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Research article

Sulfonated nitrogen and added-sulfur sources influence productivity, quality, and nutrient acquisition of soybean-wheat cropping system

Sanjay Singh Rathore [a,*], K.C. Sharma [b], Kapila Shekhawat [a], Subhash Babu [a], G.D. Sanketh [a], V.K. Singh [c], Rajiv K. Singh [a], Pravin Kumar Upadhyay [a,**], Mohd Hashim [d], Rameti Jangir [e], Harvir Singh [f]

[a] *Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, 110 012, India*
[b] *ICAR-Indian Agricultural Research Institute, Indore Centre, 452 001, India*
[c] *ICAR- Central Research Institute for Dryland Agriculture, 500 059, Hyderabad, Telangana, India*
[d] *ICAR-Indian Agricultural Research Institute, Samastipur Centre, 848 125, India*
[e] *Department of Agronomy, Agricultural University, Jodhpur, 342 304, Rajasthan, India*
[f] *ICAR- Directorate of Rapeseed Mustard Research, 321 303, India*

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ABSTRACT

Soybean-wheat is the predominant cropping system covering >2.5 Mha area in India. The lower productivity of soybean-wheat cropping system (SWCS), remains a serious concern primarily due to inadequate nutrient management. Increasing sulfur (S) deficiency is widespread, especially under oilseed-based cropping system. Hence, to standardize the S requirement through customized fertilization, an experiment was conducted in completely randomized block design (RBD) comprised of 12 nutrient sources, replicated thrice. The study aims to evaluate the agronomic performance of sulfonated nitrogen (SN) in comparison to conventional S nutrient sources in SWCS. The maximum soybean productivity was recorded under NPK + S through 40-0-0-13 (SN1), although NPK + 50% S (15 kg/ha) as basal and 50% (15 kg/ha) as top dressing through SN2 10-0-0-75 produced maximum wheat grain yield. When compared with no nitrogen (control), the application of 30 kg S ha^{-1} to both crops increased the productivity of the soybean-wheat cropping system up to 39%. The maximum system (SWCS) productivity (8.45 tha^{-1}) was obtained with the application of 50% S as basal and 50% as top dressing (SN_2-based), remaining N through urea. The highest sustainable yield index of soybean (SYIS), i.e. 0.90 was under SN1+ remaining N through urea and likewise highest sustainable yield index of wheat (SYIW) was under S splitting. The application of SN also improved the nutrient acquisition and grain quality of soybean and wheat with a positive nutrient balance in the soil. The protein content and yield of soybean and wheat grains also improved. The higher gluten content in wheat grain was produced with 60 kg S ha^{-1} applied. The agronomic efficiency of N and S (AE_N and AEs) were highest under SN_1 and SN_2, respectively (32.8 kg grain/kg N applied; 15 kg grain/kg S applied) in soybean, however in wheat, S splitting and urea application resulted in highest agronomic efficiency (AE_N and AES) of N and S (17.1 kg grain/kg N applied; 22.3 kg grain/kg S applied respectively). Hence

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* Corresponding author.
** Corresponding author.
E-mail addresses: sanjayrathorears@gmail.com (S.S. Rathore), pravin.upadhyay@icar.gov.in (P.K. Upadhyay).

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splitting of S doses of SN along with urea and recommend P, K was found efficient for the soybean-wheat cropping system.

1. Introduction

Soybean (*Glycine* max (L.) Merr.)-wheat (*Triticum aestivum* L.) cropping system is the most predominant cropping system in the vertisols of central India [1]. In India, this cropping system is being practiced on an area of ~2.5 million hectares (Mha) [2]. The area under SWCS in India is further expanding due to several advantages like the availability of suitable plant types with shorter duration, higher tolerance to stresses, and best bet agronomy which make the RWCS resilient to changing climate [3]. However, the sustainability of SWCS has been seriously threatened by the deteriorating soil health mainly due to faulty cultivation practices. One of the prominent indicators of soil health deterioration is the increasing nutrient deficiency of macro and micro elements in the soil [2,3]. The reports of macro element-sulfur (S) indicate that >50% of Indian soils are in deficit in S (<10 ppm), especially under oilseed-based cropping systems. This has become a major constraint for achieving higher crop productivity [4]. Ensuring balanced nutrient supply for the crops is one of the most effective agronomic interventions to achieve sustainable high crop production [5]. Sulfur, along with nitrogen (N), phosphorous (P) and potassium (K), S is also one of the macro-elements, which has a vital role in crop growth, yield, and quality of crop produce [5–8]. Inadequate S nutrition also cause imbalance in nutrient uptake of other essential elements in the soil [7,8]. In addition to interaction of S with other essential nutrients in soil, S has direct role in chlorophyll synthesis, glucosides, and glucosinolates, activation of enzymes, and sulphydryl (SH-) linkages etc. within plant system [9]. The higher S requirement for most of the crops is also due to its direct role in biosynthesis of essential amino acids like methionine and cysteine and about 90% of plant S is found in the form of amino acids [10]. This makes its essentiality similar to other primary elements like P and K [5]. It enhances nutritional and market quality of crop produce, which have direct bearing on farmers livelihood [11–16]. Sulfur has been reported to provide better resilience against biotic and abiotic stress (against plant diseases, insect pest, weather aberrations etc.) hence helps in climate change adaptations [6,15–20]. Thus, with increasing ecological and physiological stresses under climate change, appropriate S management is critical for sustainable crop production.

Furthermore, S deficiency has been reported for over three decades in most cultivable soils in India and elsewhere, but the negative effects of S deficiency on crop production have been highlighted recently [21,22]. S-deficient soils are unable to meet out S requirement of the crops and thus, produce sub-optimal yields and poor quality of the produce. Also, S deficiency disrupts the photosynthesis process and protein synthesis, causing more accumulation of non-protein N in cereal grains, hence deteriorates the nutritional quality [23]. The reasons for increasing S deficiency are mainly unsound nutrient management practices, with greater emphasis on usage of high analysis fertilizers, lesser use of organic manure, a marginal atmospheric S deposition, dwindling usage of S-based fungicides, nutrient exhaustive and high-yielding crop cultivars, and intensive agriculture etc, [24] In addition, over-irrigation and heavy downpour also cause S losses due to leaching and surface runoff [24]. These might be the reasons for >70% of the soil samples collected from different parts of India, were found either deficient or marginal (prone to become deficient) in plant-available S [25]. In SWCS, S application of 30–40 kg/ha, along with a recommended dose of NPK fertilizers has been reported as beneficial for

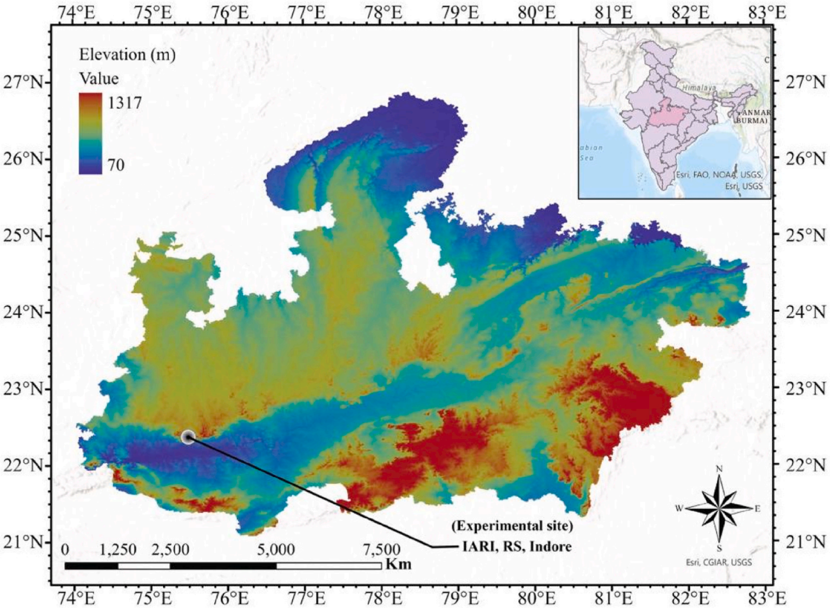


Fig. 1. Actual geographical location (Indore, MP) of the field experimentation.

sustaining higher productivity. However, efficacy of S use depends upon many factors like its sources, applications methods, splitting etc. [1]. The availability of S also varies with different soil factors, including soil texture, soil structure, soil organic matter, soil microbial properties and pH [26]. Therefore, S management needs location-specific interventions. Besides S availability in soil, its balance with available N (N:S ratio) has a crucial role in plant metabolism, especially in protein synthesis [27]. Despite being an essential element, its application has remained sub optimal due to limited availability of S-rich customized fertilizers and limited research focusing on the optimized and standardized S doses in a cropping system mode [12,24]. Additionally, the efficacy of innovative nutrient sources to maintain proper N:S ratio [28,29] needs to be estimated for sustained crop productivity. Hence, oriented research for identifying optimum dose, method, timing, and appropriate source of S fertilizer for soybean-wheat cropping system, would pave the way for the development of precise S management protocols. Therefore, a novel nutrient source, sulfonated nitrogen (SN) has been evaluated against the conventional S sources viz. super phosphate, bentonite-S, and ammonium sulfate in SWCS under vertisols. The SN contains both N and S and the compositions of SN were reported to have a synergistic effect, hence the study was conducted to quantify the impact of SN on crop growth, yield, and nutrient acquisitions in soybean-wheat. It was hypothesized that SN, as a new S source and their splitting might have a beneficial impact on growth, quality, productivity, nutrient acquisition, and efficiency in soybean-wheat cropping systems under vertisols of central plateau regions. Therefore, to optimize the new customized nutrient sources of SN for the soybean-wheat cropping system, the experiment was conducted for two years.

