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EFFECT OF SULFUR AND APPLICATION STAGES ON YIELD AND YIELD COMPONENTS OF SOYBEAN

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Abstract

Soybean is a vital crop for food and oil production, yet its yield and quality are often compromised by suboptimal nutrient management. This study aimed to address this issue by investigating the effects of sulfur and its time of application on soybean at the Research Farm of The University of Agriculture Peshawar during Kharif season of 2022. The experiment followed a randomized complete block design with three replicates. It aimed to evaluate the effects of four sulfur levels (0, 20, 40, and 60 kg ha-1) applied at three different growth stages (S1=sowing, V3=vegetative, and R1=flowering) using elemental sulfur as the sulfur source. The results showed significant impacts, particularly when sulfur was applied at a rate of 40 kg ha-1. This treatment extended days to flowering (56), improved yield components as well as biological (7917 kg ha-1) and seed yield (2882 kg ha-1). Sulfur at 40 kg ha-1 positively influenced oil content (18.95%), elevated oil yield (571 kg ha-1) and protein content (32.39%). In contrast supplementation of sulfur at 60 kg ha-1 extended days to maturity and improved the harvest index. Regarding application stages sulfur applied at V3 stage delayed flowering (56), increased leaves count and plant height. Application at R1 stage increased days to maturity (129), yield components, biological and seed yield (7992 and 2806 kg ha-1, respectively), oil content and yield (556 kg ha-1, 19.54%, respectively). Moreover, yield and yield components showed positive correlation with quality components of soybean. In last, economic analysis revealed high net benefit and BC ratio by applying 40 kg ha-1 of sulfur. In conclusion, applying 40 kg ha-1 of sulfur at the R1 stage is highly effective and economically feasible in enhancing soybean yield and quality under the agro-climatic conditions of Peshawar. Future research should explore the long-term effects of sulfur application on soil health and productivity, as well as the economic feasibility of these practices for large-scale adoption

Keywords: *Growth stages, Oil content, Plant height, Protein content, Peshawar, Soybean yield, Sulfur levels*

Introduction

Soybean is an annual summer crop originated from East Asia and is extensively cultivated for its consumable beans. It contributes significantly to global oilseed production, representing 58 %, and constitutes 69 % of the protein meal consumed by cattle worldwide. Soybean is regarded as one of the paramount protein and oil crops on a global scale. Its cultivation holds immense significance in the agricultural sector. It has proven to be a globally viable industrial and commercial oilseed crop and known as the 'Golden Bean' due to its excellent nutritional content. The crop has generated 9.47 million tons production of soybean after being planted on 8.85 million hectares throughout the world (Berger et al., 2010). Because of its nutritional value, their bi-products such as soya milk, soybean sprouts, and soya nuts, various types of tofu, cottage, cheese, and curd are in high demand. Soybeans are grown all over the world, yielding 276,406,003 tons with over 30% produced in America. Given its remarkable adaptability across diverse industries, soybean holds high economic value on a global scale, estimated at a staggering 119,516 million US dollars. Furthermore, beyond its economic impact, soybean also plays a role in mitigating symptoms associated with certain chronic conditions (Kahraman, 2017). For soybean production to keep up with the expected global population growth rate, several hurdles must be overcome. In Khyber Pakhtunkhwa and Pakistan, annual soybean production is 46 and 66 tons with 54 and 84 hectares of planted area (MNFS&R, 2014) that is not in tandem with its demand.

Sulfur, as an integral component of sulfur-containing amino acids and various metabolites, serves a critical role in various plant growth and developmental processes. Acknowledged as the 4th primary nutrient following nitrogen, phosphorus, and potassium, sulfur's significance in sustaining plant health and growth is widely recognized. Sulfur's significance in soybean seed development has been well documented a number of investigators have reported (Dubey et al., 1995). Sulfur interacts with nitrogen in soybeans, affecting nitrogen metabolism and utilization efficiency, making it vital for proper seed development and yield (Głowacka et al., 2023). Various stages of S application have a substantial impact on the quality, growth, and productivity of canola. Oil, glucosinolate, and protein content are all improved when 20 kg ha^{-1} S is applied at plantation (Ahmad et al., 2007). Sulfur application at planting time increased maturity in canola, but there was no change in plant height whether sulfur was treated at the sowing or flowering stage. When S was administered after 42 days of seeding, it resulted in lower seed production on one site, but better seed yield and improved S absorption both in seed and biomass when treated earlier (Karami et al., 2016). Sulfur is required for many plant growth and developmental processes. Plant nutrient deficiencies are the most significant restrictions to crop growth. Sulfur is important element affecting plant growth and yield in the soil (seervi et al., 2018).

