurements were carried out from 11:00 am to 1:00 pm on a sunny day under a CO_2 concentration of 400 μmol mol^{-1}.

2.5.3. Biomass Sampling and Seed Yield

Every sub block was divided into 2 equal parts. One part was used to measure the total biomass accumulation (TBA) and partitioning in different plant parts of sesame. From this part ten consecutive sesame plants, excluding the five border plants, were destructively sampled at PF, MF, LF and MF on 35, 65, 95 and 125 DAS, respectively, then sampled plants were divided into different plant parts (leaves, stem, capsule and seed) and placed in oven for one hour at 105 °C to kill the tissues and then dried at 80 °C to obtain constant weight before weighing of each sample for total biomass accumulation and partitioning analysis. For seed yield determination twenty-two plants were harvested manually from the middle rows of every sub block using sickle at ground level when all the four replications mature fully (95% of capsule achieved mature capsule color). Then all the samples were sun dried for six days by keeping plants upright along the wall. Dried plants were threshed manually and weighed to calculate the seed yield of each plant and then converted into g m^{-2}.

2.5.4. Sulphur Uptake and Distribution

At PF, MF, LF and MF, plant samples were collected from the middle row of every sub-block and divided into stem, leaves, capsules and seeds. All samples were dried in the oven at 80 °C for 72 hours to obtain dry weight. The S content of stem, leaf, capsule and seed was determined using the Turbidimetric procedure [31]. The S content in different sesame plant parts was measured by multiplying the total biomass of every plant part with the S content and calculated in a kg ha^{-1}. The total sulphur accumulation (TSA) was calculated from the summation of the sulphur in all plant parts.

2.5.5. Economic Analysis

To evaluate the economics of S treatments and sesame varieties, an economic analysis was performed. Total expenditure for sesame production was included land rent, seedbed preparation, cost of seed and fertilizers (S, N and P), weeding and thinning, harvesting and shelling of sesame crop. Gross income was calculated according to the market price for sesame seed in Pakistan. In addition, net income (NI) was assessed by subtracting the total expenditure from gross income and benefit to cost ratio (BCR) was measured as the ratio of gross income to total expenditure [32,33].

2.5.6. Statistical Analysis

All the data obtained for every measurement at each growth stage was analyzed using the Statistix software (version, 8.1. Statistix, USA). Analysis of variance (ANOVA) technique was used to testify the overall significance of data. The LSD (least significance difference) test was used to compare the means at 0.05 probability level [34]. In addition, Microsoft Excel 2013 program was employed for the graphical presentation of data using ± SE (standard error).

3. Results

3.1. Effect of Sulphur Treatments on Leaf Area Index of Sesame

Leaf area index (LAI) of sesame varieties showed significant ($p < 0.05$) variations from 35 to 125 DAS in the different sulphur treatments (Figure 2). In both experimental years, the mean maximum LAI value of 2.3, 3.8, 3.2 and 1.7 was recorded for V_3, whereas minimum 1.7, 2.7, 2.5 and 1.13 LAI were observed in V_1, at PF, MF, LF and FM, respectively. The different levels of S treatment significantly increased the LAI, the averaged highest LAI value 2.3, 3.6, 3.1 and 1.57 was measured in treatment T_3, whereas averaged lowest LAI value was observed with T_1 treatment at PF, MF, LF and FM, respectively in both years. In addition, sesame plants under treatment T_3 showed the longer duration of green leaf area as compared to treatment T_1. For example, applying 40 kg S ha^{-1} led to an increase in leaf area index at FM by 29% in 2012 and 25% in 2013, suggesting that senescence of leaves was delayed in T_3

treatment (Figure 2). The changes in LAI of sesame varieties in 2013 in different S treatments were similar to those of last year.