2. Materials and methods

2.1. Site characteristics

A field experiment on the soybean-wheat cropping system was conducted at the research farm at ICAR-Indian Agricultural Research Institute, IARI, Regional Station, Indore (Madhya Pradesh) which is located at $22,^{0}37'$N latitude and $75,^{0}50'$ E longitude with an altitude of 557 m above mean sea level (Fig. 1). The location map was generated by using the RC GIS software. The soil at the experimental site was clay loam in texture under Vertisol soil order, neutral to slightly saline in reaction (pH 8.1 and EC 0.25 dS/m); medium in soil organic carbon (OC 0.51%), low in available nitrogen (213.2 kg/ha); medium in available phosphorus (14.8 kg/ha), high in potassium (440 kg/ha), while the medium in sulfur (10.1 mg/kg). The climate is semi-arid tropical with a normal average annual rainfall (mean of 15 years) of 1020 mm [6].

2.2. Field trial details

Under the soybean-wheat cropping system, soybean (variety: JS 335) was grown during the rainy season (July to October), followed by wheat (variety: HI 8759) during the winter season (November to March) for two years, i.e., during 2019–20 and 2020–21. The field trials included 12 treatments for both crops replicated thrice under a completely randomized block design. The gross plot size

Table 1
Different fertilizer combinations used and the amount of nutrients supplied in the treatments under the experiment.

Description	Soybean				Wheat			
	N (kg/ha)	P (kg/ha)	K (kg/ha)	S (kg/ha)	N (kg/ha)	P (kg/ha)	K (kg/ha)	S (kg/ha)
T1-Rec PK + S through SSP, both crops (no-N)	0	80	40	30	0	60	40	30
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	25	80	40	0	150	60	40	0
T3- Rec NPK + S through ammonium sulfate, both crops	25	80	40	30	150	60	40	30
T4- Rec NPK + S through bentonite to both crops	25	80	40	30	150	60	40	30
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	92.3	80	40	30	92.3	60	40	30
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	92.3	80	40	30	150 (92.3 + 57.8)	60	40	30
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	25 (4 + 21)	80	40	30	150 (4 + 146)	60	40	30
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	92.3	80	40	30	150	60	40	0
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	25(4 + 21)	80	40	30	150	60	40	0
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	25 (8 + 17)	80	40	60	150	60	40	0
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	92.3 (46.15 + 46.15)	80	40	30 (15 + 15)	150 (92.3 + 57.7)	60	40	30 (15 + 15)
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	25 (4 + 21)	80	40	30 (15 + 15)	150 (4 + 146)	60	40	30 (15 + 15)

Note: P and K were supplied through diammonium phosphate (DAP) and muriate of potash (MOP) in each treatment respectively. SSP was used as a source of S in T_1 and remaining P was adjusted with DAP.

was 5 m × 4 m (20 m^2). Similar treatments were imposed for the succeeding crop to assess the residual effects in the fixed plot manner. The recommended fertilizer doses (RDF) for N, P_2O_5, K_2O, S remained 150, 60, 40, 30 kg/ha and 25, 80, 40, 30 kg/ha for wheat and soybean, respectively. The N application was done through SN combinations and the remaining N was adjusted through urea. Similarly, phosphorous and potash requirements were met through diammonium phosphate (DAP) and muriate of potash, respectively. Soybean and wheat were sown manually by the *pora* method. In wheat, 1/3rd N was applied as per treatment through different sources and the remaining 2/3rd N was top-dressed into two equal splits while in soybean all fertilizers were applied as basal, except treatment T_{11} and T_{12} where N and S were applied in splits as per the treatment. The details of the treatments applied in the experiment are given in Table 1.

2.3. *Biometric observations*

Various growth and yield attributes of soybean *viz.,* plant height, pods/plant, grains/plant, grains/pod, seed index, and of wheat *viz.*, plant height, effective tillers, spike length, spikelet/spike, grains/spike and 1000-seed weight were recorded from five tagged plants selected from the net plot. The plant samples were kept in the shade for air drying and then these samples were placed in an oven at 65 °C temperature until the weight of the entire plant was reached a constant. The SPAD (soil plant analysis development) meter was used for measuring the chlorophyll content. Three fully opened leaves from the top of plants were randomly selected from five tagged plants of wheat. The average value was recorded and expressed as SPAD reading per plant.

After the maturity of crops, the border lines were harvested first and were removed from the experimental area, and then net plots were harvested and kept for drying in the respective plots for one week. The drying during this period brought down moisture content of 12–13% in grain, which was safe for storage. After drying the biological yield of the net plot was recorded and the produce of each plot was threshed and cleaned. The grains yield was recorded in kilogram per net plot, the straw yield was obtained by deducting the grain yield (kg/plot) from the biological yield (kg/plot) and then converted into tonnes per hectare.

2.4. *Plant and soil analysis*

Soil and plant samples of grain and straw/stover of both soybean and wheat were analyzed. For the analysis of the N content of plant materials, samples were digested with concentrated H_2SO_4 containing catalyst mixture of K_2SO_4 and $CuSO_4$ (10:1) and analyzed by using the Kjeldahl method. For S content in plant materials, samples were digested on di-acid ($HClO_4$ + HNO_3; 3:10), and the observance was read at 420 nm on a spectrophotometer [30], followed by a calculation of nutrient uptake.

The nutrient (NPKS) uptake was worked out by using the following formula (1).

$$\text{Nutrient uptake (kg / ha)} = \frac{\text{Nutrient concentration (\%)}}{100} \; X \; \text{Biomass (kg / ha)} \tag{1}$$

For quantitative determination of plant total sulfur, the wet digest is taken from the di-acid digestion method and then determined by barium sulfate turbidimetry method. During wet digestion of the sample, all the plant S is converted to sulfate form, treated with $BaCl_2$ which is precipitated as $BaSO_4$. The generated turbidity is measured and the higher the turbidity of the solution, more is the amount of sulfate present. Gum *Acacia* solution is added to help stabilize turbidity. The turbidity of the samples was read from a colorimeter using a blue filter or on a spectrophotometer using 420 nm wavelength. A standard curve was drawn by plotting the absorbance against the concentrations., lastly the step with 10 ml of the di-acid digest of the sample was repeated and the readings were taken [31].

For the soil analysis, the initial and after-crop harvest samples were taken from 0 to 15 cm depth during both the years of experimentation. The soil available N was extracted by oxidization with alkaline potassium permanganate ($KMnO_4$) [29]. The available S was extracted with 0.15% $CaCl_2$ in a 1:5 soil: extractant ratio and determined by the turbidity method using a $BaCl_2$ and gum acacia and ethanol mixture [31].

2.5. *Quality parameters*

Treatment-wise samples selected for the study were milled in the laboratory by Willey mill (0.5 mm) and used for the assessment of the biochemical quality parameters of soybean and wheat. Wiley mill is widely used for grinding purposes of various materials like grains, fertilizer materials etc. for further analysis of biochemical parameters. The desired materials are being ground, dried properly till the desired moisture level is achieved. In willy mills, the material is cut into pieces and loaded into a hopper. From here, the material falls gravitational forces into revolving hard steel sharp blades by an e-motor. Ultimately a powder form material is prepared by the revolving knives, which work against stationary knives. The powdered material then drops into a waiting collection vessel underneath and is used for further laboratory analysis of soybean and wheat grains [30,32].

2.5.1. *Biochemical parameters of wheat*

Starch content in the wheat flour samples was analyzed by hydrolyzing the wheat flour in perchloric acid by anthrone methods [32]. The basic principle used for this to treat the sample with 80% alcohol for separation of the sugars and then starch is being extracted with perchloric acid. In a hot acidic medium starch is hydrolyzed to glucose and dehydrated to hydroxymethyl furfural. This compound forms a green-colored product with anthrone. To finally estimate the starch content, the glucose content is multiplied by a factor of 0.9. Also, the glucose is estimated in the sample using the standard graph. The amount and quality of wet gluten after washing on glutomatic (Polish Norm 93-A-74042/02) and total Zeleny content were determined in the flour [33].

2.6. Nutrient use efficiency

The nutrient use efficiency in terms of the derived indices, viz., agronomic efficiency (2), recovery efficiency (3), and partial factor productivity (4) were estimated to assess the resource use efficiencies in response to the applied nutrients. The derivations were computed using the following empirical equations [34]:

$$AE_{N\ \&\ S} = (Y_t - Y_o) / Na \tag{2}$$

Table 2
Effect of various nutrient sources and doses on growth and yield attributes of soybean and wheat under the soybean-wheat system (pooled over 2 years).