Sulfur is essential for numerous plant processes, including photosynthesis, chlorophyll production, and nitrogen fixation and is required for protein synthesis. Cysteine and methionine are two sulfur-containing amino acids found in soybean crops. Soybean uses nearly the same amount of sulfur as they use phosphorus (Paul et al., 2019). Sulfur application can result in increased soybean yield and dry matter. However, lack of sulfur can result in increased nitrates in soybean seeds (Zhao et al., 2006). When sulfur levels are low, deficiency can occur, causing pale green colour, diminished plant growth and plants require sulfate ion (SO_4), and however, elemental sulfur is still not plant-available and should be transformed to the sulfate form by soil bacteria. Sulfur (Vora et al., 2018). Maintaining an optimal level of sulfur in the soil is pivotal for promoting the production of substantial quantities of high-quality seeds of soybean. Generally, adequate sulfur application significantly enhances both crop growth and the quality of oilseed crops by amplifying protein and oil content (Ahmad et al., 2018). To optimize seed and oil yield, sulfur should be administered in split doses. This approach ensures that the crop receives adequate sulfur throughout its growth and development stages. Applying sulfur in split doses ensures a continuous supply of these essential nutrients to the crop. Notably, applying sulfur before flowering is particularly advantageous as it enhances both the photosynthetic efficiency and the crop's potential yield. It's crucial to note that after the flowering stage, the crop ceases to expand its foliage, limiting further enhancement in yield potential, emphasizing the significance of timely sulfur application before this critical growth stage (Ahmad et al., 2011).

Because the majority of soils in soybean-growing areas are poor in accessible sulfur, and their correct time of application is still in doubt. A systematic study of sulfur nutrition is required in order to increase soybean productivity. Therefore, a trial was performed by subjecting soybean crop to various sulfur levels applied at different application stages to find out the best level and time of application in Peshawar region.

MATERIALS AND METHODS

The experiment was conducted during the summer of 2022 at the University of Agriculture Peshawar, utilizing a randomized complete block design (RCBD) with three replications. Each plot measured 3 meters by 4 meters, providing a net area of 12 m^2. Within each plot, six rows were planted, with a spacing of 50 cm between each row. The study involved the commencement of four sulfur levels (0, 20, 40, and 60 kg ha^{-1}) at three stages: during sowing, at the vegetative stage (V3), and at the flowering stage (R1). These factors were chosen for ensuring the nutrient is available at critical stages to support optimal development, yield and quality and to evaluate which level and which time of application is the best. Elemental sulfur served as the sulfur source, and the Malakand-96 variety was planted at a rate of 80 kg ha^{-1}. To fulfill the requirement of micronutrients, N, P and K were applied at 40, 40 and 20 kg ha^{-1} from urea, DAP and MOP, respectively. Three irrigation sessions were conducted throughout the season: the first three weeks after emergence, the second at the flowering stage, and the third during the pod-filling stage. Manual weeding was performed using a hand hoe, and all necessary cultural practices were consistently applied throughout the trial duration. Following parameters were studied during the trail.

Days to flowering and maturity

It was collected by tallying the days from the initial planting date to the emergence of flowers within each individual plot. Similarly, the maturity days of the crop were documented by tracking the duration from the sowing date to the point at which the pods exhibited a yellowish color within each subplot.

Growth attributes

Plant height (cm) measurements were collected by randomly selecting four plants within each plot and measuring from the base to the top of the plant. These measurements were then averaged to represent the overall plant height for that specific plot. Similarly, the number of leaves per plant was determined by randomly selecting five plants within each plot and counting the number of leaves on each plant. The counts were then averaged to obtain the number of leaves per plant for the entire plot.

Yield and yield attributes

At maturity, pods on five selected plants from the two central rows were counted and averaged to determine pods per plant. For pod length, ten pods were randomly selected from five plants within each plot and measured, with the average length calculated. To record thousand grain weight (TGW), mature pods were dried, and the weight of 100 grains was multiplied by 10. Biological yield (kg ha^{-1}) was obtained by sun drying and weighing the harvested central two rows. Grain yield (kg ha^{-1}) was determined by drying, threshing, and weighing the yield from the central two rows. The harvest index was calculated by dividing grain yield by biological yield and multiplying by 100.

Soy bean quality

To determine oil content, a 2-gram dried sample was placed in a paper thimble attached to a Soxhlet extractor. Ether extracted the components over 5 hours, with the residue dried in an oven at 70-80°C for 2 hours, then weighed. Oil content percentage was calculated following AOAC (1990) guidelines. Oil yield (kg ha-1) was obtained by multiplying the oil content percentage by the total seed yield (kg ha-1) from each subplot, then dividing by 100. Protein content of soybean grains was assessed using the Kjeldahl distillation method following sulfuric acid mineralization (Kjeldhal, 1883).

Economic analysis

Economic yield was obtained by below mentioned equation:

$$\text{Economic yield} = \frac{\text{Total cost}}{\text{Total income}}$$

Statistical analysis

The collected data were analyzed using analysis of variance (ANOVA) tailored for the randomized complete block (RCB) design. Post hoc comparisons were conducted using the least significant difference test to determine significant differences between treatment means at a probability level of 0.05 (Jan et al., 2009).

