



Sulphur Fractions Under Soybean–Wheat Cropping System in 50-years Old Long-term Fertilizer Experiment on a Vertisol

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ABSTRACT

The present experiment was conducted during *rabi* season, 2021–22 at Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur, Madhya Pradesh, to evaluate the effect of long-term application of inorganic fertilizers and organic manure on sulphur dynamics under a 50-year-old soybean–wheat cropping system in a Vertisol. The results revealed that the application of 100% NPK along with FYM @ 5 t ha⁻¹ recorded the highest organic carbon content and available nitrogen, phosphorus, and potassium at both 0.0–0.15 m and 0.15–0.30 m soil depths, whereas the lowest values were observed under the control plot. The integrated use of balanced fertilizers and FYM significantly enhanced available sulphur and different sulphur fractions in comparison to the control and sulphur-free treatments (100% N and 100% NPK-S). Among the sulphur fractions, their relative abundance followed the order: Total-S > Organic-S > Heat Soluble-S > Water Soluble-S. Significant positive correlations were observed between soil organic carbon, available N, P, K and S and the various sulphur fractions at both soil depths. Continuous application of sulphur-free fertilizers resulted in depletion of available sulphur compared to its initial status. The study concluded that the conjoint application of balanced fertilizers with organic manure, improved sulphur availability, maintained soil fertility, and sustained crop productivity. Therefore, sulphur application along with balanced fertilization was found essential for the long-term sustainability of the soybean–wheat cropping system.

KEYWORDS: Sulphur, long-term experiment, productivity, soybean-wheat cropping system, vertisol

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1. INTRODUCTION

The soybean (*Glycine max* L.)–wheat (*Triticum aestivum* L.) cropping system is one of the most important and widely adopted cropping sequences in the Vertisols of central India, particularly in the Vindhyan Plateau and extensive areas of Madhya Pradesh (Khandagle et al., 2020). Long-term Fertilizer Experiments (LTFEs) provide an excellent opportunity to assess the cumulative effects of different nutrient management practices on crop productivity, soil fertility, and nutrient dynamics. Results from these experiments have demonstrated that balanced fertilization and integrated nutrient management improve crop yield, nutrient-use efficiency, and sustainability of intensive agriculture (Bagde et al., 2023). The combined application of inorganic fertilizers and organic manure (FYM), has been reported to enhance soil physical, chemical, and biological properties, thereby improving nutrient availability and sustaining crop productivity over long periods (Patel et al., 2018; Dwivedi et al., 2019; Pathariya et al., 2022). In contrast, imbalanced fertilizer application often leads to nutrient depletion and deterioration of soil quality. In vertisols, nutrient availability is influenced not only by the inherent soil characteristics but also by nutrient management practices because a considerable proportion of applied nutrients becomes fixed in the soil and remains unavailable to plants (Thakur et al., 2025a; Dwivedi et al., 2026). Among the essential plant nutrients, sulphur (S) is recognized as the fourth major nutrient after nitrogen, phosphorus, and potassium because of its vital role in plant growth and metabolism. Sulphur is particularly important for oil-seed crops as it forms an integral part of sulphur-containing amino acids such as cysteine, cystine, and methionine, which are involved in protein synthesis and oil formation. Adequate sulphur nutrition enhances seed quality, oil content, and crop productivity, whereas its deficiency adversely affects crop growth and yield (Thakur and Sawarkar, 2009). In recent decades, sulphur deficiency has emerged as a major nutritional constraint in Indian agriculture due to intensive cropping, increased use of high-analysis sulphur-free fertilizers, and reduced application of organic manures. More than 41% of Indian soils are reported to be deficient in sulphur, especially in major oilseed-growing states including Madhya Pradesh, Gujarat, Maharashtra, Rajasthan, Uttar Pradesh, Karnataka, Andhra Pradesh, Tamil Nadu, Odisha, and Punjab (Singh, 2001). Sulphur exists in soils in both organic and inorganic forms. Generally, 70–90% of total soil sulphur is present in organic form, while only a small fraction occurs as inorganic sulphate and sulphide forms. The availability of sulphur to plants is regulated by different sulphur fractions such as water-soluble S, sulphate-S, heat-soluble S, organic-S, and total-S. Among these fractions, organic sulphur constitutes the major pool