Treatments	Soybean					Wheat					
	Plant height (cm)	Pods/ plant	Grains/ pod	Grains/ plant	Seed index (gm)	Plant height (cm)	Effective tillers/m^2	Spike length (cm)	Spikelets /spike	Grains /spike	1000 seed weight (g)
T1-Rec PK + S through SSP, both crops (no-N)	45.2	26.1	1.6	32	9.4	71.1	246	5.9	14	37	47.7
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	53.1	32.6	1.7	52	9.7	79.2	321	7.2	17	46	50.2
T3- Rec NPK + S through ammonium sulfate, both crops	56.3	36.4	1.8	55	9.9	78.7	335	7.4	17	47	49.8
T4- Rec NPK + S through bentonite to both crops	56.1	37.2	1.8	57	10.1	80.5	346	7.7	17	48	50.6
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	50.5	33.0	1.7	46	9.7	76.0	309	7.0	16	45	49.6
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	62.3	42.4	1.8	68	10.7	82.0	353	7.9	17	50	50.8
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	61.2	41.1	1.8	65	10.7	83.1	359	8.2	18	52	52.3
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	57.1	37.7	1.8	60	10.3	81.3	352	7.8	17	50	51.2
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	57.5	39.2	1.8	58	10.4	82.5	360	8.4	18	52	51.8
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	61.2	39.9	1.8	63	10.6	82.7	350	7.8	17	51	50.9
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	59.3	40.6	1.8	62	10.5	82.4	355	7.7	17	52	50.7
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	59.5	39.8	1.8	61	10.4	84.0	363	8.3	18	53	51.8
CD$_{0.05}$	2.81	2.44	0.11	5.02	0.68	2.53	12.42	0.38	0.76	2.64	1.37

$$RE_{N\ \&\ S} = [(U_t - U_o) / Na]*100 \tag{3}$$

$$PFP_{N\ \&\ S} = (Y_t / Na) \tag{4}$$

where, Y_t = grain yield in test treatment (kg ha^{-1}); Na = amount of nutrient added (kg ha^{-1}); Y_o = grain yield in control treatment (kg ha^{-1}); U_t = nutrient uptake in test treatment (kg ha^{-1}); U_o = nutrient uptake in control treatment (kg ha-^{1}).

2.7. Statistical analysis

The data obtained from the field experiments were analyzed statistically by analysis of variance (ANOVA) and the sources of variation were; year, source of fertilization, and their maximum two-order interaction. Before performing the ANOVA, the homogeneity of variance of all characteristics was verified according to Bartlett's tests. The comparison of means was done by assessing the critical difference (LSD). The pooled analysis of two years of data was worked out as per the method described by Panse and Sukhatme, 1967 [35]. The analysis was done by using the software SAS (version 9.3).

3. Results

3.1. Effect of sulfur sources on growth, yield attributes, and yield of soybean and wheat

The amount and schedule of N and S applied at variable doses through different nutrient sources have been shown in Table 1. Two control treatments were taken for both soybean and wheat as No–N and No–S to understand the yield response with variable nutrient doses and sources. Plant growth and yield parameters in both soybean and wheat were significantly influenced by the application of different S and N-containing nutrient sources (Tables 2 and 3). In soybean, maximum growth and yield parameters were obtained where SN_1 was applied as a customized source of N and S. Most of the growth and yield attributes with the application of SN_2 remained at par with it. The splitting of S as basal and remaining as top-dressing also resulted in higher growth and yield attributes over other

Table 3
Effect of various nutrient sources and doses on grain yields (t ha-1), system productivity, and sustainability of soybean and wheat under soybean-wheat system (pooled of 2 years).

Treatments	Grain yield		System productivity	Wheat equivalent yield	Wheat equivalent System productivity	Sustainable yield index	Sustainable yield index
	Soybean	Wheat				Soybean	Wheat
T1-Rec PK + S through SSP, both crops (no-N)	1.66	3.5	5.16	3.38	6.88	0.55	0.47
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	2.03	5.4	7.43	4.14	9.54	0.70	0.78
T3- Rec NPK + S through ammonium sulfate, both crops	2.21	5.53	7.74	4.50	10.03	0.77	0.80
T4- Rec NPK + S through bentonite to both crops	2.22	5.63	7.85	4.52	10.15	0.77	0.82
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	1.93	5.09	7.02	3.93	9.02	0.66	0.73
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	2.55	5.7	8.25	5.19	10.89	0.90	0.83
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	2.48	5.88	8.36	5.05	10.93	0.87	0.86
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	2.35	5.68	8.03	4.79	10.47	0.82	0.83
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	2.34	5.84	8.18	4.77	10.61	0.82	0.85
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	2.46	5.76	8.22	5.01	10.77	0.87	0.84
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	2.39	5.72	8.11	4.87	10.59	0.84	0.83
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	2.38	6.07	8.45	4.848	10.92	0.84	0.890
$CD_{0.05}$	0.14	0.2	–	–	–	–	–

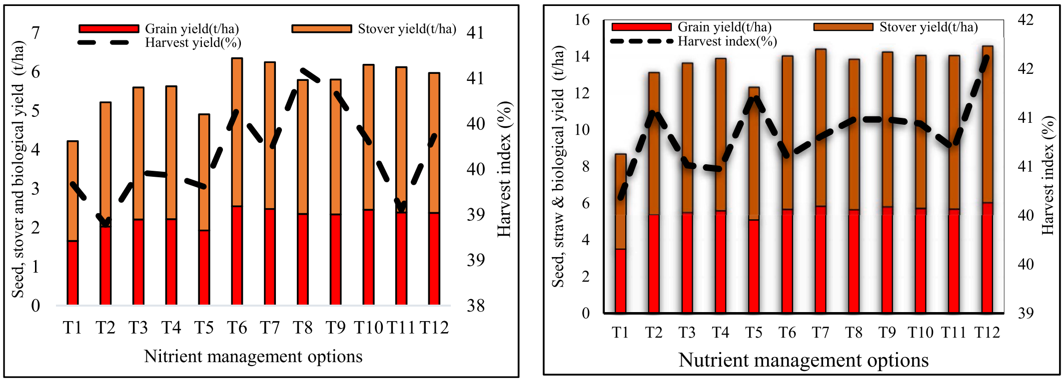
conventional N and S sources.

A significantly higher growth, yield attributes and seed yield of soybean was produced with SN_1 application and it remained statistically similar to SN_2 application and 60 kg/ha S application, respectively (Tables 2 and 3). The at-par soybean yield with SN_1, either 30 and 60 kg S through SN_2 application indicates that SN_2, which supplied 25 kg N and 30 kg S, remained a better source of combined N and S application. Also, no significant enhancement in soybean yield was recorded beyond 30 kg S/ha. A 34.9% enhancement in yield was recorded with SN_1 over No–N. This increase was 20.3 and 8.23% respectively, over No–S and SN_2 treatment (30 kg S/ha with RDF (Fig. 2A). Also, the lowest wheat and soybean yields were noted under T_1 (No–N) and were followed by T_2 (control for S). It shows that N has a larger impact on the cropping system productivity than S.

The growth and yield attributes of the wheat improved with the application of both SN_1 (40-0-0-13) and SN_2 (10-0-0-75) as combined S and N sources. A significantly higher plant height and effective tillers/m^2 were recorded with the application of recommended NPK +50% S (15 kg/ha) as basal and 50% (15 kg/ha) as top dressing (SN_2-based), which remained at par with other treatments containing either of SN_1 or SN_2 along with conventional N supplement (Table 2). The maximum spike length was recorded with the SN_2-based application, which remained on par with the split S application. The spikelets/spike were also recorded statistically similar under all treatments except under control where no N was applied. The application of S splits through SN_2 recorded the highest grains/spike and other treatments either with SN_2 applications or S splitting remained at par with this treatment. Further, the 1000-seed weight in all other treatments was found significantly similar to each other except either under control or single S treatment. Among all treatments, 50% S (15 kg/ha) as basal and 50% (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea produced maximum grain and biological yield of wheat (Table 3 and Fig. 2B) and was found at par with SN_2 and remaining N application through urea. The percent increase in wheat yield with SN_2 [T_{12}: Rec NPK + S 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea] was 42.3% over No–N. However, this increase was 11.03% with SN_2 application over no-S [T_2: Rec. NPK (no-S)]. The splitting of S with the available SN_2 showed that a 5.76% higher seed yield was obtained over the splitting of SN_1 [T_{11}: 50% (15 kg/ha) as a top dressing (SN_1-based) + remaining N through urea].

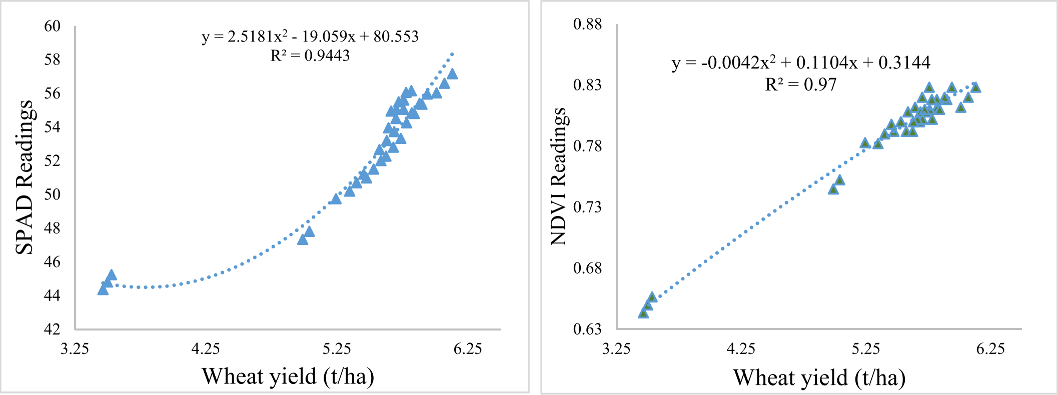
The cropping system productivity, wheat equivalent yield (WEY) and wheat equivalent cropping system productivity (WECSP), sustainable yield index (SYI) of both soybean and wheat have been shown in (Table 3). The crop yield, cropping system productivity, and SYI were found relatively higher with the newer customized nutrient formulations over the conventional sources. The cropping system productivity was obtained highest with the splitting of SN_2 [T_{12}: Rec NPK + S 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea]. However, the WEY and WESP were obtained highest with SN_1 application (T_6). The SYI of soybean and wheat were higher under SN1 and the remaining N was applied through urea and split S application with Urea N, respectively. A 1.6- and 1.9-fold increase in the SYI of soybean and wheat were recorded over No–N with the application of SN_1-based and SN_2-based applications, respectively. In general, the SYI of both soybean and wheat was higher from T_6 to T_{12} treatments, where SN as a source of N and S were applied.