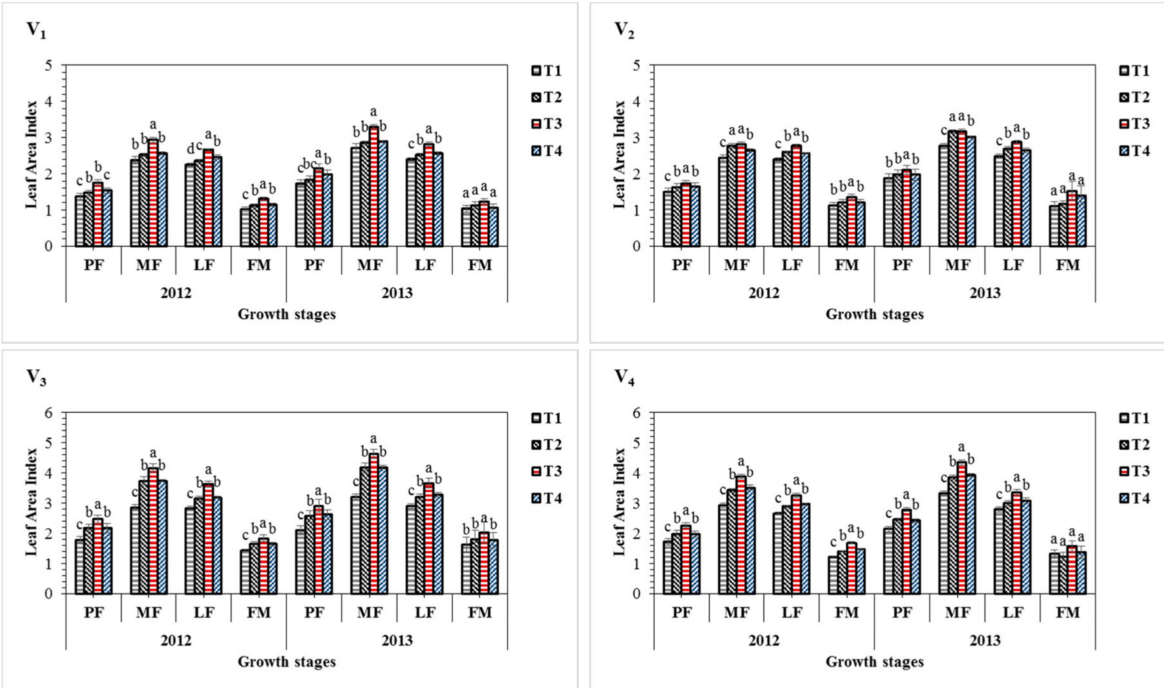

Figure 2. Variations in leaf area index (LAI) of sesame varieties as affected by sulphur treatments during 2012 to 2013 cropping season. PF, MF, LF and FM refer to four sesame growth stages pre-flowering, mid-flowering, late-flowering and full-maturity described by Langham (2007), $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$ and $\mathbf{V_4}$ represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. All the values are average of four replicates. Bars show ± standard errors, (n = 3). Bars with the same letter are not significantly different ($p < 0.05$).

3.2. Effect of Sulphur Treatments on Photosynthetic Rate of Sesame

To verify the variations in photosynthesis rate of sesame varieties in response to different S treatments in rainfed conditions, the photosynthetic rate of sesame leaves was measured at PF, MF and LF (Table 2). The S treatments and sesame varieties showed considerable effect on photosynthetic rate (Pn) with mean maximum Pn 22.7, 27.4 and 22.5 (mmol m^{-2} s^{-1}) at PF, MF and LF measured in V_3, while mean minimum Pn 20.6, 25.8 and 22.4 (mmol m^{-2} s^{-1}) at PF, MF and LF was recorded with V_1 in both study years. However, Pn was improved as S rate increased from 20 to 50 kg ha^{-1} (T_1 to T_4). The average highest Pn was 22.5, 27.5 and 22.4 at PF, MF and LF, respectively for 2012 and 2013 in treatment T_3. Overall, S fertilization increased Pn at PF, MF and LF by 9%, 8% and 10%, respectively in T_3 in comparison with T_1, showing that Pn was closely related with the changes in LAI.

3.3. Effect of Sulphur Treatments on Biomass Accumulation and Seed Yield of Sesame

The S treatments significantly increased total biomass accumulation (TBA) and demonstrated considerable differences among sesame varieties. The mean highest TBA was 429.3, 974.2, 1122.9 and 876.4 g m^{-2} with V_3, 425.5, 965.9, 1120.6 and 884.9 g m^{-2} under T_3 treatment at PF, MF, LF and FM, respectively (Table 3). Furthermore, applying 40 kg S ha^{-1} increased the TBA at maturity (FM) by 25% and 23%, in 2012 and 2013, than T_1 respectively. The S treatments changed the pattern of biomass partitioning among different plant organs of sesame varieties (Figure 3). During all growth stages (PF, MF, LF and FM) of sesame, the maximum allocation of biomass was observed in stem followed by leaves, capsule and seed. The biomass partitioning in reproductive parts (capsule + seed) was increased at LF and FM and the mean maximum biomass accumulation in the capsule (286.7 and 303.7 g m^{-2}) and seed (121.2 and 166.3 g m^{-2}) were found in sesame variety V_3. The S treatments increased the biomass partitioning to reproductive parts and highest biomass partitioning to the capsule (286.7 and 316.6 g m^{-2}) and seed (119.9 and 164.3 g m^{-2}) was observed in T_3 treatment at LF and FM, respectively. In addition, treatment T_3 substantially increased the allocation of biomass into reproductive parts than other treatments T_1, T_2 and T_4 (Figure 3; V_3). On average, at maturity (FM), capsule and seed biomass increased by 33% and 23% in comparison with T_1, respectively. Sulphur treatments considerably affected the seed yield. The seed yield of sesame varieties increased with S fertilization and seed yield in V_3 (162.1 and 170.6 g m^{-2} in 2012 and 2013, respectively) was significantly higher than other sesame varieties (V_1, V_2 and V_3). Maximum seed yield was obtained under T_3 (152.9 and 175.7 g m^{-2} in 2012 and 2013, respectively) treatment than other S treatments in both years. Relative to T_1 treatment, sesame plants under T_3 treatment produced 21% in 2012 and 24% in 2013 higher seed yield.