and plays a dominant role in controlling sulphur availability through mineralization processes (Parihar et al., 2010 and Birla et al., 2015). Moreover, sulphur is relatively mobile in the soil profile and is susceptible to leaching losses under frequent irrigation and heavy rainfall conditions (Thakur et al., 2010). Permanent manurial experiments provide valuable information on the long-term effects of different nutrient sources and their combinations on crop productivity, soil health, and nutrient balance under intensive cropping systems (Thakur et al., 2022; Tiwari et al., 2024). Although the beneficial effects of integrated nutrient management on crop performance and soil fertility have been widely reported, information regarding long-term sulphur balance under soybean–wheat cropping systems in vertisols is limited. Therefore, the present investigation was undertaken to evaluate sulphur balance in a 50-year-old long-term fertilizer experiment under soybean–wheat cropping system in a vertisol and to develop sustainable nutrient management strategies for maintaining soil fertility and crop productivity.

2. MATERIALS AND METHODS

2.1. Soil and soil characteristics

The field experiment was carried out during 2021–22 after 50 cropping cycle of soybean–wheat in a vertisol. The study was conducted under All India Coordinated Research Project on Long-Term Fertilizer Experiment at the Department of Soil Science and Agricultural Chemistry, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur, Madhya Pradesh, India, which was commenced in 1972. The experimental site is positioned at 23°10' N latitude and 79°57' E longitude and located at 393 meters above sea level. It has a distinctive semi-arid and sub-tropical weather with a feature of dry summer and cold winter. The average temperature throughout the winter period varied from 9.92°C to 26.8°C, with relative humidity ranging from 70% to 90% (November to February). During summer, the weather is usually dry and warm from March to June and temperature can reach upto 46°C. The monsoon season is lasting from mid-June until mid-September and temperature varied from 22°C to 35°C, with relative humidity ranging from 41% to 92%. The region's having yearly rainfall averages 1130 to 1440 mm.

The soils of the experimental field are belongs to montmorillonitic hyperthermic having 56.8% clay contents (Kheri series) of *Typic Haplustert* family (Vertisol). At the start of the experiment basic properties of surface soil (0.0 – 0.15 m depth) had pH of 7.6, electrical conductivity 0.18 dS m⁻¹ (1:2.5 soil : water ratio) and organic carbon 5.7 g kg⁻¹. The soil available N, P, K and S were 193, 7.6, 370 and 15.6 kg ha⁻¹, respectively. Also, the concentrations of soil available Zn, Fe, Mn and Cu, in the surface soil were 0.33, 2.47, 16.10 and 0.11 mg kg⁻¹ soil, respectively.

2.2. Experimental details

The long term fertilizer experiment was laid out for 10 treatments with four replications at the Research Farm. It was arranged in the randomized block design. The size of individual plots was 17m×10.8 m (183.6 m²). The spacing between the replications is 2.0 m, which is separated with a permanent bund; while spacing between the treatments is 1.0 m. However, only eight treatments were used for the present investigation *i.e.* T₁=50% NPK, T₂=100% NPK, T₃=150% NPK, T₄=100% NP, T₅=100% N, T₆=100% NPK+FYM, T₇=100% NPK (-S) and T₈=Control.

The crops soybean and wheat were grown in rotation and the recommended fertilizer applications (100% NPK) for these crops were as 20:80:20 and, 120:80:40 kg ha⁻¹, respectively. The sources of N, P and K were single super phosphate (SSP) and muriate of potash, respectively. In sulphur free treatment *i.e.* 100% NPK(-S), the diammonium phosphate (DAP) was used instead of SSP as source of P. The application of organic manure @ 5 t FYM ha⁻¹ year⁻¹ is being practiced only to soybean crop during *Kharif* season. Soybean crop (variety JS 9752) was sown as rainfed during *kharif* season and wheat crop (variety GW 366) was sown under irrigated condition during *rabi* season. The wheat was irrigated 3–4 times at critical phases of crop expansion. The suitable control measures were kept during insects/pest attack and diseases infestations. After maturity of soybean and wheat crops having 07–10% moisture content both the crops were harvested and thresh out for recording yield data. For the estimation of total crop productivity, the sum of grain yield of soybean and wheat were used.