Table 1 Physiochemical properties of experimental soil before plantation at various depths.

Physiochemical properties of soil	Analyzed values	
Soil depth (cm)	0-20	20-40
Texture	Silt loam	
pH	7.1	7.6
Moisture content (%)	7.41	9.38
Bulk density (gcm^{-3})	1.68	1.71
Porosity (%)	39	36
Organic matter (%)	0.27	0.16
% sand	20.56	20.85
% silt	66.12	65.98
% clay	13.32	13.17
Soil total nitrogen (mg kg^{-1})	513	487
Available P (mg kg^{-1})	14.54	12.79
Available potassium (mg kg^{-1})	82.76	81.89

RESULTS

Soil analysis of the experimental site was conducted before commencing the field trial to determine soil physicochemical properties. It was observed during the analysis that the soil at the experimental site has a silt loam texture. The recorded values for pH, moisture content, bulk density, porosity, organic matter, soil total nitrogen, available phosphorus, and potassium at depths of 0-20 cm and 20-40 cm are presented in Table 1. Moreover, data on various parameters of soybeans are presented below.

Days to flowering

Significant impacts of sulfur levels and application stages were observed on both growth stages (Table 2). However, the interaction between sulfur levels and application stages was not significant. Delayed flowering, occurring at 56 days, was noted with the use of 40 kg S ha^{-1}, while earlier flowering, at 52 days, was observed in the control plots. Similarly, delayed physiological maturity, with 128 days, was recorded in units treated with 60 kg ha^{-1} sulfur, whereas control plots exhibited earlier maturity at 125 days. Application of sulfur at the vegetative stage resulted in delayed flowering with 56 days compared to the sowing stage and control plots. Moreover, plants treated with sulfur at the flowering stage took 129 days to reach maturity compared to those treated at the vegetative stage, with control plots exhibiting the earliest maturity at 124 days.

Table 2 Physiology and growth of soybean under different sulfur levels applied at various application stages.

Application stages (APP)	Days to flowering	Days to Maturity	Plant height (cm)	Leaves plant^{-1}
At sowing stage	52 c	124 c	66 b	112 c
At V3 stage	56 a	127 b	68 a	119 a
At R1 stage	55 b	129 a	67 a	115 b
$LSD_{(0.05)}$	1	1	2	2
Sulfur levels (S)				
Control	52 d	125 d	65 c	109 d
20 kg ha^{-1}	54 c	126 c	67 b	114 c
40 kg ha^{-1}	56 a	127 b	69 a	122 a
60 kg ha^{-1}	55 b	128 a	68 ab	117 b
$LSD_{(0.05)}$	1	2	1	3
APP×S	ns	ns	ns	ns

The use of different alphabetic labels within the same groups indicates statistically significant differences at a 5% probability level.

Growth attributes

Significant variations were observed in growth parameters due to sulfur levels and application timings, although the interaction between these factors was not significant (Table 2). Plants treated with 40 kg ha^{-1} sulfur reached maximum height (69 cm), followed closely by those treated with 60 kg ha^{-1} sulfur (68 cm), while control plots had the minimum height (65 cm). Similarly, subplots treated with 40 kg ha^{-1} sulfur exhibited the highest leaf count (122), with 60 kg ha^{-1} sulfur treatments closely behind (117 plant^{-1}), whereas control plots had the lowest leaf count (109 plant^{-1}). Regarding application stages, plants treated with sulfur at the vegetative stage (V3) displayed maximum plant height (68 cm) and leaf count (119 plant^{-1}), while those treated at the flowering stage (R1) had slightly lower values (67 cm and 115 plant^{-1}, respectively).

Yield and yield attributes

The data analysis revealed significant effects of sulfur levels and application stages on yield and yield attributes of soybean. However, the interactive effect of sulfur rates on various application stages (APP×S) remained non-significant (Table 3). Significant influence of sulfur levels and application stages on pods per plant was observed, with 40 kg S ha^{-1} resulting in the highest pod count (69 pods) compared to the control (62 pods). Application at the flowering stage (R1) produced the highest pods per plant (66), followed closely by the vegetative stage (V3) treatment (65 pods), while the control had the lowest count (64 pods). For pod length, 40 kg ha^{-1} sulfur resulting in the longest pods (4.58 cm) compared to the control (3.94 cm). The flowering stage (R1) application also yielded the longest pods (4.50 cm), while the control had the shortest (4.14 cm). TGW varied significantly across different application stages and sulfur levels, with the highest weight observed at the R1 stage (149 g) and with 60 kg ha^{-1} sulfur supplementation (149 g), while the control had the lowest TGW (142 g).