The SPAD (Fig. 3A) and NDVI (Fig. 3B) readings were also observed at the maximum flowering stage in wheat as an indirect indicator of higher crop growth and productivity. The wheat grain yield was found positively correlated with SPAD readings (Fig. 3A) as well as NDVI readings (Fig. 3B). The higher transmission ratio gives higher values of these sensor's readings which indicates higher chlorophyll concentration in the plant. Since chlorophyll is the major driving force of yield generation, the high value of the coefficient of determination (R^2) as 0.94 for SPAD and 0.97 for NDVI with the wheat grain yield indicates a strong positive correlation of seed



Soybean (A) Wheat (B)

Fig. 2. Effect of various nutrient management options on seed, straw and biological yields and harvest index of soybean (A) and wheat (B). (T1-Rec PK + S through SSP, both crops (no-N), T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops, T3- Rec NPK + S through ammonium sulfate, both crops, T4- Rec NPK + S through bentonite to both crops, T5- Rec NPK + S as SN1 (40-0-0-13), both crop, T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea, T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea, T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea, T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea, T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea, T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea, T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea).



(A) (B)

Fig. 3. Correlation of wheat yield with SPAD (A) and NDVI (B) readings at flowering stage (85 DAS).

yield and NDVI/SPAD meter readings.

3.2. *Effect of sulfur sources on plant nutrient concentration and acquisition in soybean and wheat*

A significant improvement was observed in nutrient concentration and their uptake by seed and stover of soybean (Table 4) as well as grain and straw of wheat (Table 5) with SN fertilization. The N concentration in the grain and stover of soybean remained maximum where SN$_1$ was applied [T$_6$: Rec NPK + S as SN$_1$ (40-0-0-13), both crops + remaining N through urea], however, it remained at par with the SN$_2$ application [T$_7$: Rec NPK + S as SN$_2$ (10-0-0-75), both crops + remaining N through urea]. In the treatments where equal S was applied (T$_6$ and T$_7$), even the low N application in T$_7$ resulted in at par N concentration in both grain and stover. The N uptake in soybean seed and stover was recorded highest with SN$_1$ application (T$_6$), and SN$_2$ (T$_7$) remaining at par with it.

The S concentration in seed and stover of soybean was recorded highest under SN$_1$ (T$_6$) and with SN$_2$-based 60 kg S/ha [T$_{10}$: Rec NPK +60 kg S/ha to soybean (SN$_2$-based) + remaining N through urea]. The S uptake in seed and stover of soybean also remained highest with SN$_1$ (T$_6$), but it remained at par with SN$_2$ (T$_7$: 30 kg S/ha and T$_{10}$: 60 kg S/ha). It indicates that the S concentration in both seed and stover did not increase beyond 30 kg S/ha application.

In the case of wheat, the maximum N concentration and uptake in both seed and straw was in T$_{12}$ (15 kg S/ha, each as basal and top

Table 4
Effect of various nutrient sources and doses on nitrogen and sulfur content and uptake by soybean under the soybean-wheat system (pooled of 2020–21 to 2021–22).

Treatments	S concentration (%)		S uptake (kg ha^{-1})			N concentration (%)		N uptake (kg ha^{-1})		
	Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T1-Rec PK + S through SSP, both crops (no-N)	0.21	0.44	7.4	5.4	12.8	5.17	2.56	85.9	15.9	101.8
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	0.20	0.41	8.4	6.3	14.7	5.68	2.71	115.4	32.5	147.9
T3- Rec NPK + S through ammonium sulfate, both crops	0.22	0.47	10.4	7.6	18.0	5.94	2.75	131.3	32.9	164.2
T4- Rec NPK + S through bentonite to both crops	0.23	0.49	10.8	8.0	18.8	5.91	2.76	130.9	35.6	166.5
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	0.22	0.46	8.9	6.5	15.4	5.42	2.65	104.4	28.3	132.7
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	0.27	0.54	13.8	10.2	24.0	6.50	2.94	165.9	36.1	202.0
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	0.27	0.53	13.1	10.2	23.3	6.44	2.91	159.9	37.9	197.8
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	0.24	0.51	12.0	8.4	20.4	6.25	2.84	146.8	35.5	182.2
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	0.25	0.51	11.9	8.5	20.4	6.22	2.79	145.5	37.5	182.8
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	0.27	0.54	13.4	10.2	23.54	6.46	2.90	158.9	35.9	194.8
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	0.25	0.52	12.4	9.4	21.76	6.40	2.86	153.2	36.2	189.4
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	0.25	0.51	12.1	9.1	21.18	6.29	2.87	149.5	38.9	188.4
CD$_{0.05}$	0.02	0.02	0.82	0.81	1.89	0.20	0.11	8.11	1.71	14.22

Table 5
Effect of various nutrient sources and doses on nitrogen and sulfur content and uptake by wheat under the soybean-wheat system (pooled of 2019–20 to 2020–21).

Treatments	S concentration (%)		S uptake (kg ha^{-1})			N concentration (%)		N uptake (kg ha^{-1})		
	Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T1-Rec PK + S through SSP, both crops (no-N)	0.14	0.12	4.8	4.7	9.46	1.73	0.39	60.6	15.9	76.5
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	0.09	0.07	5.1	4.5	9.5	2.09	0.48	112.6	32.5	145.1
T3- Rec NPK + S through ammonium sulfate, both crops	0.16	0.14	8.7	9.2	17.87	2.14	0.48	118.3	32.9	151.2
T4- Rec NPK + S through bentonite to both crops	0.17	0.14	9.6	9.9	19.48	2.15	0.51	121.1	35.6	156.7
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	0.15	0.13	7.7	7.9	15.58	2.03	0.45	103.5	28.3	131.8
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	0.17	0.14	9.8	9.9	19.72	2.16	0.51	122.9	36.1	159.1
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	0.18	0.15	10.3	10.8	21.1	2.20	0.52	129.3	37.9	167.2
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	0.16	0.14	9.3	9.5	18.81	2.17	0.50	123.2	35.4	158.6
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	0.17	0.14	9.7	10.3	19.98	2.20	0.52	128.9	37.3	166.2
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	0.20	0.16	11.2	11.4	22.67	2.15	0.51	123.8	35.9	159.7
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	0.18	0.14	10.4	10.1	20.48	2.18	0.51	124.9	36.2	161.1
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	0.20	0.14	12.0	10.5	22.49	2.22	0.53	134.6	38.9	173.5
CD$_{0.05}$	0.01	0.01	0.80	0.90	1.23	0.14	0.02	6.88	1.71	12.60

dressing through SN$_2$), however it remained at par with SN$_2$ (T$_7$: 30 kg S/ha). An increase of 54.9% in N uptake in wheat grain was recorded with the application of SN$_2$ (T$_{12}$) over No–N. This increase was, however, 16.3 and 7.2% with T$_{12}$ over No–S (T$_2$) and SN$_1$ splitting (T$_{11}$), respectively. The S content in wheat grain, straw, and total S uptake was maximum under T$_{10}$ (SN2:60 kg S/ha to soybean) and SN2 splitting (T$_{12}$). The increase in S uptake by grain was up to 60.3% under SN$_2$ splitting (T$_{12}$) over No–N. this increase was however, 58 and 13% with T$_{12}$ over No–S (T$_2$) and SN$_1$ splitting (T$_{11}$), respectively.

3.3. *Effect of sulfur sources on nutrient use efficiencies*

The AE$_N$ in soybean was recorded higher with SN$_2$-based applications over conventional N and S sources (Table 6). The lower AE$_N$

Table 6
Effect of various nutrient sources and doses on AE$_{N\&S}$ (kg seed/kg nutrient), RE$_{N\&S}$ (%), and PFP$_N$&$_S$ (kg seed/kg nutrient applied) under the soybean-wheat system (pooled of 2019–20 to 2020–21).

Treatments	Soybean		Wheat		Soybean	Wheat		Soybean		Wheat	
	AE$_N$	AE$_S$	AE$_N$	AE$_S$	RE$_S$	RE$_N$	RE$_S$	PFP$_N$	PFP$_S$	PFP$_N$	PFP$_S$
T1-Rec PK + S through SSP, both crops (no-N)	–	−12.33	–	−63.33	−6	0	0	0.0	55.3	–	116.7
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	14.8	–	12.7	–	0	46	0	81.2	–	36.0	–
T3- Rec NPK + S through ammonium sulfate, both crops	22.0	6.00	13.5	4.33	11	50	27.9	88.4	73.7	36.9	184.3
T4- Rec NPK + S through bentonite to both crops	22.4	6.33	14.2	7.67	14	53	33.3	88.8	74.0	37.5	187.7
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	2.9	−3.33	17.2	−10.33	2	60	20.3	20.9	64.3	55.1	169.7
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	9.6	17.33	14.7	10.00	31	55	34.1	27.6	85.0	38.0	190.0
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	32.8	15.00	15.9	16.00	29	60	38.7	99.2	82.7	39.2	196.0
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	7.5	10.67	14.5	–	19	55	0	25.5	78.3	37.9	–
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	27.2	10.33	15.6	–	9	60	0	93.6	39.0	38.9	–
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	32.0	14.33	15.1	–	30	55	0	98.4	82.0	38.4	–
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	7.9	12.00	14.8	10.67	24	56	36.6	25.9	79.7	38.1	190.7
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	28.8	11.67	17.1	22.33	22	65	43.3	95.2	79.3	40.5	202.3

under SN_1 is due to the over-application of N. No significant yield enhancement was recorded with additional N doses beyond the recommendation of 30 kg/ha in soybean. The AE_S in soybean was recorded highest with SN application [{T_6: Rec NPK + S as SN_1 (40-0-0-13), both crops + remaining N through urea} and {T_7: Rec NPK + S as SN_2 (10-0-0-75), both crops + remaining N through urea}]. The AE_S remained higher in treatments where either SN_1 or SN_2 was applied over conventional sources. The minimum AE_S was recorded in no-N treatment (12.33 kg/kg S applied) due to poor yield obtained under no-N which indicates that the response of N dominates the response of S for yield enhancement. The poor N application in SN_1 (wheat: 92.3 kg/ha) in succeeding wheat resulted in lower AE_S of the cropping system, however, the AE_N in wheat was recorded highest under T_5 (17.2 kg/kg N applied) due to less N application and under S splitting and urea application (17.1 kg/kg N applied) due to highest wheat grain yield. The other treatments remained similar, but relatively higher AE_N was recorded with SN formulations. The AE_S in wheat was recorded highest under S splitting and urea application (22.3 kg/kg S applied) due to the maximum obtained yield. The negative AE_S under control and conventional S sources indicate that optimum N application is required. Even, the response of applied S is more where optimum N is applied, and under N-deficit conditions, the yield penalty is more as compared to no-S.