2.3. Soil and plant analysis

The surface (0.0–0.15 m) and subsurface (0.15–0.30 m) soil samples were collected after 50 cropping cycles of soybean-wheat during 2021–22 from various treatments. The soil samples were analyzed to different parameters by following standard procedures for soil pH and EC (Jackson, 1973), organic carbon (Walkley and Black, 1934) available nitrogen (Subbaiah, and Asija, 1956), available phosphorous (Olsen et al., 1954), available potassium (Muhre et al., 1965) and available sulphur (Williams and Steinbergs, 1959). The oven dried plant (grain and straw) samples were ground and one gram of ground plant sample was taken and digested in 100 ml conical flask with 20 ml of 1 : 2.5 ratio diacid mixture of nitric and perchloric acid. The digested material was filtered in 100 ml volumetric flask and filtrate was diluted up to mark and this aliquot was used for the estimation of S contents by spectro-photometer as described by Bardsley and Lancaster, (1960).

2.4. S-fractionations

The available S and water-soluble sulphur contents were estimated by Williams and Steinbergs (1959). The organic

sulphur content in soil was estimated by Bardsley and Lancaster (1960). However, the soil samples were heated for three hours at 500°C with sodium bicarbonate (NaHCO₃) in an electric furnace for the estimation of heat soluble sulphur content in soil as described by Williams and Steinberg (1959). The total sulphur in the soil was determined by the method of Choudhary and Cornfield (1966).

2.5. Soil sulphur balance

Sulphur balance was calculating by total sulphur inputs in soil through diverse sources and output through total sulphur uptake by the crops. The contribution of sulphur from the soil reserve pool was computed by taking into consideration these attributes with initial sulphur status in the 1972 and final sulphur status in soil during 2021–22.

2.6. Statistical analysis

The data generated on soil analysis, grain yields of both crops and their sulphur uptake were statistically analyzed to describe appropriate implication as per standard method (Panse and Sukhatme, 1970).

3. RESULTS AND DISCUSSION

3.1. Soil pH and electrical conductivity (EC)

The data of soil pH and EC of 0.0–0.15 m and 0.15–0.30 m soil depth are presented in Table 1 and found that pH and EC value have not changed significantly due to the long-term application of different fertilizers alone or in combination with FYM over last 50 years in a Vertisol under soybean-wheat cropping system. This might be due to high buffering capacity of soil and presence of free calcium carbonate in the soil (Thakur et al., 2009). Further, the soil pH and EC values were increased with increasing soil depth from 0–0.15 m to 0.15–0.30 m, which indicates the leaching of calcium and consequently its precipitation as a carbonate at 0.15–0.30 m soil depth. Similar results were also noted under soybean – wheat cropping system in a Vertisol (Thakur et al., 2021 and Thakur et al., 2025a).

3.2. Soil organic carbon

The data of organic carbon contents in soil (Table 1) significantly increased from its initial value 5.7 g kg⁻¹ (1972) by long term application of inorganic fertilizers and organic manure in all the treatments except control plot and 100% N alone treatments at surface soil (0.0–0.15 m). The soil organic carbon content varied from 4.7 to 8.7 g kg⁻¹ and 4.1 to 7.9 g kg⁻¹ at surface and subsurface soils, respectively. The data of soil organic carbon contents was noted the OC value 4.7 and 4.1 g kg⁻¹ at surface and surface soils, respectively in control plot. The highest value of soil organic carbon content was noted in 100% NPK + 5 t FYM ha⁻¹ treatment, which is due to incorporation of FYM and higher productivity added extra carbon in soil. Patel et al. (2018) observed that

Table 1: Effect of long-term application of fertilizer and manure on physico-chemical properties of surface and subsurface soil