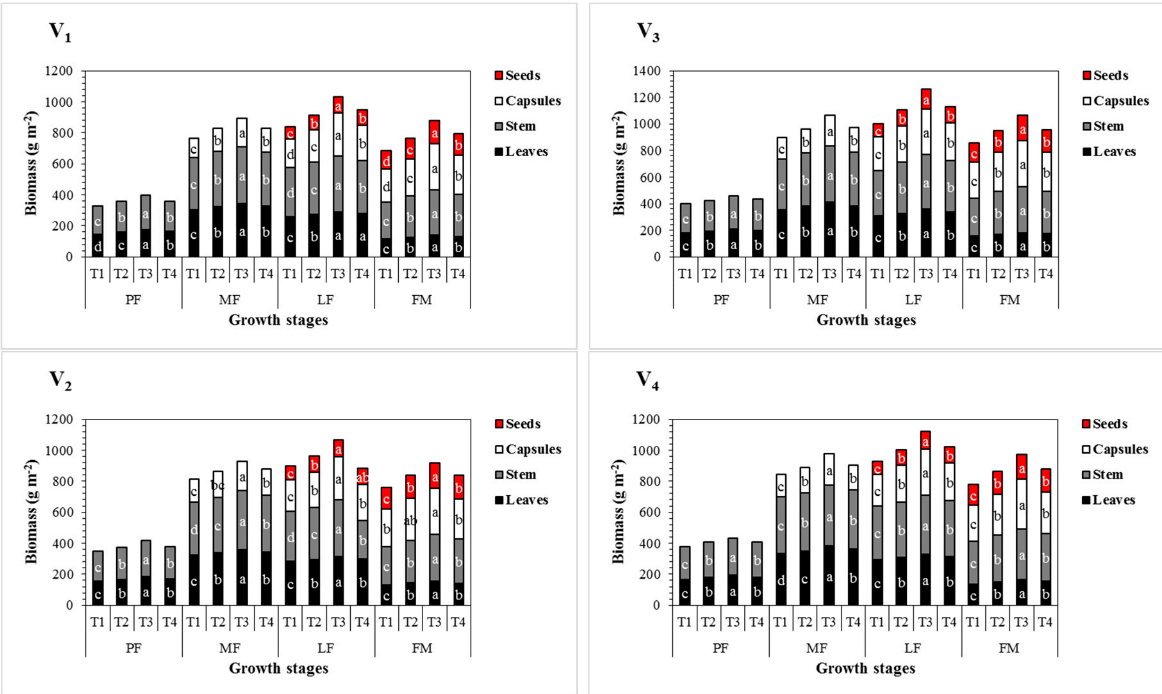

Figure 3. Biomass accumulation and partitioning in different plant parts of sesame varieties as affected by sulphur treatments averaged over 2012 and 2013 cropping seasons. PF, MF, LF and FM refer to four sesame growth stages pre-flowering, mid-flowering, late-flowering and full-maturity described by Langham (2007), $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$ and $\mathbf{V_4}$ represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. Within a bar, different lowercase letters show a significant difference (p < 0.05) between treatments. All the values are average of four replicates.

Table 2. Effect of sesame varieties and sulphur treatment on photosynthetic rate (mmol m^{-2} s^{-1}) at different growth stages.