The highest RE_S in soybean was recorded in T_6 (31%) due to higher S uptake under optimum S application through SN. Similarly, the highest RE_N as well as RE_S in wheat was obtained under S splitting and urea application [T_{12}: Rec NPK + S 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea] due to higher nutrient uptake. In general, the application of SN resulted in higher RE_N over conventional N sources. The PFP_N under soybean was recorded highest under SN_2 application along with urea (T_7; 99.2 kg/ka N applied), followed by other SN_2-based formulations (T_{10}, T_{12}, and T_9) due to low N application and higher yield. Relatively less PFP_N was recorded with conventional sources under No–S and conventional S sources over SN. Relatively poor yield enhancement beyond 25 kg N/ha resulted in low PFP_N under SN_1-based fertilization (T_5, T_6, and T_{11}). The highest PFP_S in soybean was recorded under SN_1-based S application (T_6; (85 kg/kg S applied), followed by SN_2-based S application ($T_{7+;}$ 82.7 kg/kg S applied) due to higher grain yield with optimum S application (30 kg/ha). The PFP_N in wheat was recorded highest under SN_1-based S application (T_5; 55.1 kg/kg N applied) due to low N application. The PFP_N under remaining all treatments did not show much variation. The PFP_N is governed by the nutrient applied and it remained constant for all treatments in wheat (150 kg N/ha), except T_5. The maximum PFP_S in wheat was recorded under S splitting and through SN_2 and the rest N through urea T_{12} (202.3 kg/kg S applied) due to higher grain yield. The low PFP_S in no-N (T_1) is due to the no-N application which resulted in significant yield reduction. Likewise, low PFP_S under SN_1-based S application (T_5) is also due to sub-optimal N application.

3.4. *Effect of sulfur sources on quality parameters*

The major quality parameters like protein content, protein yield, starch content, wet gluten, and Zeleny sediment were estimated in wheat (Table 7). A significant variation due to the application of different nutrient sources was observed. The highest protein content (40.6%) was found in SN_1-based S application with urea in soybean grain (T_6), however, it remained statistically similar with SN_1-

Table 7

Effect of various nutrient sources and doses on quality of wheat and soybean grains (pooled of 2020–21 to 2021–22) and soil chemical properties after two-year experimentation under soybean-wheat system.

Treatments	Soybean		Wheat				
	Protein content (%)	Protein yield (kg/ha)	Protein content (%)	Protein yield (kg/ha)	Starch content (%)	Wet gluten (%)	Zeleny sediment
T1-Rec PK + S through SSP, both crops (no-N)	35.0	537	9.9	345	66.8	22.9	25.58
T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops	36.2	721	11.9	642	66.0	31.4	39.23
T3- Rec NPK + S through ammonium sulfate, both crops	38.6	821	12.2	674	65.8	30.3	40.38
T4- Rec NPK + S through bentonite to both crops	37.8	818	12.3	690	65.7	28.6	39.80
T5- Rec NPK + S as SN1 (40-0-0-13), both crop	35.3	653	11.6	590	66.3	27.7	36.03
T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea	40.6	1037	12.3	701	65.5	29.8	38.30
T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea	40.5	1000	12.5	737	65.2	29.7	38.82
T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea	39.6	917	12.4	702	65.5	29.7	41.02
T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea	39.3	909	12.6	735	65.4	29.4	42.18
T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea	40.4	993	12.3	705	64.9	31.9	41.98
T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea	40.1	957	12.5	712	65.5	30.7	37.98
T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea	39.2	935	12.6	767	65.1	28.9	37.53
$CD_{0.05}$	1.21	50.70	0.79	39.24	0.63	1.81	2.67

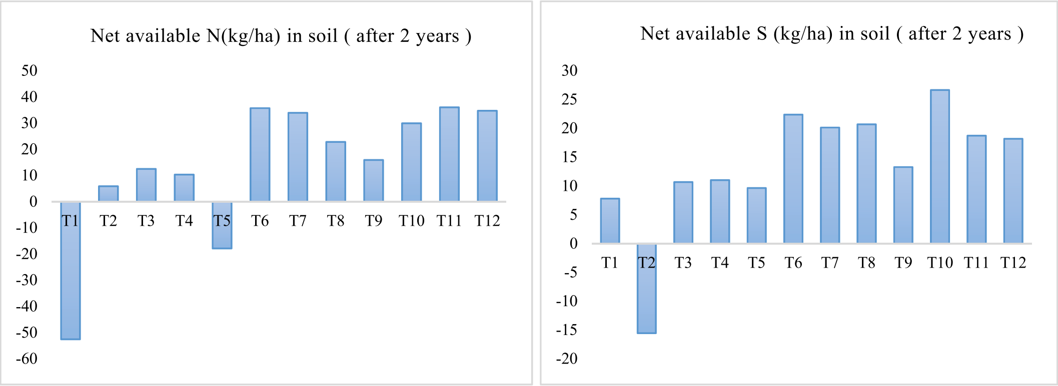
based S application treatments (T_7, T_{10}, T_{11}). The lowest protein (35%) content was found in No–N in soybeans. The protein content in wheat varied significantly with different treatments and remained highest (12.6%) with both single and split application noted in protein yield of wheat where SN_2-based S application (T_{12}, T_7, and T_{10}) remained significantly superior to all other treatments. The range of starch content in wheat varied from 64.9 to 66.8%. It was recorded highest (66.8%) in T_1 where no-N was applied and remained lowest (64.9%), where 60 kg S was applied under T_{10}. The higher gluten content in wheat grain was also produced with T_{10} where 60 kg S/ha was applied. The highest Zeleny sediment (42.18) was recorded with 30 kg S applied (T_9). Whereas, the lowest wet gluten and zeleny sediments were noted under T_1 with no N fertilization.

3.5. Soil nutrient balance

The soil nutrient balance for N (Fig. 4A) and S (Fig. 4B) was estimated by considering the amount of nutrient application in two cycles, removal by crops, and the final soil available content. The net soil balance was obtained by deducting the actual balance from the initial soil available nutrients. A significant variation in soil available N and S balance has been recorded after the two cycles. The maximum soil available net balance for N was noted with the application of 50% S as basal and the remaining 50% as top dressing of SN_1 [T_{11}: Rec NPK +50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN_1-based) + remaining N through urea]. However, significantly highest soil available S was noted under 60 kg SN_2-based to soybean [T_{10}: Rec NPK +60 kg S/ha to soybean (SN_2-based) + remaining N through urea]. Also, a higher positive S balance was noted with SN application which, however, decreased with other conventional fertilizer sources. Interestingly, a negative S balance was recorded with no S application treatment [T_2: Rec. NPK (no-S)]. The residual effect of the nutrients applied in the preceding crop was also recorded. The nitrogen harvest index (NHI) in soybean is positively correlated with that of soil available N, however, it increased with a decreasing rate (R^2 value: 0.7) and plateaued at nearly 250 kg soil available N/ha (Fig. 5A). Similarly, a positive correlation (R^2: 0.69) existed between the sulfur harvest index (SHI) and soil available S also (Fig. 5B). However, it increased at an increasing rate in soybeans.

4. Discussion

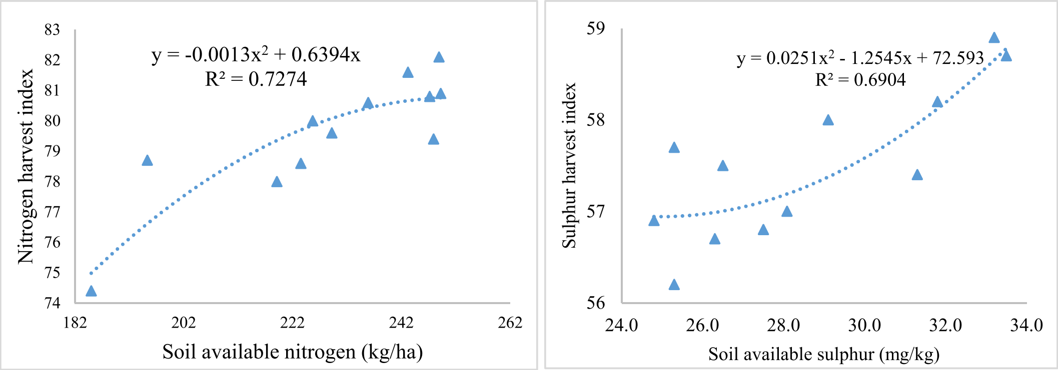
The results of the study demonstrated that the variable sulfur nutrient sources and their rates significantly influenced the growth yield, and quality as well as residual soil nutrient status under the soybean-wheat cropping system. The availability of soil inherent and indigenous nutrient resources has been circumscribed, especially for S due to intensive crop cultivation and the use of straight fertilizers. The major focus on primary nutrients and inadequate use of secondary nutrients have posed serious challenges for sustaining higher crop productivity. Among secondary nutrients, the increasing sulfur deficiency has also been highlighted by the Fertilizer Association of India (FAI) in the recent past, as S-free fertilizers usage peaked over S-containing complex fertilizers [36]. The spike in the use of S-free complex fertilizers resulted in declining crop yield. The mutual interaction of N and S and with most of the other elements is synergistic, hence their limitation in plants disrupts most of the vital biochemical processes of plants viz. photosynthesis, protein synthesis, and non-protein N accumulation in cereal grain [23,37].