Treatments	Soil pH		Soil EC (dS m ⁻¹)		Soil organic carbon (g kg ⁻¹)		Available nutrients (kg ha ⁻¹)					
							Nitrogen (N)		Phosphorous (P)		Potassium (K)	
	Soil Depth (m)											
	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30
50% NPK	7.50	7.52	0.15	0.16	5.8	5.2	221	196	21.9	16.9	260	245
100% NPK	7.54	7.57	0.17	0.18	7.3	6.5	265	232	32.2	22.6	304	280
150% NPK	7.57	7.61	0.18	0.19	8.0	7.2	298	265	36.1	27.5	328	294
100% NP	7.54	7.56	0.16	0.17	6.6	5.8	235	210	28.0	19.3	241	218
100% N	7.45	7.47	0.11	0.12	5.1	4.4	210	189	9.1	8.7	240	216
100% NPK+FYM	7.47	7.50	0.12	0.13	8.7	7.9	316	284	37.9	28.1	337	301
100% NPK (-S)	7.53	7.56	0.16	0.17	7.2	6.1	262	230	31.7	22.1	301	278
Control	7.49	7.51	0.13	0.14	4.7	4.1	180	167	8.2	7.9	236	212
SE _m ±	0.20	0.18	0.02	0.02	0.31	0.27	13.26	10.35	2.26	1.38	13.58	9.58
CD (<i>p</i> =0.05)	NS	NS	NS	NS	0.91	0.79	39.01	30.44	6.64	4.07	39.94	28.19

conjoint use fertilizers with FYM built up organic carbon content in soil. Dwivedi et al., 2012 also found that the conjoint use of inorganic fertilizers with FYM sustained soil health and crop productivity (Bairwa et al., 2021 and Thakur et al., 2025b).

The data further revealed that the organic carbon content in both surface and subsurface soil increases with graded level of fertilizers from 50% to 150% NPK. It could be due to augment in crop productivity which resulted better incorporation of residual biomass through crop roots, rhizo-depositions, stubbles and leaves (Singh et al., 2012). However, the organic carbon content was decreases with increasing soil depth; the higher value of soil organic carbon was noted in surface soil as compared to subsurface soil (Table 1). It could due to the continuous cropping of soybean and wheat crops improved and enhanced the decomposition process of crop residues at surface soil (Thakur et al., 2023).

3.3. Available nutrients (NPK)

Long-term fertilizer experiments over fifty years in the soybean–wheat cropping system revealed distinct effects of nutrient management practices on the availability of nitrogen, phosphorus, and potassium in soil. The available N content ranged between 180–316 kg ha⁻¹ (0–0.15 m) and 167–284 kg ha⁻¹ (0.15–0.30 m), with the highest values recorded under 100% NPK+FYM treatments, attributed to enhanced mineralization of organic matter, while balanced fertilizer applications (50%, 100%, and 150% NPK) consistently improved soil N compared to control and imbalanced fertilization (N alone) (Bairwa et al., 2021; Kushwaha et al., 2017; Dubey et al., 2016).

In the case of phosphorus, nutrient imbalance (no fertilizer or 100% N alone) caused significant depletion due to continuous crop removal, whereas the application of 100% NP and especially 100% NPK+FYM markedly increased available P, with maximum values of 37.9 and 28.1 kg ha⁻¹ in surface and sub-surface soils, respectively, highlighting the positive role of organic matter in maintaining soil P status (Khandagle et al., 2020; Sharma et al., 2021; Bagde et al., 2023).

Conversely, potassium availability showed a sharp decline from its initial value of 370 kg ha⁻¹ in 1972 to a range of 236–337 kg ha⁻¹ after five decades, with the greatest depletion under control, 100% N, and 100% NP treatments. The application of balanced NPK, particularly in conjunction with FYM, not only minimized K depletion but also enhanced soil K status through both direct K addition and reduced fixation, recording maximum values of 337 and 301 kg ha⁻¹ at 0–0.15 m and 0.15–0.30 m depths, respectively (Sawarkar et al., 2013; Pathariya et al., 2022; Inwati et al., 2022). These results emphasize that integrated use of organic and inorganic fertilizers is crucial to sustain soil fertility, as current recommendations, particularly for K, may be inadequate for long-term productivity.