Years			Pre-Flowering	Mid-Flowering	Late-Flowering
2012	Varieties (V)	V_1	20.4 ^{c}	25.2 ^{c}	19.7 ^{c}
		V_2	20.6 ^{bc}	25.4 ^{c}	20.5 ^{b}
		V_3	22.3 ^{a}	26.9 ^{b}	22.1 ^{a}
		V_4	21.6 ^{ab}	26.0 ^{b}	21.6 ^{a}
	LSD (0.05)		1.12	0.47	0.73
	Sulphur Treatments (T)	T_1	20.2 ^{d}	24.9 ^{c}	20.1 ^{d}
		T_2	21.1 ^{c}	25.8 ^{b}	20.8 ^{c}
		T_3	22.2 ^{a}	27.0 ^{a}	22.0 ^{a}
		T_4	21.6 ^{b}	25.9 ^{b}	21.1 ^{b}
	LSD (0.05)		0.39	0.22	0.28
	Interaction (V × T)		NS	*	NS
2013	Varieties (V)	V_1	21.1 ^{c}	26.2 ^{c}	20.5 ^{c}
		V_2	21.2 ^{bc}	26.5 ^{bc}	21.3 ^{b}
		V_3	23.0 ^{a}	27.9 ^{a}	22.9 ^{a}
		V_4	22.4 ^{ab}	26.9 ^{b}	22.4
	LSD (0.05)		1.11	0.54	0.73
	Sulphur Treatments (T)	T_1	20.9 ^{d}	25.9 ^{c}	20.8 ^{d}
		T_2	21.7 ^{c}	26.7 ^{b}	21.6 ^{c}
		T_3	22.8 ^{a}	28.0 ^{a}	22.8 ^{a}
		T_4	22.3	26.9 ^{b}	21.9 ^{b}
	LSD (0.05)		0.38	0.23	0.29
	Interaction (V × T)		NS	NS	NS

V_1, V_2, V_3 and V_4 represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. Means do not share the same letters in the column differ significantly at $p \leq 0.05$; * = Significant; NS = Non-significant.

Table 3. Effect of sulphur treatment on total biomass accumulation (TBA) grain yield of sesame varieties.

Years			Total Biomass Accumulation (g m^{-2})				Grain Yield
			PF	MF	LF	FM	(g m^{-2})
2012	Varieties (V)	V_1	335.5 ^{d}	785.3 ^{d}	883.5 ^{d}	648.4 ^{b}	128.5 ^{d}
		V_2	355.2 ^{c}	827.6 ^{c}	927.1 ^{c}	656.0 ^{b}	138.0 ^{b}
		V_3	404.0 ^{a}	931.3 ^{a}	1071.5 ^{a}	760.1 ^{a}	162.1 ^{a}
		V_4	379.5 ^{b}	858.6 ^{b}	969.1 ^{b}	697.6 ^{b}	133.8 ^{c}
	LSD (0.05)		9.97	16.25	12.91	54.42	2.88
	Sulphur Treatments (T)	T_1	339.4 ^{c}	786.4 ^{d}	866.9 ^{d}	612.4 ^{c}	126.0 ^{d}
		T_2	366.3 ^{b}	840.6 ^{c}	945.1 ^{c}	684.5 ^{b}	140.2 ^{c}
		T_3	400.9 ^{a}	922.1 ^{a}	1070.3 ^{a}	771.2 ^{a}	152.9 ^{a}
		T_4	368.4 ^{b}	853.6 ^{b}	969.1 ^{b}	694.1 ^{b}	143.1 ^{b}
	LSD (0.05)		4.30	8.14	8.70	12.3	2.57
	Interaction (V × T)		*	*	*	NS	*
2013	Varieties (V)	V_1	384.2 ^{d}	872.6 ^{d}	982.2 ^{d}	815.7 ^{c}	144.3 ^{c}
		V_2	404.0 ^{c}	913.5 ^{c}	1028.2 ^{c}	881.8 ^{b}	164.3 ^{ab}
		V_3	454.6 ^{a}	1017.1 ^{a}	1174.2 ^{a}	992.7 ^{a}	170.6 ^{a}
		V_4	432.6 ^{b}	945.7 ^{b}	1068.4 ^{b}	912.0 ^{b}	159.8 ^{b}
	LSD (0.05)		12.58	16.3	15.94	37.8	10.08
	Sulphur Treatments (T)	T_1	389.9 ^{c}	872.5 ^{d}	967.3 ^{d}	807.4 ^{c}	142.1 ^{c}
		T_2	415.0 ^{b}	928.0 ^{c}	1045.4 ^{c}	893.6 ^{b}	159.0 ^{b}
		T_3	450.0 ^{a}	1009.6 ^{a}	1170.9 ^{a}	998.5 ^{a}	175.7 ^{a}
		T_4	418.6 ^{b}	938.9 ^{b}	1069.3 ^{b}	903.7 ^{b}	162.2 ^{b}
	LSD (0.05)		4.70	7.97	8.44	13.63	5.38
	Interaction (V × T)		*	*	NS	NS	NS

PF, MF, LF and FM refer to four sesame growth stages pre-flowering, mid-flowering, late-flowering and full-maturity described by Langham [30], V_1, V_2, V_3 and V_4 represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. Means do not share the same letters in the column differ significantly at $p \leq 0.05$; * = Significant; NS = Non-significant.