As for biological yield, applying 40 kg S ha^{-1} resulted in the highest biological yield of 7917 kg ha^{-1}, while the control treatment yielded the minimum at 7745 kg ha^{-1}. The experimental units treated with 40 kg ha^{-1} sulfur exhibited the highest grain yield of 2882 kg ha^{-1}, followed by 60 kg ha^{-1} sulfur, yielding 2739 kg ha^{-1}. Conversely, the control displayed the lowest grain yield of 2547 kg ha^{-1}. Moreover, 60 kg ha^{-1} sulfur exhibited the maximum harvest Index of 36.78%, followed by 40 kg ha^{-1} sulfur, showing a Harvest Index of 34.67%. Conversely, the control plots demonstrated the minimum Harvest Index of 32.92%. Regarding application stages, introducing sulfur at flowering stage exhibited the highest biological yield at 7992 kg ha^{-1}, while the lowest yield was recorded when sulfur was applied at the sowing stage, producing 7633 kg ha^{-1}. Similarly, for grain yield (kg ha^{-1}), the highest yield of 2806 kg ha^{-1} was achieved when sulfur application coincided with the flowering stage (R1). Following closely, the treatment during the vegetative stage (V3) resulted in a yield of 2717 kg ha^{-1}. Conversely, the lowest yield of 2588 kg ha^{-1}was observed with sulfur introduced at the stage of planting. The harvest index of soybean remained unaffected regardless of applying sulfur at various growth stages of soybean (Table 4).

Table 3 Yield and yield related attributes of soybean under different sulfur levels applied at various application stages.

Application stages (APP)	Pods plant^{-1}	Pod length (cm)	Thousand grain weight (g)	Biological yield (kg ha^{-1})	Grain yield (kg ha^{-1})
At sowing stage	64 b	4.14 b	143 c	7633 c	2588 c
At V3 stage	65 a	4.31 b	146 b	7884 b	2717 b
At R1 stage	66 a	4.50 a	149 a	7992 a	2806 a
$LSD_{(0.05)}$	1	0.2	2	59	117
Sulfur levels (S)					
Control	62 d	3.94 d	142 c	7745 c	2547 c
20 kg ha^{-1}	64 c	4.31 c	145 b	7830 b	2645 bc
40 kg ha^{-1}	69 a	4.58 ab	147 ab	7917 a	2882 a
60 kg ha^{-1}	66 b	4.45 a	149 a	7855 ab	2739 b
$LSD_{(0.05)}$	2	0.2	2	69	101
APP×S	ns	ns	ns	ns	ns

The use of different alphabetic labels within the same groups indicates statistically significant differences at a 5% probability level.

Soy bean quality

Mean data regarding quality of soybean showed significant variations when subjected to different sulfur levels at various application stages. The interactive effect (APP×S) remained non-significant expect for protein content (Table 4). The highest oil content (18.95%) and oil yield (571 kg ha^{-1}) were recorded in plots treated with 40 kg ha^{-1} sulfur, followed closely by those treated with 60 kg ha^{-1}sulfur (18.15% oil content and 534 kg ha^{-1}oil yield). Conversely, control plots exhibited the lowest oil content (16.90%) and oil yield (448 kg ha^{-1}). Application at the flowering stage (R1) resulted in the highest oil content (19.54%) and oil yield (556 kg ha^{-1}), while the lowest values were observed when sulfur was applied at sowing. In terms of protein content, the highest protein content (32.39%) was achieved with 60 kg ha^{-1} sulfur, while the control plots exhibited the lowest protein content (29.77%). among application stages, the highest protein content (34.28%) was recorded when sulfur was applied at the flowering stage (R1), while the lowest content (29.15%) was observed at the sowing stage.

Table 4 Yield and yield related attributes of soybean under different sulfur levels applied at various application stages.

Application stages (APP)	Harvest index (%)	Oil content (%)	Oil yield (kg ha^{-1})	Protein content (%)
At sowing stage	33.95	16.67 c	462 c	29.15 b
At V3 stage	34.50	17.50 b	520 b	29.96 b
At R1 stage	35.17	19.54 a	556 a	34.28 a
$LSD_{(0.05)}$	ns	0.71	11	1.07
Sulfur levels (S)				
Control	32.92 c	16.90 c	448 d	29.77 c
20 kg ha^{-1}	33.79 bc	17.60 bc	496 c	30.80 bc
40 kg ha^{-1}	34.67 b	18.95 a	571 a	31.56 ab
60 kg ha^{-1}	36.78 a	18.15 ab	534 b	32.39 a
$LSD_{(0.05)}$	1.47	0.82	13	1.23
APP×S	ns	ns	ns	**

The use of different alphabetic labels within the same groups indicates statistically significant differences at a 5% probability level.

Association between different attributes under different sulfur levels at various application stages in soybean

Scatter plots explained the association between studied variable when evaluated against different sulfur levels applied at various growth stages. It was found out that plant height was positively associated with biological yield and leaves number plant^{-1} with a Pearson's correlation coefficient (R^2) of 0.56 and 0.80, respectively (Figure 1). The increase in biological yield and leaves number was prominent when the height of plants improved. The association of grain yield with pods plants^{-1} and TGW was not significant (P = 0.07 and 0.51, respectively).