3.4. Distribution of sulphur fractions

3.4.1. Available / sulphate sulphur

The results of investigation depicted in Table 2 and found that the decline in available/sulphate sulphur in soil 5.3 mg kg⁻¹ in control, followed by 5.7 mg kg⁻¹ in 100% N alone and 5.6 mg kg⁻¹ in sulphur free treatment (100% NPK-S)

Table 2: Effect of long-term application of fertilizers and manure on available sulphur and its fractions in surface and subsurface soils

Treatments	Various sulphur fractions (mg kg ⁻¹)									
	Sulphate-S		Organic-S		Water soluble-S		Heat soluble-S		Total-S	
	Soil Depth (m)									
	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30	0.0-0.15	0.15-0.30
50% NPK	11.3	10.7	63.3	50.1	18.1	12.9	34.0	31.0	167	144
100% NPK	16.0	14.1	71.0	57.5	27.0	20.2	36.5	34.5	183	168
150% NPK	17.8	15.3	73.5	65.4	31.5	25.1	40.8	36.3	201	186
100% NP	15.0	13.6	65.7	52.9	25.3	19.5	35.2	33.0	174	156
100 % N	5.7	5.5	40.0	33.7	11.5	8.6	24.8	22.4	89	79
100% NPK+FYM	18.9	16.1	74.2	65.5	32.9	26.2	43.2	42.5	203	190
100% NPK (-S)	5.6	5.3	42.7	34.3	11.1	8.8	25.1	22.6	95	82
Control	5.3	5.1	39.8	32.6	11.0	8.1	24.1	22.1	85	78
SEm±	0.47	0.30	1.59	1.10	0.84	0.59	0.84	0.89	10.04	5.03
CD (<i>p</i> =0.05)	1.34	0.84	4.68	3.24	2.36	1.75	2.35	2.61	29.54	14.79

from its initial value 7.8 mg kg⁻¹ (1972) under soybean–wheat cropping system. This could be due to continuous application of di-ammonium phosphate (DAP) instead of single super phosphate (SSP) as a source P, leading sulphur deficiency in 100% NPK (-S) treatment, resulting in reduced crop yield (Thakur et al., 2010; Dwivedi et al., 2026). However, substantial augment in available S content was noticed in 100% NPK where P was applied through SSP it contains 12% S additionally with 16% P₂O₅. Further, findings revealed that the integrated application of 100% NPK with FYM was significantly increased available S content 18.9 mg kg⁻¹ in the soil. Similar, results were also reported by Birla et al. (2015) and found that the continuous sulphur fertilizer addition increased the sulphate-S content under continuous cropping of soybean-wheat in a Vertisol. However, the available/sulphate S content was decreases with increasing soil depth, the higher value of available S were found in surface soil (0.0–0.15 m) as compared to sub surface soil (0.15–0.30 m). It can be ascribed the fact that the aerobic conditions prevailed in surface soil only due to narrow pore size distribution. Thus, the distributions of available S contents follow such behaviour irrespective of its application or prevailing soil conditions (Birla et al., 2015 and Raghuwanshi et al., 2026).

3.4.2. Organic–Sulphur (Org.-S)

The data on organic sulphur (Org.-S) are listed in Table 2 and depicted that the maximum content of Org.-S (74.2 mg kg⁻¹) in the 100% NPK+FYM treatment, followed by 150% NPK treatment (73.5 mg kg⁻¹) at 0.0–0.15 m soil depth. Similarly, at 0.15–0.30 m soil depth the maximum

value 65.5 mg kg⁻¹ of organic sulphur was also noted in 100% NPK+FYM, while the minimum value 32.6 mg kg⁻¹ found in control plot. Further, findings revealed that the graded level of fertilizer application was linearly increased the Org.-S contents in both soil depths. However, the continuous application of sulphur free fertilizer i.e. 100% NPK (-S) resulted in depletion of Org.-S contents by 66.3% and 67.6% over 100% NPK treatments at surface and sub surface soils, respectively. Birla et al. (2015) also found similar findings that the continuous application of 100% NPK without sulphur soybean- wheat cultivation resulted in decline in Org.-S content.