3.4. Effect of Sulphur Treatments on Total Sulphur Accumulation and Distribution

The S treatments substantially increased total S accumulation and showed significant difference among sesame varieties (Figure 4). The peak TSA was reached at FM and LF in 2012 and 2013, respectively, while mean maximum TSA 8.6, 24.1, 38.1 and 37.6 was found with sesame variety V_3, 8.4, 23.9, 36.0 and 34.8 kg ha^{-1} was recorded under T_3 treatment at PF, MF, LF and FM in 2012 and 2013, respectively (Figure 3; V_3**)**. Differences among S treatments revealed that plant under T_3 treatment had accumulated 48% more S than T_1 treatment at FM. The pattern of S distribution in plant organs is shown in Figure 5 for all S treatments and sesame varieties. Large fluctuations were observed for S content in leaf, stem, capsule and seed at all growth stages. At PF and MF maximum distribution of S was observed in stem and leaves, whereas at LF and FM, there was a decline in stem and leaves S content among sesame varieties. The mean maximum S content in stem (13.5 mg g^{-1}), capsule (6.8 mg g^{-1}) and seed (10.2 mg g^{-1}) and leaf (13.7 mg g^{-1}) were found at FM and LF, respectively in sesame variety V_3, (13.1 mg g^{-1}), capsule (7.1 mg g^{-1}) and seed (8.2 mg g^{-1}) and leaf (12.8 mg g^{-1}) were observed at FM and LF, respectively. The S treatments increased stem, leaf, capsule and seed S content and mean highest S content in the stem (13.1 mg g^{-1}), capsule (7.1 mg g^{-1}) and seed (8.2 mg g^{-1}) and leaf (12.8 mg g^{-1}) were observed at FM and LF, respectively under treatment T_3. Overall, at harvest (FM) S treatment T_3 increased S content in seed by 46% as compared to T_1 (Figure 5).

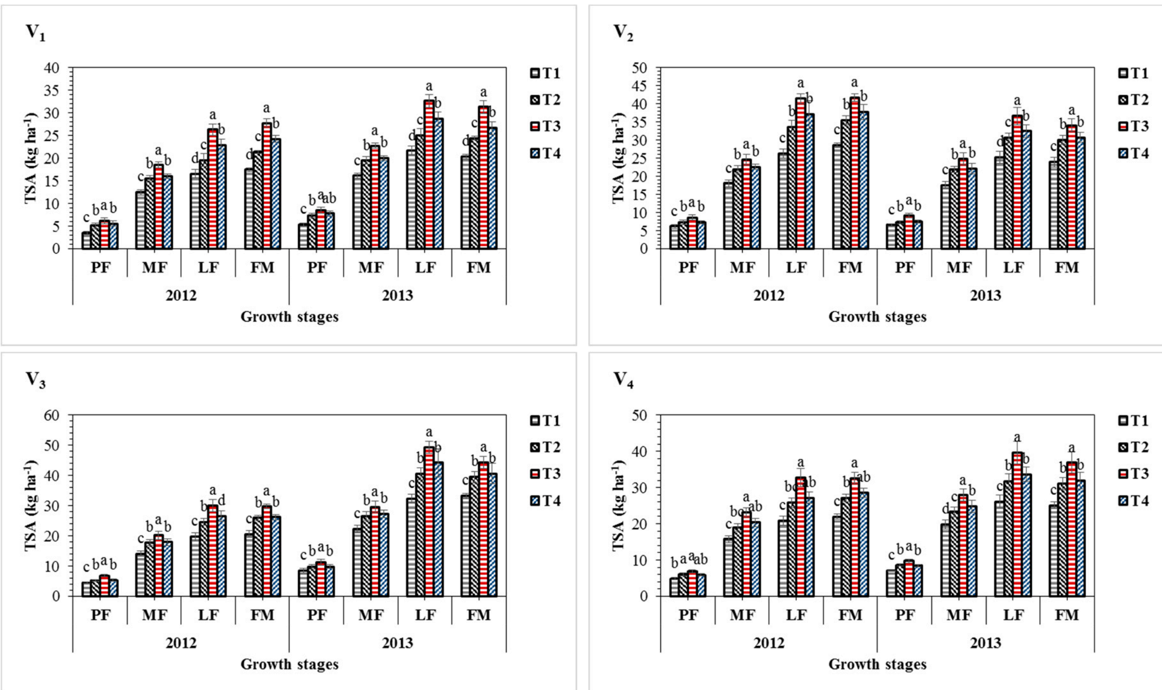

Figure 4. Total sulphur accumulation (TSA) in sesame varieties as affected by sulphur treatments during 2012 and 2013 cropping seasons. PF, MF, LF and FM refer to four sesame growth stages pre-flowering, mid-flowering, late-flowering and full-maturity described by Langham (2007), $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$ and $\mathbf{V_4}$ represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. Within a bar, different lowercase letters show a significant difference ($p < 0.05$) between treatments. All the values are average of four replicates.