However, the correlation was observed to be positive between grain yield and oil yield (R^2 = 0.66) that showed that improvement in oil yield was notable when grain yield of soybean was increased (Figure 2). Moreover, positive and significantly higher correlation was observed between oil and protein content (R^2 = 0.92) that revealed synergistic effect between oil and protein content of soybean (Figure 3

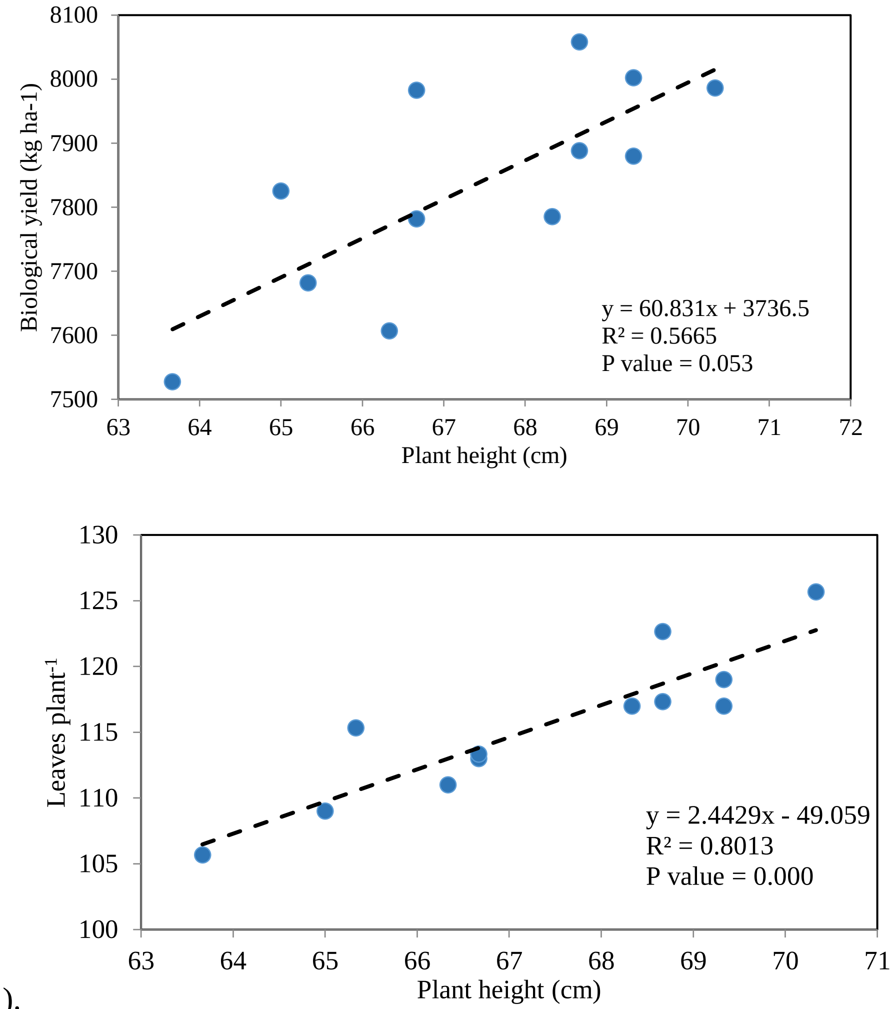

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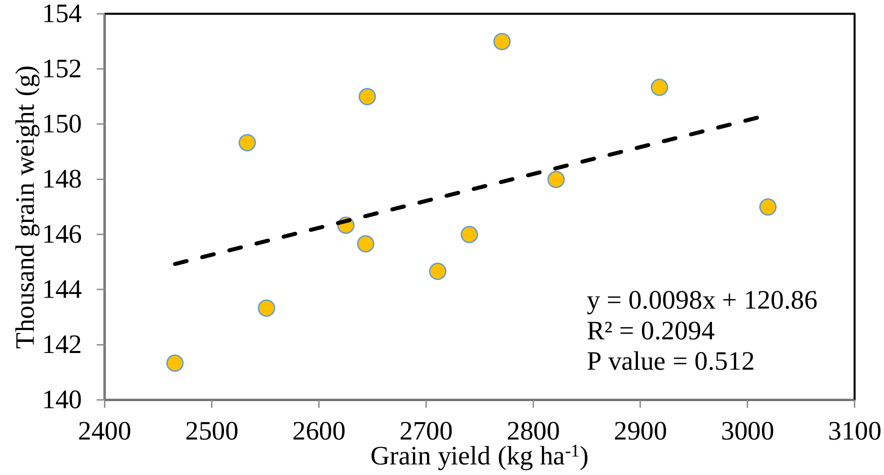
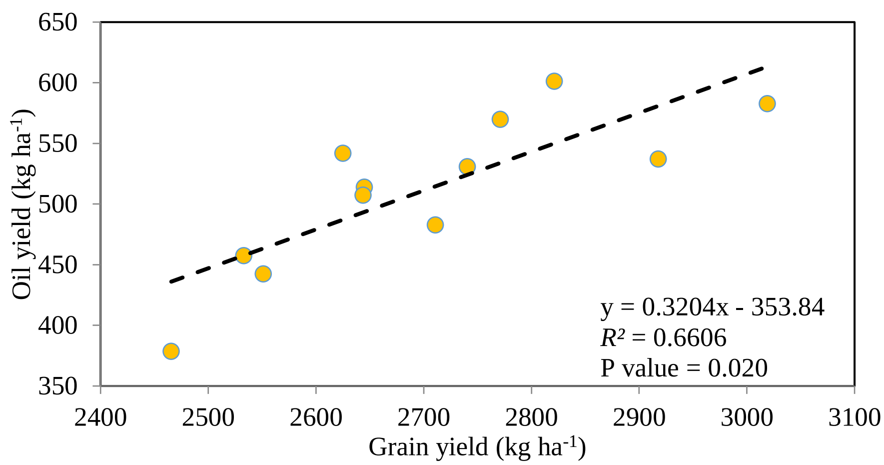
Figure 1: Scatter plots for plant height VS biological yield and leaves plant-1 under different sulfur levels applied at various application stages