3.4.3. Water soluble–sulphur (WS-S)

The perusal of data (Table 2) of water soluble sulphur contents ranged from 11.0 mg kg⁻¹ to 32.9 mg kg⁻¹ at 0.0–0.15 m soil depth and 8.8 mg kg⁻¹ to 26.2 mg kg⁻¹ at 0.15–0.30 m soil depth. The maximum concentration of WS-S was found in 100% NPK+FYM (32.9 and 26.2 mg kg⁻¹), followed by in 150% NPK treatments (31.5 and 25.1 mg kg⁻¹) at 0.0–0.15 and 0.15–0.30 m soil depths, respectively. While, control plot were showed the lowest value of water soluble sulphur, followed by 100% N alone and 100% NPK (-S) treatment. The results further revealed that the application of fertilizer S (100% NPK) increased WS-S content as compared to 100% NPK (-S) (Birla et al., 2015).

3.4.4. Heat soluble–sulphur (HS-S)

Heat soluble-S is a key fraction for the assessment of sulphur status in soils. This provides a measure of sulphate-S plus

a fraction of organic-S. Most of the sulphur released by heat treatment is organic in nature, and it is apparent that small amount of organic sulphate can easily separated from organic matter by heat. The heat soluble sulphur (Table 2) was increased 36.5 mg kg^{-1} in 100% NPK treatment over control (24.1 mg kg^{-1}) and 100% NPK (-S) treatments (25.1 mg kg^{-1}) at 0.0–0.15 m soil depth this may be due to the conversion of applied sulphur containing fertilizer into storage of heat-soluble sulphur in the soil (Birla et al., 2015). Further, the concentration of heat soluble-S decreased with increasing soil depths in all the treatments. The higher concentration of HS-S in surface soil is maybe due to the mineralization of crop residues and high organic carbon contents in upper soil layer. It is evident as this form of sulphur is connected with organic-S and organic-S decreases with increasing soil depth.

3.4.5. Total-sulphur (Total-S)

Perusal of data (Table 2) of Total-S contents indicated that the 100% NPK+FYM treatment was found maximum Total-S content (203 and 190 mg kg^{-1}) in soil, which is at par with 150% NPK (201 and 186 mg kg^{-1}) treatments at 0.0–0.15 and 0.15–0.30 m soil depth, respectively. While, minimum value was noted in control plot (85 and 78 mg kg^{-1}) for 0.0–0.15 and 0.15–0.30 m soil depth, respectively. Further, data showed that the total sulphur content was gradually increased from 167, 183, 201 mg kg^{-1} with 50%, 100% and 150% NPK treatments, respectively. The maximum increase confined to 203 mg kg^{-1} when recommended dose of NPK was used with farmyard manure at 0.0–0.15 m soil depth. This may prove that FYM has a synergistic effect in accelerating the conversion of all soil sulphur to crop use (Birla et al., 2015). Similar trend were also observed at 0.15–0.30 m soil depth. According to Das et al. (2006) the maximum amount of Total-S form was only present near the surface and then decreased as depth developed, showing a trend for Total-S form to decrease. This might be explained by Total-slower S mobility, which prevents movement below certain depths.

3.4.6. Sulphur balance

Sulphur nutrient balances must be calculated to achieve the desired abundance without depleting native sulphur reserves and to maintain and improve soil fertility. Sulphur drain is calculated based on crop removal which were harvested (grain plus straw). The sulphur balance data presented in Table 3 indicated a positive balance of sulphur in the recommended dose of fertilizer with or without organic manure practices under soybean – wheat cropping system. Further, available S was also depleted from its initial value in control, 100% N alone and 100% NPK (-S) treatments due to the absence of sulphur in these treatments. Thus, the findings clearly indicated that the addition of sulphur

Table 3: Sulphur balance under soybean–wheat cropping sequence after 50 crop cycles (2021–22)

Treatments	Available S (mg kg^{-1})	Changes from initial (mg kg^{-1})	Increase / decrease ($\text{mg kg}^{-1} \text{ yr}^{-1}$)
50% NPK	11.3	3.5	0.07
100% NPK	16.0	8.2	0.16
150% NPK	17.8	10.0	0.20
100% NP	15.0	7.2	0.14
100 % N	5.7	-2.1	-0.04
100% NPK+ FYM	18.9	11.1	0.22
100% NPK (- S)	5.6	-2.2	-0.04
Control	5.3	-2.5	-0.05
Initial value (1972)	7.8	-	

is much essential with recommended dose of NPK for sustainable crop production and soil fertility (Thakur and Sawarkar, 2009; Thakur et al., 2010 and Sarvade et al., 2025).