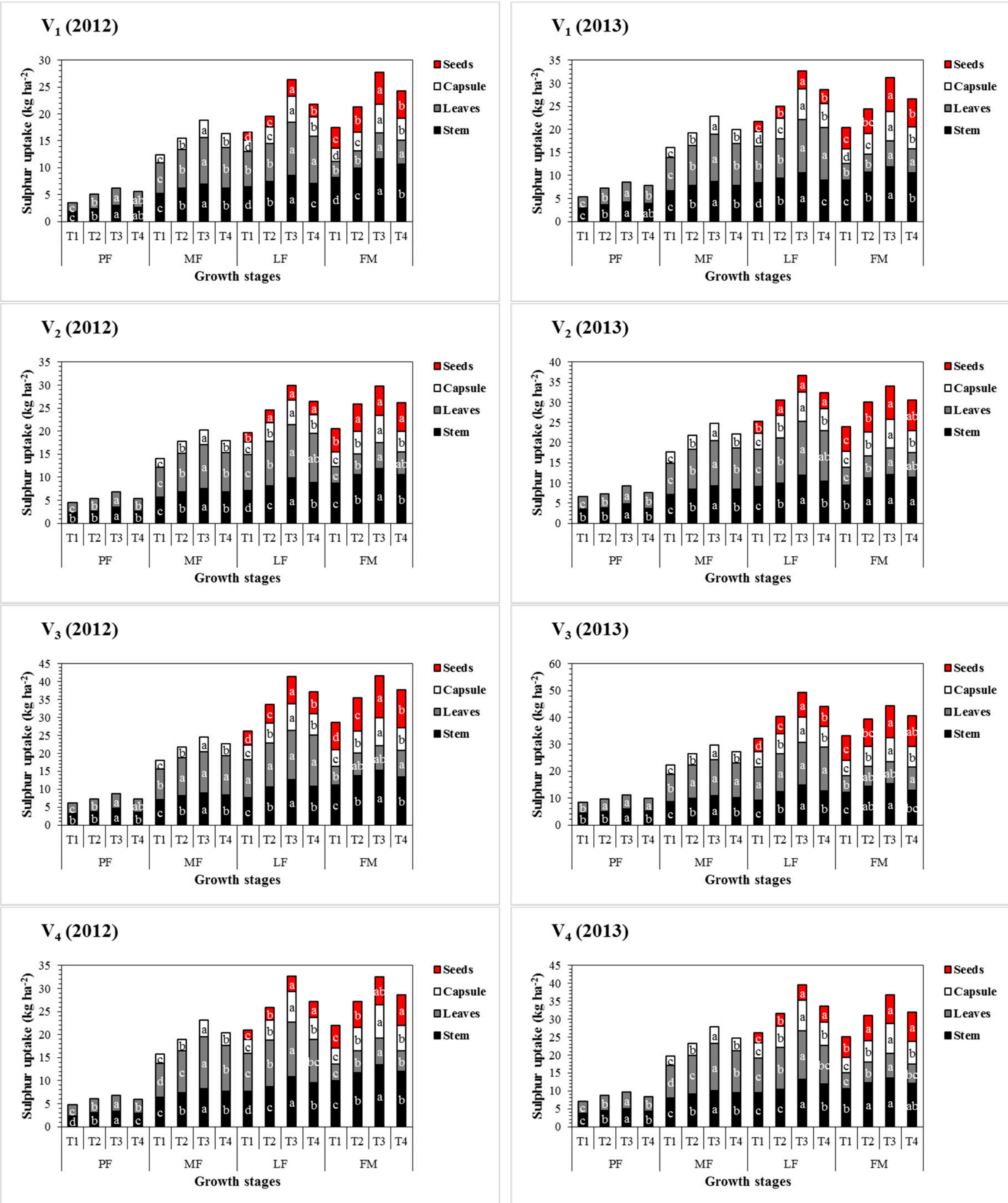

Figure 5. Sulphur distribution in different plant parts of sesame varieties as affected by sulphur treatments during 2012 and 2013 cropping seasons. PF, MF, LF and FM refer to four sesame growth stages pre-flowering, mid-flowering, late-flowering and full-maturity described by Langham (2007), $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$ and $\mathbf{V_4}$ represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively. Within a bar, different lowercase letters show a significant difference ($p < 0.05$) between treatments. All the values are average of four replicates.