Thousand grain weight (g)
154
152
150
148
146
144
142
140
2400
2500
2600
2700
2800
2900
3000
3100
Grain yield (kg ha-1)
y = 0.0098x + 120.86
R² = 0.2094
P value = 0.512


Oil yield (kg ha-1)
650
600
550
500
450
400
350
2400
2500
2600
2700
2800
2900
3000
3100
Grain yield (kg ha-1)
y = 0.3204x - 353.84
R² = 0.6606
P value = 0.020

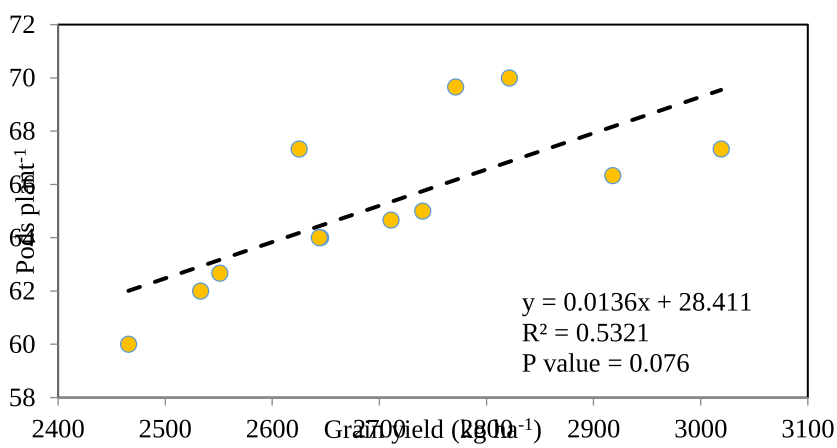

Pods plant-1
72
70
68
62
60
58
2400
2500
2600
2700
2800
2900
3000
3100
Grain yield (kg ha-1)
y = 0.0136x + 28.411
R² = 0.5321
P value = 0.076

Figure 2: Scatter plots for Grain yield VS pods plant-1, TGW and oil yield under different sulfur levels applied at various application stages.

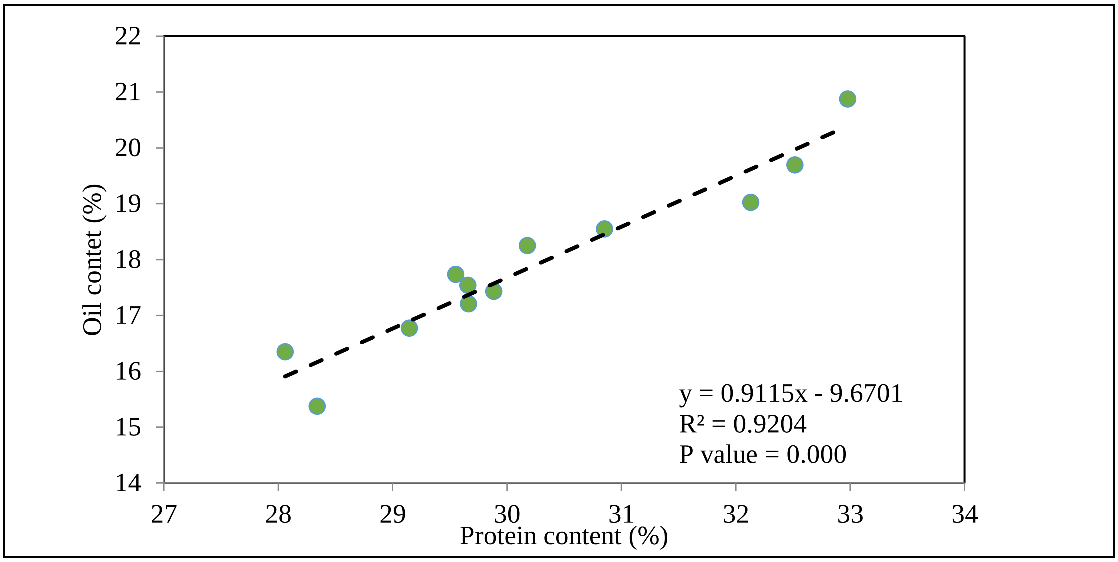


Figure 3: Scatter plots for Protein content VS oil content under different sulfur levels applied at various application stages