3.5. Grain yield of and sulphur uptake by soybean–wheat cropping system

The average yield and total productivity of soybean and wheat are shown in Figure 1. The long term applications fertilizers alone or in combination with FYM under soybean–wheat cropping system in a Vertisol noted that the 100% N alone treatment had enhanced the yield by 23.5% and 38.6% for soybean and wheat, respectively as compared to control plot. The addition of phosphorus with nitrogen *i.e.* 100% NP treatment the yields were noted to be increased by 59.4% and 132.2% in soybean and wheat, respectively over 100% N alone treatment. Further, the

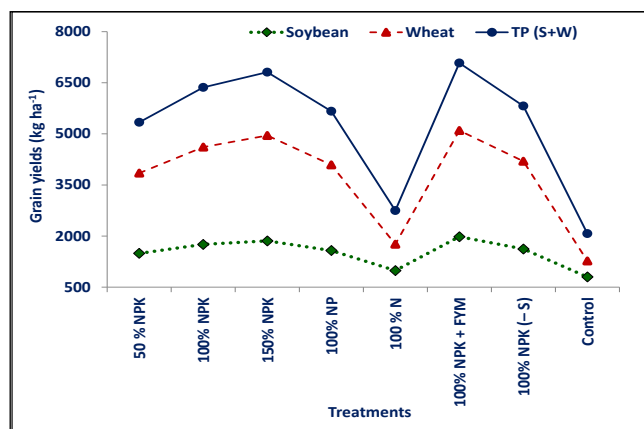


Figure 1: Effect of different nutrient management on soybean and wheat grain yields

application of potassium with nitrogen and phosphorous (100% NPK) also enhanced the yield by 11.4% and 12.8%, respectively over 100% NP treatment (Dwivedi et al., 2016, Meshram et al., 2018 and Dwivedi et al., 2019). However, the deficiency of S *i.e.* 100% NPK (-S) treatment has been manifested through yield reduction 7.7% in soybean and 9.0% in wheat against 100% NPK treatment. Hence, the addition of S becomes essential under intensive cropping. These results clearly showed that the highest grain yield was observed in 100% NPK+FYM treatment (1981 and 5100 kg ha⁻¹ in soybean and wheat, respectively) and the lowest yield of soybean (800 kg ha⁻¹) and wheat (1271 kg ha⁻¹) were recorded in control plot. The integration of recommended dose of inorganic fertilizers (100% NPK) with organic manure (FYM) showed a significant positive response for sustainable crop production in long term basis, because the addition of organic manure improved the overall soil health. Thus, the findings clearly indicated that the recommended dose of inorganic fertilizer with or without FYM is essential for sustainable crop production and soil health (Sawarkar et al., 2010 and Gupta et al., 2019).

Total S uptake by soybean and wheat are illustrated in Figure 2. The total S uptake was ranged between 2.3 to 18.9 kg ha⁻¹ in soybean and 6.3 to 46.3 kg ha⁻¹ in wheat, respectively.

The findings indicated that the highest S uptake by both the crops was found with 100% NPK + FYM, followed by the 150% NPK treatments, while, the lowest S uptake was observed in control plot. A similar result was also reported

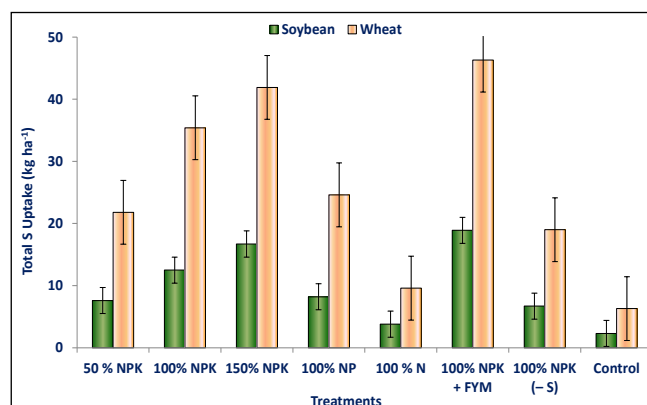


Figure 2: Effect of different nutrient management on total S uptake by soybean and wheat crops

by Birla et al. (2015).