3.5. Effect of Sulphur Treatments on Economic Analysis

Results of the economic analysis are presented in Table 4. In our field experiments, V_3 produced mean maximum net profit (NI) (924.0 US $ ha^{-1}) and BCR (3.3) as compared to other sesame varieties in both study years. Among S treatments, 40 kg S ha^{-1} (T_3) gave mean maximum NI (909.1 US $ ha^{-1} for 2012 and 924.0 US $ ha^{-1} for 2013) and BCR (3.2), while mean minimum NI (670.9 US $ ha^{-1} for 2012 and 924.0 US $ ha^{-1} for 2013) and BCR (2.7) were recorded with treatment (T_1) during both years. Overall, sesame varieties with 40 kg S ha^{-1} (T_3) had 36% higher NI as compared to 20 kg S ha^{-1} (T_1) treatment.

Table 4. Economic analysis (US $ ha^{-1}) for the effect of different sulphur treatments on sesame varieties performance under rainfed conditions.

Treatments	Total Expenses		Gross Income		Net Income		Benefit-Cost Ratio	
	2012	2013	2012	2013	2012	2013	2012	2013
V_1	405.1	402.9	1007.8	1179.4	602.7	776.5	2.5	2.9
V_2	407.5	405.3	1082.4	1342.8	674.8	937.5	2.7	3.3
V_3	410.0	407.7	1271.4	1394.3	861.4	986.6	3.1	3.4
V_4	412.5	410.1	1049.4	1306.1	637.0	896.0	2.5	3.2
T_1	405.1	402.9	988.4	1161.4	583.3	758.5	2.4	2.9
T_2	407.5	405.3	1100.5	1299.5	692.9	894.2	2.7	3.2
T_3	410.0	407.7	1199.9	1436.0	789.9	1028.3	2.9	3.5
T_4	412.5	410.1	1122.6	1325.7	710.1	915.6	2.7	3.2

V_1, V_2, V_3 and V_4 represent four sesame varieties SG-27, SG-30, SG-36 and SG-51 and T_1, T_2, T_3 and T_4, represent four sulphur treatments 20, 30, 40 and 50 kg S ha^{-1} respectively.

4. Discussion

The management of S for oilseed crops can improve crop produce and productivity in rainfed conditions. Previous studies have documented the positive impact of S fertilization on growth and development of cereal and oilseed crops [1,8]. However, the effects of S fertilization on biomass accumulation and partitioning to different plant parts in sesame varieties under rainfed conditions have remained largely undiscovered. The aims of this study were to investigate the response of sesame varieties to different S treatments and its impact on leaf area index, photosynthesis rate, seed yield and total biomass accumulation and partitioning at different growth stages (PF, MF, LF and FM). Leaf area index is an important component affecting crop growth and development [35], at 65 (MF) DAS, the LAI of all sesame varieties reached a maximum value in treatment T_3. Higher LAI resulted from S treatment indicates optimum leaf expansion, which helped in better interception and utilization of sunlight, after that LAI of all sesame varieties gradually decreased in all S treatments. This pattern might be because of reduction in crop canopy and senescence of older leaves [36,37]. However, we noted that sesame plants with the S treatments attained higher LAI (Figure 2), which might be due to longer duration of green leaf area and delayed leaf senescence [38,39].

Sesame is an oilseed C3 plant that features lower photosynthetic activity than C4 crops [40]. An increase in LAI can improve light use efficiency and seed yield by increasing the photosynthetic rate [41]. Moreover, photosynthesis rate (Pn) is affected by S fertilization and its deficiency reduce the Pn in oilseed crops [42]. In our experiment, S treatments increased the Pn of all sesame varieties, plants under T_3 (40 kg S ha^{-1}) and exhibited a maximum Pn at PF, MF and LF growth stages of sesame (Table 2). This increase in Pn might be due to the optimum availability of S during the early growth stages of sesame that might have improved the chlorophyll production and ratio between Rubisco and soluble protein in sesame plants. This result is similar to previously documented results, in which they reported that the S fertilization increases the chlorophyll content [43], photosynthesis rate [39] and maintains the balance between the ratio of Rubisco and soluble protein in oilseed crops [44]. Additionally, S fertilization to oilseed crops also decreases the uptake of toxic elements which are harmful to crops [45] The reason why the application of 40 kg S ha^{-1} (T_3) was adequate for Pn might be associated with the delayed leaf senescence (i.e., the longer leaf green area in V_3; Figure 4). This experiment provides the critical data on total biomass accumulation (Table 3). The enhanced photosynthetic rate is one of the major factors for biomass production in crops [46]. Previously, it had been described that S deficiency at early growth stages of oilseeds inhibited the plant growth potential and caused the reduction in total biomass production [47,48]. Our results proposed that an early application of 40 kg S ha^{-1} (T_3), sesame plants adequately absorbed and stored sulphur for their growth and physiological process and maintained maximum biomass production which ultimately increased the seed yield of all sesame varieties. This result was similar to previous findings [39,42]. Furthermore, it suggested that S fertilization accelerated the biomass production in all sesame varieties at PF, MF, LF and FM, this may be linked with the utilization and availability of important nutrients (N, P and K) as these essential nutrients increased with S fertilization in sesame [5].