Economic analysis

In our finding economic analysis indicated that the net profit from harvest of the soybean was more than the cost on its cultivation. Data regarding economic study of the production from soybean are presented in Table 5. It presents the total experimental field area (432 m^{-2}), which included labor cost (Rs.700 day^{-1}), seed cost (Rs.250 @ Rs.80 kg^{-1}), elemental sulfur cost (Rs.180), straw cost (Rs.5 kg^{-1}), urea cost (Rs.72 kg^{-1}) and cost of SSP (Rs.36 kg^{-1}). Maximum net income (206334 /-) was obtained when 40 kg sulfur ha^{-1} was introduced at reproductive stage as compared to control (186494 /-).

Table 5: Economic analysis of soybean as affected by sulfur levels and application stages

Production Technology	Production (kg ha^{-1})		Output Value (Rs. ha^{-1})			Total Charges (Rs. ha^{-1})						Net income	BCR
Sulfur Levels (kg ha^{-1})	Grain yield	Straw yield	Grain value	Straw value	Gross income	N cost	P cost	Sulfur cost	Labor cost	Seed cost	Total cost		
0	2547	7745	178290	38725	217015	596	155	0	5600	20000	26351	190664	6.9
20	2645	7830	185150	39150	224300	596	155	4320	5600	20000	30671	193629	6.2
40	2882	7917	201740	39585	241325	596	155	8640	5600	20000	34991	206334	5.5
60	2739	7855	191730	39275	231005	596	155	12960	5600	20000	39311	191694	4.6
Application Stages													
Sowing	2588	7633	181160	38165	219325	596	155	6480	5600	20000	32831	186494	5.6
Vegetative	2717	7884	190190	39420	229610	596	155	6480	5600	20000	32831	196779	4.9
Reproductive	2806	7992	196420	39960	236380	596	155	6480	5600	20000	32831	203549	6.1

Whereas,

Price of soybean seed kg^{-1} = Rs. 250

Price of straw kg^{-1} = Rs. 5

Price of grain kg^{-1} = Rs. 70

Cost of sulfur kg^{-1} = Rs. 180

Cost of urea (N) kg^{-1} = Rs. 72

Cost of ssp. (P) kg^{-1} = Rs. 36

Labor charges day^{-1} = Rs. 700

DISCUSSION

The analyzed results showed that sulfur levels and application stages notably impacted the phonological development, specifically the duration taken for flowering and physiological maturity in soybeans. Higher sulfur dose significantly prolonged the days to flowering in soybean i.e. supplementing 40 kg ha^{-1} sulfur caused delay in flowering in comparison with control plots. This delay in flowering associated with higher sulfur levels could be attributed to sulfur role in augmenting chlorophyll content and enhancing photosynthetic processes, consequently fostering improved and prolonged vegetative growth in the crop. A study by Shiplei et al. (2012) noted that increased sulfur levels led to delay in flowering in soybean, particularly observing delayed flowering occurrences at the 40 kg S ha^{-1} level. Application stages (APP) of sulfur significantly affect days to flowering and maturity. Sulfur applied at vegetative stage (V3) delayed flowering. While minimum was recorded at sowing stage. Similarly, delayed maturity was seen at 60 kg S ha^{-1} as compared to control plot. Sulfur applied at flowering stage (R1) had delayed maturity as compared to sowing stage in soybean. According to Haruna et al. (2011) late flower formation in soybean might be due to high nitrogen and sulfur application which produce vigorous plant growth and prolonged vegetative growth stage resulted in delay flowering and physiological maturity.