3.6. Relationship of various sulphur fractions with soil properties and crop productivity

The correlation study between various types of sulphur are

Table 4: Correlation between soil properties and sulphur fractions at 0.0–0.15 m soil depth

	pH	EC	OC	N	P	K	Total S	Sulphate-S	Org.- S	WS-S	HS-S
pH	1										
EC	0.98**	1									
OC	0.44	0.40	1								
N	0.35	0.32	0.99**	1							
P	0.58	0.56	0.97**	0.97**	1						
K	0.34	0.29	0.95**	0.95**	0.86**	1					
Total S	0.44	0.45	0.74*	0.72*	0.76**	0.61*	1				
Sulphate S	0.44	0.42	0.77**	0.75*	0.78**	0.63*	0.98**	1			
Organic S	0.46	0.47	0.75*	0.73*	0.77**	0.62*	0.99**	0.98**	1		
Water soluble S	0.46	0.43	0.80**	0.79**	0.76**	0.69*	0.96**	0.99**	0.96**	1	
Heat soluble S	0.36	0.35	0.79**	0.78**	0.77**	0.76**	0.99**	0.98**	0.98**	0.97**	1

*: Significance ($p=0.05$) level; **: Significance ($p=0.01$) level

Table 5: Correlation between soil properties and sulphur fractions at 0.15–0.30 m soil depth

	pH	EC	OC	N	P	K	Total S	Sulphate-S	Org.- S	WS-S	HS-S
pH	1										
EC	0.96**	1									
OC	0.49	0.45	1								
N	0.42	0.35	0.98**	1							
P	0.62*	0.59	0.98**	0.95**	1						

Table 5: Continue...

	pH	EC	OC	N	P	K	Total S	Sulphate-S	Org.- S	WS-S	HS-S
K	0.49	0.45	0.91**	0.92**	0.91**	1					
Total S	0.42	0.47	0.81*	0.75*	0.80**	0.63*	1				
Sulphate S	0.42	0.45	0.82**	0.75*	0.79**	0.60*	0.99**	1			
Organic S	0.43	0.46	0.84*	0.79*	0.82**	0.67*	0.98**	0.99**	1		
Water soluble S	0.43	0.40	0.87**	0.83**	0.83**	0.66*	0.96**	0.98**	0.97**	1	
Heat soluble S	0.26	0.29	0.80**	0.78**	0.80**	0.65*	0.97**	0.97**	0.97**	0.96**	1

*: Significance ($p=0.05$) level; **: Significance ($p=0.01$) level

presented in Table 4 and 5 showed significant correlations of all sulphur fractions with organic carbon and available nutrients (NPK) at both soil depth 0.0–0.15 m and 0.15–0.30 m. The values of correlation coefficient were 0.74*, 0.77**, 0.75**, 0.80** and 0.79** for total-S, sulphate-S, organic-S, water soluble-S and heat soluble-S contents with soil organic carbon, respectively at surface soil. While, soil pH and EC were noted non-significant relationship with all sulphur fractions (Birla et al., 2015).

4. CONCLUSION

The study concluded that long-term application of fertilizers and organic manure under soybean–wheat cropping system improved sulphur fractions and maintained sulphur balance in Vertisol. The 100% NPK+5 t FYM ha⁻¹ treatment sustained soil fertility and crop productivity. However, continuous use of sulphur-free fertilizers reduced soybean and wheat yields and decreased sulphur fractions at 0.0–0.15 m and 0.15–0.30 m soil depths. Sulphur fractions showed significant positive correlations with soil organic carbon, available NPK, and crop productivity.

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