Nitrogen (A)

Sulphur (B)

Fig. 4. The net nitrogen (A) and sulfur (B) balance in soil after two cycles of soybean-wheat system.(T1-Rec PK + S through SSP, both crops (no-N), T2- Rec NPK (no-S), T3: Rec NPK + S through ammonium sulfate, both crops, T3- Rec NPK + S through ammonium sulfate, both crops, T4- Rec NPK + S through bentonite to both crops, T5- Rec NPK + S as SN1 (40-0-0-13), both crop, T6- Rec NPK + S as SN1 (40-0-0-13), both crops + remaining N through urea, T7- Rec NPK + S as SN2 (10-0-0-75), both crops + remaining N through urea, T8- Rec NPK + 30 kg/ha S to soybean only (SN1-based) + remaining N through urea, T9- Rec NPK + S (30 kg/ha) to soybean only (SN2-based) + remaining N through urea, T10- Rec NPK + 60 kg S/ha to soybean (SN2-based) + remaining N through urea, T11- Rec NPK + 50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN1-based) + remaining N through urea, T12- Rec NPK + 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN2-based) + remaining N through urea).



(A) (B)

Fig. 5. Correlation of nitrogen (A) and sulfur (B) harvest index with soil available nitrogen and sulfur in soybean.

4.1. *Growth and yield attributes*

The soybean yield was maximum under recommended NPK + S through SN_1, and SN_2 remained at par with it. Likewise, in wheat, the maximum yields were obtained in SN_2 splitting along with the recommended NPK. A 16, 15, and 21% higher soybean grain yield was recorded under T_8 [Rec NPK + 30 kg/ha S to soybean only (SN_1-based) + remaining N through urea], T_9, [Rec NPK + S (30 kg/ha) to soybean only (SN_2-based) + remaining N through urea] and T_{10} [Rec NPK +60 kg S/ha to soybean (SN_2-based) + remaining N through urea] treatments, respectively where SN was applied over T_2 (No–S). The S application improves plant growth and development by increasing the translocation of nutrients and photosynthates toward the generative organs for yield enhancement [3,37]. It also regulates carbohydrate metabolism, protein synthesis, energy transformation, and chlorophyll synthesis. The chlorophyll transmission is characteristically high in the near-infrared range and very low in the red range because green plants absorb visible radiation for photosynthesis. The S application in soybean had a positive residual effect in the succeeding wheat in terms of yield. The residual effect of S application in soybean, where 30 kg S/ha in T_8 and T_9 and 60 kg S/ha in T_{10} was applied, resulted in 4.9, 7.5, and 6.3% wheat yield enhancement, respectively over no-S (T_2). Singh et al., 2015 have also reported a quadratic response in succeeding crops with S application in previous crops. In the present study, the yield response in wheat due to S application in soybean was recorded higher at 30 kg S/ha (T_9) over 60 kg S/ha (T_{10}).

Sulfur performs a special function in N metabolism and transformation for conversion into protein, thus N also has a great yield-promoting effect [38]. With a deficiency of either of these nutrients, the response to fertilization is poor; and the maximum yield can be achieved only when both elements are in adequate amounts [39]. Soybean has a relatively higher N demand during initial crop growth and meets the N demand before biological N_2 fixation occurs. However N demand of soybean remains up to the seed-filling stage, and therefore lower starter fertilizer may not supply an adequate amount of N for full exploitation of the plant's yield potential [40]. Therefore, N application during generative growth may potentially increase crop yields [3,33].

Similarly, a significantly higher grain and biological yield of wheat was produced under the split application of SN_2: 50% S (15 kg/ha) as basal and 50% (15 kg/ha) as a top dressing + remaining N through urea [T_{12}: Rec NPK + S 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea]. Soybean-wheat cropping system productivity in terms of wheat equivalent yield (WEY) and sustainable yield index (SYI) improved under the application of 30 kg/ha S in the form of SN applied to both crops. Ali et al., 2012 also studied the effect of different S levels on the productivity of wheat and reported that the maximum wheat grain yield was achieved with the application of 50 kg S/ha which was 26% more than the control. Similar results have been also reported by other researchers [41–43].

4.2. *Plant nutrient concentration and acquisition*

Soybeans responded positively to the applied N, hence N and S concentration and uptake were recorded higher under the recommended dose of fertilizer (RDF) with split application of SN through either 10-0-0-75 or 40-0-0-13. The increase in seed yield can be ascribed to the increase in photosynthesis due to balanced N and S supply. Better nutrient acquisitions increased the concentration of N and S with SN along with RDF [42 50]. The concentration and uptake of N in wheat grain and straw remained highest under split application of 50% S as basal and 50% as top dressing (SN_2-based) + remaining N through urea [T_{12}: Rec NPK + S 50% S (15 kg/ha) as basal & 50 % (15 kg/ha) as a top dressing (SN_2-based) + remaining N through urea], followed by split application through SN_1 40-0-0-13 [T_{11}: Rec NPK +50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN_1-based) + remaining N through urea] was probably due to better response in plant growth and attributes, higher biomass. The combination of RDF with SN and splitting resulted in maintaining synchrony between crop demand and supply of N and S, hence resulting in better growth and nutrient acquisition [44,45,46].

Similarly, total S uptake by soybean was recorded highest with SN_1 followed by SN_2, however in wheat maximum S uptake was recorded under SN_2 application either as basal or split application. This might be due to the slow and long release of nutrients from SN [47,48]. The uptake of S and their metabolization depends on soil N and S balance, water supply, timing, and rates of N and S application [44,45]. Similar to yield, a significant increase in total S uptake in soybean grain and stover due to residual effect was recorded in the treatments receiving 30 or 60 kg S/ha (T_9, T_8, T_{11}, and T_{10}) in the preceding soybean crop. Interestingly, the S requirement to produce one ton of cereals is relatively low but the uptake per unit area is almost equal to that of oilseeds due to higher productivity of cereals [49,50].

4.3. *Nutrient use efficiencies*

Adequate S supply is essential for achieving full yield potential and efficient utilization of applied nutrients. The AE_N and AE_S in soybean was recorded higher where SN was the source of N and S and it declined with over-application of N for soybean. No significant yield enhancement was recorded with additional N doses beyond the recommendation of 30 kg/ha. The response of N dominates the response of S for yield enhancement. Even, the response of applied S was recorded more where optimum N is applied, and under N-deficit conditions, the yield penalty is more as compared to No–S. In general, the application of SN resulted in higher RE_N over conventional N sources. The oxidized states of S form mineral acid like sulfur acid (H_2SO_3) reducing the soil pH in the vicinity of the rhizosphere. It also increases the microbial activity for atmospheric nitrogen fixation and improves nutrient use efficiencies [51]. The highest RE_N in soybean and wheat was obtained under Split S application and N through urea (T_{12}) due to higher nutrient uptake and optimum N application. The highest RE_S in soybean was recorded in SN_1-based S application [T_6: Rec NPK + S as SN_1 (40-0-0-13), both crops + remaining N through urea] due to higher S uptake under optimum S application through SN [46,48,50]. The highest PFP_S in soybean was also recorded under SN_1-based S application (T_6), followed by SN_2-based S application [T_7: Rec NPK + S as SN_2 (10-0-0-75), both crops + remaining N through urea] due to higher grain yield with optimum S application (30 kg/ha). However, the conventional S sources [T_2: Rec. NPK (no-S); T_3: Rec NPK + S through ammonium sulfate, both crops and T_4: Rec NPK + S through bentonite to both crops] were recorded with low PFP_N over SN. Likewise, S is an essential constituent of nitrate reductase involved in N metabolism and N assimilation. Also, due to the synergy in S and N; application of S increases the N uptake by the crop Ram et al. [46]. The PFP_N in wheat was highest under SN_1 alone [T_5: Rec NPK + S as SN_1 (40-0-0-13), both crop] due to low N application. The low PFP_S in T_1 [PK & S through SSP, both crops (no-N)] is due to no-N application which resulted in significant yield reduction. Likewise, low PFP_S under SN_1 alone [T_5: Rec NPK + S as SN_1 (40-0-0-13), both crop] is also due to sub-optimal N application. Also, S improves the growth of roots and shoots of the plants, especially in high S-requiring crops, so plant roots enhance the uptake of both N and S [6,51]. Higher S application in soybean decreases the utilization of applied S in the case of direct application, however, a positive effect in succeeding wheat was evident in terms of yield and nutrient uptake [45,49,48].

4.4. *Quality parameters*

Both N and S are essential components of the plant enzymes [52] and also have a crucial role in the synthesis of essential S-containing amino acids [27,53] *viz.* cystine, cysteine, and methionine [41,54]. In leguminous oilseeds like soybean, S positively affects both the quantity and quality of crude protein by regulating the N metabolism in the plants. The inverse relationship of S with grain asparagine improves the quality of final produce in wheat also [45,55,56]. The highest protein content in soybean under T_6 [Rec NPK + S as SN_1 (40-0-0-13), both crops + remaining N through urea] with the application of SN_1 has been recorded due to the synergistic effect of N and S in plant metabolism. The S and N interact at the metabolic level such that any imbalance in their availability reduces yields and quality [55,56]. Therefore, S must be included in fertilizer recommendations in soil with S deficiency, and S and N should be administered in balanced quantities to obtain optimum yield and quality.