Plants subjected to higher sulfur levels, particularly at 40 kg ha^{-1}, displayed taller plants with maximum number of leaves. This enhancement linked to increased sulfur levels could be attributed to sulfur role as a constituent in plant tissue, significantly influencing soybean height, as indicated by Shahid et al. (2009). Conversely, the decrease observed in these parameters at lower sulfur application levels might be due to the stunted growth and limited development of plants under sulfur deficiency. Consistent with these findings, studies by Varun et al. (2011) and Burkitbayev et al. (2021) noted that sulfur led to enhanced plant height and increased leaf count per plant. Their rationale centered on the capacity of sulfur to alter soil physicochemical properties, thereby enhancing nutrient availability and fostering plant growth and development. This, in turn, facilitated nutrient translocation towards generative organs, positively influencing photosynthesis, and ultimately contributing to augmented yields and structural yield elements. Moreover, Begum et al. (2015) noted that the tallest plants and more branches were evident in the high sulfur treatment, surpassing the lower treatment groups. Concerning sulfur application stages, maximal plant height and leaf count were observed when sulfur was applied during the vegetative stage (V3). Conversely, the lowest plant height and leaf count were observed when sulfur was applied at the sowing stage. This disparity might be attributed to the duration of the vegetative period being shorter compared to other stages, particularly given that most soybean cultivars are categorized as short-day plants. This aligns with Kumar et al. (2017) affirming the positive impacts of fertilizer application during the vegetative phase on the physiological aspects of soybean cultivation, particularly on plant height and leaf count per plant.

Among yield components of soybeans, specifically rise in pod count per plant was evident with an increasing application of sulfur, especially up to 40 kg S ha^{-1}, alongside a simultaneous increase in pod length. This improvement can be linked to the essential role of sulfur in diverse plant growth and developmental processes. Sulfur, a vital element in amino acids containing sulfur, may have played a role in fostering the transition of tissue from somatic to reproductive states, stimulating meristematic activity, and contributing to overall plant development, which resulted in increased pod quantity and size. These observations align with the findings of Chaubey et al. (2000), who noted significant enhancements in pod quantity, length with sulfur. TGW weight was positively influenced by higher levels of sulfur when applied at R1 stage of growth. This might be due to sulfur that enhanced nutritional conditions, leading to improved carbohydrate metabolism and aiding in the transfer of photosynthates to seeds, thereby resulting in larger grains. This observation is corroborated by research indicating a correlation between sulfur treatment and increased seed weight as stated by Sharifi et al. (2012). Similarly, applying sulfur at a rate of 40 kg S ha^{-1} during the reproductive stage (R1) produced higher grain yield compared to sowing stage application. Dhaker et al. (2010) also documented a significant rise in soybean seed yield with 40 kg S ha^{-1} application. Likewise, Casteel et al. (2019) reported a substantial increase in soybean grain yield in response to sulfur application in their study on soybean production.

Commencement of sulfur and the timing of sulfur application significantly influenced biomass yield and harvest indices of soybeans. Specifically, sulfur at a rate of 40 kg ha^{-1} during the reproductive stage (R1) notably increased the biological yield. Moreover, applying 60 kg ha^{-1} sulfur during the reproductive stage led to a higher harvest index. Shah et al. (2013) reported that escalating sulfur rates substantially enhanced the biological yield by stimulating chlorophyll content and protein synthesis, promoting increased photosynthesis and ultimately elevating biomass production. It is crucial to highlight that the adequacy of soil fertilization and subsequent plant nutrition plays a major role in intensifying agricultural production, as emphasized by Diacono and Montemurro (2010).

Elevating dose of sulfur from 0 to 40 kg ha^{-1} resulted in a substantial increase in both the oil content and oil yield. However, further increasing the sulfur level resulted in a reduction in both oil content and yield. This change could be linked to sulfur's role in synthesizing fatty acids and improving protein quality by aiding in the production of particular amino acids (Konyak et al., 2016).When sulfur was applied during the flowering stage (R1), it resulted in higher oil content and yield compared to the application at the sowing stage. This difference could be due to increased metabolic activity in soybean crops during the flowering stage, leading to an enhanced production of secondary metabolites. Additionally, a preference for allocating cysteine towards glutathione and protein synthesis might contribute to these differences (D'Hooghe et al., 2013). In last, protein content was soybean differed significantly by different levels of sulfur. Studies have shown that sulfur-containing agrochemicals, particularly in the form of powdery and solute applications, lead to higher growth, yield, and protein content in soybeans compared to control conditions (Głowacka et al., 2023). Application of sulfur fertilizer has been found to positively impact protein concentrations and oil content in soybeans, ultimately enhancing yield and nutritional quality as also claimed by Mahato, (2023).

Conclusion

In conclusion, the study underscores the significant effects of sulfur levels and application stages on soybean growth and yield components. The most beneficial results were achieved with sulfur applied at a rate of 40 kg ha^{-1}, which enhanced plant height, leaf number, pod size, and both biological and grain yields. Moreover, this sulfur level improved oil and protein content, thus boosting overall seed quality. For farmers, these findings imply that incorporating sulfur into their agronomic practices can lead to substantial improvements in soybean productivity. Specifically, applying sulfur at the flowering stage (R1) is recommended, as it effectively maximizes seed, oil yields and economically friendly. Adopting this practice could enhance crop performance and profitability, making it a valuable practice in soybean cultivation in the region.

Conflict of interest

All the authors who contributed in the manuscript declared no conflict of interest.

Authors' contributions

The contributions of all the authors are appreciated and acknowledged.

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