We also assessed the biomass partitioning in stem, leaves, capsule and seed of sesame varieties in response to sulphur treatments (Figure 5). The biomass partitioning among plant organs changed significantly at PF, MF, LF and FM in all sesame varieties. At PF and MF, when reproductive parts were the weak sink, maximum translocation of biomass was noted in stems followed by leaves. After that, at LF the pattern of biomass partitioning re-translocated and major part of the biomass distributed to reproductive parts (capsule and seed) in all sesame varieties [49]. At LF, decreased the translocation of photosynthates to stem and leaves, while increased biomass partitioning to seed was observed under 40 kg S ha^{-1} application which might be due to increased translocation of assimilates to reproductive organs at maturity [6,7,50,51]. Moreover, previous researchers reported the photosynthetic ability of pea [52] and soybean [53]. It is possible that S treatments initiated the photosynthetic activity of capsule and accelerated the utilization of assimilates from the stem for seed growth. In the present experiment, seed yield of sesame varieties was increased with S fertilization. This increase in seed yield might be due to the improvement in LAI, the synthesis of additional chlorophyll content, higher photosynthetic rate and cell division, more translocation of photosynthates towards capsule and seed than vegetative parts because higher partitioning of photosynthates towards sink increased with S fertilization [54] Furthermore, seed yield is related to the crop growth rate of crops [55] and 40 kg S ha^{-1} considerably increased the growth rate of sesame varieties under rainfed conditions [6]. The TSA by sesame varieties was improved by applying S at the rate of 40 kg ha^{-1} (T_3) however, the level of response varied among sesame varieties (Figure 4). Our results are in accordance with the previous studies that revealed that S accumulation in sesame plants was increased with the increased application of S, sesame and oilseed rape has shown to accumulate sulphur up to 40 and 100 kg ha^{-1}, respectively [7,12]. The highest TSA observed in this study is attributable to both optimum availability of S during the early growth stages of the crop which in turn increased the total biomass production. Therefore, we concluded that in S deficient field areas, application of S can promote the vegetative and reproductive growth of sesame plants under rainfed conditions. The S distribution in different plant organs significantly changed in all sesame varieties. The S content in stems, leaves, capsules and seeds of V_3 was recorded considerably higher than other sesame varieties (V_1, V_2 and V_4) as a result of higher biomass accumulation and partitioning in reproductive parts (Figure 3). Our findings are consistent with the results of others, they reported changed S distribution in different plant tissues using different sesame and rapeseed [7,12,51].

Local farming communities only adopt that new innovation or technology which produces more profit with fewer expenses [56]. In our present experiment, the economic analysis revealed that higher profit (net return) and BCR were obtained by applying 40 kg S ha^{-1} to sesame variety V_3 in both years than other S treatments and sesame varieties (Table 4). Results of the present study revealed that S fertilization significantly increased the total biomass accumulation and distribution towards the reproductive parts in all sesame varieties under rainfed conditions and gave maximum profit to the farmer.

5. Conclusions

The S fertilization to sesame plants grown in rainfed conditions led to increase in total biomass accumulation and seed yield. This increase in seed yield of sesame varieties was probably attributed to increased leaf area index and photosynthetic rate at the critical crop stages (PF, MF and FM) of sesame varieties. The early accumulation of sulphur helped the crop to partition more biomass towards seed than other plant parts in sesame. A prominent seed yield of V_3 may be the result of higher biomass accumulation and better adaptability to the prevailing climatic conditions and higher accumulation of sulphur in V_3 may be attributed to the genetic differences among the genotypes. Differences among S treatments revealed that plant under T_3 treatment had accumulated 48% more S than T_1 treatment and increased S content in seed by 46% at full-maturity. In addition, 40 kg S ha^{-1} substantially increased the NI and BCR of sesame crop under rainfed conditions. Therefore, our results suggest that early application of sulphur can increase total biomass accumulation and distribution towards reproductive parts than other plant parts in oilseed crops under rainfed conditions. Further studies are required to elucidate the effect of various nutrients on the biomass accumulation and partitioning for making the appropriate nutrient application decisions. Moreover, by the selection of an appropriate crop variety and S level, we can obtain higher seed yield and NI in arid areas. To the best of our knowledge, this experiment is the first to report the effect of S fertilization on biomass accumulation and partitioning in sesame varieties at different growth stages under rainfed conditions.

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