The starch content in wheat was recorded highest with T_1 [PK & S through SSP, both crops (no-N)] due to No–N application, which indicates the inverse relationship between N concentration in plants and carbohydrate accumulation. Staugaitis et al. [27], also reported that starch in grains decreased with increasing fertilizer rates. The S deficiency is known to promote the accumulation of arginine and asparagine in wheat grains which increases the risk of acrylamide formation when products of wheat flour are cooked [38]. The synthesis of o-acetyl serine also depends on N nutrition. It is the precursor of cysteine amino acid and is required at adequate levels for the assimilation of sulfates in plants [54]. Likewise, S is needed for the activation of certain quality-improving enzymes as an essential component of ferredoxin involved in photosynthesis, N assimilation, and protein synthesis.

4.5. *Soil nutrient balance*

The soil nutrient balance for N and S was estimated by considering the amount of nutrient application, plant uptake, and partitioning in two cycles. A significant variation in soil available N and S balance has been recorded after the two cycles. The maximum soil available net balance for N was noted with the application of 50% S as basal and 50% as the top dressing of SN_1 [T_{11}: Rec NPK +50% S (15 kg/ha) as basal & 50% (15 kg/ha) as a top dressing (SN_1-based) + remaining N through urea]. However, significantly highest soil available S was noted under 60 kg SN_2-based to soybean [T_{10}: Rec NPK +60 kg S/ha to soybean (SN_2-based) + remaining N through urea]. The microscopic size of the S particles (<40 μm) in SN ensures quick oxidation making S readily available for the crops and thereby reducing the nutrient losses through leaching [48,57]. Also, a higher positive S balance was noted with SN application which decreased with other fertilizer sources. The mobile S concentration in soil is the only means of S supply in the soil [56,57] and it migrates rapidly through the soil profile and is subjected to losses [39]. In the present study growth and yield attributes of soybean and wheat crops improved under different S fertilization as compared to control treatments (No–N and No–S). A significantly higher yield was recorded with SN as compared to other fertilizer sources i.e. bentonite, SSP, and ammonium sulfate. Instead of elemental-S coated urea, SN emulsified micron-sized particles distribute evenly forming a homogeneous emulsion. A positive S balance has been recorded with 30 kg S/ha soil application [57] and in the treatment where low N was applied than RDN, a negative balance has been recorded [58].

5. Conclusion

The soybean-wheat cropping system under study has potential in terms of food security, edible oil security, and environmental sustainability. It is both, a nutrient-responsive and a nutrient-exhaustive cropping system and therefore, appropriate and balanced nutrient management practices, especially for S are vital for achieving sustainability for this cropping system. Among the various nutrient sources, an unconventional S and N source: sulfonated nitrogen (SN) was evaluated for its efficacy under two grades, viz., SN_1 (40-0-0-13) and SN_2(10-0-0-75). From the results of two-year experimentation, it was observed that the soybean-wheat cropping system fertilized with the recommended NPK + S through SN_1 (40-0-0-13) as a basal application enhanced growth, yield, nutrient, and protein content of soybean. However, in wheat, 50% S (15 kg/ha) as basal and 50% (15 kg/ha) as top dressing (SN_2-based) remaining N through urea (T_{12}) resulted in improved growth, grain and biological yield, nutrient accumulation and also grain quality. For producing maximum WEY and SYI, NUE, and positive balance of nutrients, the soybean-wheat cropping system can be fertilized with the application of S through 10-0-0-75 (SN_2) either as a basal or split application. A substantial direct and residual responses viz. maximum S recovery of cropping system under application of NPK + S (30 kg/ha) to first crop through both grades; i.e. 10-0-0-75 and 40-0-0-13 confirms the higher need for S application, particularly in intensive cropping systems. However, there is a need to assess N and S dynamics in the soil-plant-atmosphere under contrasting environments to use these findings for better adaptation under climate change scenarios for sustainable production.

Additional information

No additional information is available for this research paper.

Data availability statement

All data are available within the manuscript. Additional data will be made available on request by the corresponding author.

CRediT authorship contribution statement

Sanjay Singh Rathore: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization, Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **K.C. Sharma:** Project administration, Methodology, Investigation. **Kapila Shekhawat:** Funding acquisition, Formal analysis, Data curation. **Subhash Babu:** Writing – review & editing, Visualization, Validation, Supervision. **G.D. Sanketh:** Data curation. **V.K. Singh:** Visualization, Funding acquisition, Conceptualization. **Rajiv K. Singh:** Software, Resources, Methodology, Investigation. **Pravin Kumar Upadhyay:** Project administration, Formal analysis, Data curation. **Mohd Hashim:** Writing – review & editing, Methodology. **Rameti Jangir:** Project administration, Methodology, Formal analysis, Data curation. **Harvir Singh:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sanjay Singh Rathore reports was provided by Shell India Private Limited. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] U.K. Behera, A.R. Sharma, H.N. Pandey, Sustaining productivity of wheat–soybean cropping system through integrated nutrient management practices on the Vertisols of central India, Plant Soil 297 (1) (2015) 185–199.
[2] Ministry of Agriculture and Farmers Welfare, Second Advance Estimates of Production of Major Crops for 2021-22 Released, PIB, Delhi, 2022.
[3] V.K. Singh, B.S. Dwivedi, A.K. Shukla, V. Kumar, B. Gangwar, M. Rani, S.K. Singh, R.P. Mishra, Status of available sulfur in soils of north-western Indo-Gangetic plain and western Himalayan region and responses of rice and wheat to applied sulfur in farmer's fields, Agric. Res. 4 (1) (2015) 76–92.
[4] T. Zenda, S. Liu, A. Dong, H. Duan, Revisiting sulphur—TheOnce Neglected nutrient: it's roles in plant growth, metabolism, stress tolerance and crop production, Agriculture 11 (2021) 626, https://doi.org/10.3390/agriculture11070626.
[5] H.W. Scherer, Sulphur in crop production — invited paper, Eur. J. Agron. 14 (2) (2001) 81–111, https://doi.org/10.1016/S1161-0301(00)00082-4.
[6] S.S. Rathore, S. Babu, V.K. Singh, K. Shekhawat, R.K. Singh, P.K. Upadhyay, M. Hashim, K.C. Sharma, R. Jangir, R. Singh, Sulfur sources Mediated the Growth, Productivity, and nutrient acquisition Ability of Pearlmillet–mustard cropping systems, Sustainability 14 (2022) 14857, https://doi.org/10.3390/su142214857.

[7] A.A. Abdallah, A.I. Mohamed, E.M. El-Sikhry, O.M. Ali, Effect of sulphur application on wheat production in Calcareous soil under saline irrigation water conditions, J Soil and Water Sci 1 (2013) 7–11. Suez Canal University.

[8] A. Ali, M. Arshadullah, S.I. Hyder, I.A. Mahmood, Effect of different levels of sulfur on the productivity of wheat in a saline sodic soil, Soil Environ. 31 (1) (2012) 91–95.

[9] K. Mengel, E.A. Krikby, Principles of Plant Nutrition, IPI, Bern, Switzerland, 1987.

[10] H.L.S. Tandon, D.L. Messick, Practical Sulphur Guide, The Sulphur Institute, Washington, D.C. 20, 2002.

[11] R. Xie, S. Dong, C. Hu, K. Wang, The role of nitrogen and sulphur interaction in maize quality (*Zea mays* L.), Agric. Sci. China 2 (2003) 527–532.

[12] K.N. Tiwari, B.R. Gupta, Sulphur for sustainable high yield agriculture in Uttah Pradesh, Indian J. Fertil. 1 (2006) 37–52.

[13] M. Jarvan, L. Edesi, A. Adamson, L. Lukme, A. Akk, The effect of sulphur fertilization yield, quality of protein and baking properties of winter wheat, Agron. Res. 6 (2008) 459–469.

[14] S. Nasreen, S.M. Imamul Haq, M.A. Hossain, Sulphur effects on growth, responses and yield of onion, Asian J. Plant Sci. 2 (2003) 897–902.

[15] M.H. Ullah, S.M.I. Huq, M.D.U. Alam, M.A. Rahman, Impacts of sulphur levels on yield, Storability and Economic Return of onion, Bangladesh J. Agric. Res. 33 (2018) 539–548.

[16] S. Kopriva, A. Calderwood, S.C. Weckopp, A. Koprivova, Plant sulphur and Big data, Plant Sci. 241 (2015) 1–10.

[17] R. Nazar, N. Iqbal, A. Masood, S. Syeed, N.A. Khan, Understanding the significance of sulphur in improving salinity tolerance in plants, Environ. Exp. Bot. 70 (2011) 80–87.

[18] P. Santisree, S.S. Adimulam, P. Bommineni, P. Bhatnagar-Mathur, K.K. Sharma, Hydrogen Sulfide in plant abiotic stress tolerance: Progress and Perspectives, in: Reactive Oxygen, Nitrogen and Sulfur Species in Plants: Production, Metabolism, Signaling and Defense Mechanisms, JohnWiley & Sons, New York, NY, USA, 2019, pp. 743–775.

[19] M. Giordano, J.A. Raven, Nitrogen and Sulfur assimilation in plants and algae, Aquat. Bot. 118 (2014) 45–61.

[20] S.S. Rathore, D.R. Chaudhary, G.N. Boricha, A. Ghosh, B.P. Bhatt, S.T. Zodape, J.S. Patolia, Effect of seaweed extract on the growth, yield and quality of soybean (Glycine max) under rainfed conditions, South Afr. J. Bot. 75 (2009) 351–355.

[21] M.V. Singh, Importance of sulpur in balanced fertilizer use in India, Fertil. News 46 (2001), 13-18, 21-28 and 31-35.

[22] F.U. Rasool, B. Hassan, I.A. Jahangir, Growth and yield of sunflower (*Helianthus annus* L.) as influenced by nitrogen, sulphur and farmyard manure under temperate conditions, SAARC J. Agric. 11 (2013) 81–89.

[23] M. Skwierawska, Z. Benedycka, K. Jankowski, A. Skwierawski, Sulphur as a fertiliser component determining crop yield and quality, J. Elementology. 21 (2) (2016) 609–623, https://doi.org/10.5601/jelem.2015.20.3.992.

[24] A. Jamal, Y. Moon, M.Z. Abdin, Sulphur—a general overview and interaction with nitrogen, Aust. J. Crop. Sci. 4 (2014) 523–529.

[25] Tsi–Fai–Ifa, Proceedings of TSI-FAI-IFA symposiumcum workshop on sulphur in balanced fertilisation held at New Delhi, in: R.K. Tewatia, R.S. Chaudhary, S. P. Kalwe (Eds.), The Fertliser Association of India, 2006, p. 223. New Delhi.

[26] S.K. Trivedi, K.N. Bansal, R.A.S. Tomar, R.S. Verma, Vertical distribution of forms of sulphur in some profiles of Morena and Bhind district of Madhya Pradesh, J. Indian Soc. Soil Sci. 48 (2000) 238–241.

[27] G. Staugaitis, K. Poškus, Z. Brazienė, D. Avižienytė, Effect of sulphur and nitrogen fertilisation on winter wheat in *Calcaric Luvisol*, Zemdirbyste-Agriculture. 109 (3) (2022) 211–218, https://doi.org/10.13080/z-a.2022.109.027.

[28] V.B. Awasarmal, S.U. Pawar, R.A. Kolgane, G.D. Gadade, Effect of integrated nutrient management on growth and yield of soybean [Glycine max. (L.) Merril.], Adv. Res. J. Crop Improv. 4 (1) (2013) 62–64.

[29] B.V. Subbiah, G.L. Asija, A rapid procedure for the determination of available nitrogen in soils, Curr. Sci. 25 (1956) 259–260.

[30] R. Prasad, Y.S. Shivay, D. Kumar, S.N. Sharma, Learning by Doing Exercises in Soil Fertility (A Practical Manual for Soil Fertility), Division of Agronomy, Indian Agricultural Research Institute, New Delhi, 2006.

[31] C.H. Williams, A. Steinberg, Soil sulphur fractions as chemical indices of available sulphur in some Australian soils, Aust. J. Agric. Res. 10 (1959) 340–352.

[32] S. Sadasivam, A. Manikam, in: Biochemical Methods for Agricultural Sciences, Wiley Eastern Limited, New Delhi and TNAU, Coimbatore, India, 1992, pp. 122–123, 5-11, 22, 34.

[33] I.S.M. Farhad, M.N. Islam, S. Hoque, M.S.I. Bhuiyan, Role of potassium and sulphur on the growth, yield and oil content of soybean (*Glycine max* L.), Acad. J. Plant Sci. 3 (2010) 99–103.

[34] Y.S. Shivay, R. Prasad, A. Rahal, Genotypic variation for productivity, zinc utilization efficiencies and kernel quality in aromatic rices under low available zinc conditions, J. Plant Nutr. 33 (2010) 1835–1848.

[35] V.J. Panse, P.V. Sukhatma, "Statistical Method for Agricultural Workers", second ed., I.C.A.R., New Delhi, 1967.

[36] FAI, Fertiliser Statistics, The Fertiliser Association of India, New Delhi, 2020.

[37] K. Shekhawat, S.S. Rathore, O.P. Premi, B.K. Kandpal, J.S. Chauhan, Review article advances in agronomic management of Indian mustard (*Brassica juncea* (L.) Czernj. Cosson): an Overview, Int J Agronomy (2012) 1–14.

[38] N.G. Halford, T.Y. Curtis, N. Muttucumaru, J. Postles, J.S. Elmore, D.S. Mottram, The acrylamide problem: a plant and agronomic science issue, J. Exp. Bot. 63 (2012) 2841–2851.

[39] J. Eriksen, Soil sulfur cycling in temperate agricultural cropping systems, Adv. Agron. 102 (2009) 55–89, https://doi.org/10.1016/S0065-2113(09)01002-5.

[40] G. Barth, E. Francisco, J.T. Suyama, F. Garcia, Nutrient uptake illustrated for modern, high-yielding soybean, Better Crops Plant Food 102 (2018) 11–14.

[41] M. Burkitbayev, N. Bachilova, M. Kurmanbayeva, K. Tolenova, N. Yerezhepova, M. Zhumagul, A. Mamurova, B. Turysbek, G. Demeu, Effect of sulfur-containing agrochemicals on growth, yield, and protein content of soybeans (*Glycine max* (L.) Merr), Saudi J. Biol. Sci. 28 (1) (2021) 891–900.

[42] A. Ali, Z. Iqbal, S.W. Hassan, M. Yasin, T. Khaliq, S. Ahmed, Effect of nitrogen and sulphur on phenology, growth and yield parameters of maize crop, Sci. Int. 25 (2013) 363–366.

[43] H.W. Scherer, Sulphur in crop production — invited paper, Eur. J. Agron. 14 (2) (2001) 81–111, https://doi.org/10.1016/S1161-0301(00)00082-4.

[44] L. Ercoli, I. Arduini, M. Mariotti, L. Lulli, A. Masoni, Management of sulphur fertiliser to improve durum wheat production and minimise S leaching, Eur. J. Agron. 38 (2012) 74–82.

[45] F.J. Zhao, M. Hawkesford, S. McGrath, Sulphur assimilation and effects on yield and quality of wheat, J. Cereal. Sci. 30 (1999) 1–17.

[46] V. Ram, R.N. Singh, K. Singh, Studies on integrated use of FYM, nitrogen and sulphur on growth, yield attributes and yield on winter maize (*Zea mays* L.), Plant Archieves 6 (2) (2006) 749–752.

[47] H. Klikocka, M. Cybulska, B. Barczak, B. Narolski, B. Szostak, A. Kobiałka, A. Nowak, E. Wójcik, The effect of sulphur and nitrogen fertilization on grain yield and technological quality of spring wheat, Plant Soil Environ. 62 (5) (2016) 230–236, https://doi.org/10.17221/18/2016-PSE.

[48] Anonymous, Shell Thiogro Urea-Es Technology, 2015. www.shell.com/sulphur/thiogro.

[49] R.K. Sutar, A.M. Pujar, B.A. Kumar, N.S. Hebsur, Sulphur nutrition in maize-a critical review, International Journal of Pure and Applied Biosciences 5 (6) (2017) 1582–1596.

[50] S.S. Rathore, Kapila Shekhawat, B.K. Kandpal, O.P. Premi, S.P. Singh, Dhiraj Singh, Sulphur management for increased productivity of Indian mustard: a review, Annals of Plant and Soil Research 17 (1) (2015) 1–12.

[51] C.L. Rawat, S. Dimree, R.K. Pathak, U.S. Tiwari, R. Kumar, Response of sulphur and zinc nutrients on nutrient uptake in maize and wheat crop and effect of various treatments on quality of maize-wheat cropping system, J. Pharmacogn. Phytochem. 10 (2) (2021) 873–877.

[52] P.R. Shewry, A.S. Tatham, Disulphide bonds in wheat gluten proteins, J. Cereal. Sci. 25 (1997) 207–227, https://doi.org/10.1006/jcrs.1996.0100.

[53] H.V. Jordan, L.E. Ensminger, The role of sulfur in soil fertility, Adv. Agron. 10 (1959) 407–434, https://doi.org/10.1016/S0065-2113(08)60071-1.

[54] H. Hesse, V. Nikiforova, B. Gakiére, R. Hoefgen, Molecular analysis and control of cysteine biosynthesis: Integration of nitrogen and sulphur metabolism, J. Exp. Bot. 55 (2004) 1283–1292.

[55] B. Barczak, T. Knapowski, W. Kozera, M. Ralcewicz, Effects of sulphur fertilisation on the content and uptake of macroelements in narrow-leaf lupin, Rom. Agric. Res. 31 (2014) 1–7.

[56] A. Jamal, I. Saleem Fazli, S. Ahmad, M.Z. Abdin, S.J. Yun, Effect of nitrogen and sulphur application on nitrate reductase and ATP-sulphurylase activities in soybean, Korean J. Crop Sci. 51 (2006) 298–302.

[57] Ankit, R.S. Bana, K.S. Rana, R. Singh, S. Godara, M. Grover, A. Yadav, A.K. Choudhary, T. Singh, M. Choudhary, No-tillage with Residue Retention and Foliar sulphur nutrition enhances productivity, mineral Biofortification and crude protein in rainfed Pearl millet under typic Haplustepts: Elucidating the responses imposed on an Eight-year long-term experiment, Plants 11 (2022) 943, https://doi.org/10.3390/plants11070943.

[58] A. Kanal, T. Kautz, F. Ellmer, J. Rühlmann, Effects of long-term organic and mineral fertilization on sulphur and nitrogen supply of spring barley in Berlin-Dahlem (Germany) and Tartu (Estonia). Archives Agron, Soil Sci. 49 (5) (2003) 543–553, https://doi.org/10.1080/03650340310001594808 (in German).