



RESEARCH ARTICLE

Impact of nutrient management practices on sulphur availability in soils under rice-wheat cropping system

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Abstract

A study was carried out to understand the impact of different nutrient management practices on soil sulphur (S) fractions under rice-wheat cropping system (RWCS) in the Indo-Gangetic Plains. Soils from 6 sites representing integrated nutrient management (IntNM) and exclusive inorganic nutrient management (InoNM) practices in Punjab (PB), Haryana (HR) and Uttar Pradesh (UP) were evaluated for water-soluble sulphur (WSS), organic sulphur (OS), available S (CaCl₂-extractable S), sulphur availability index (SAI) and organic carbon-organic sulphur (SOC:OS) ratio across three soil depths (0–15, 15–30 and 30–60 cm) using standard protocols. Results showed that InoNM maintained higher WSS with maximum values at 0–15 cm depth under PB-InoNM (17.0 mg kg⁻¹), while IntNM enhanced OS, attaining 235 mg kg⁻¹ under HR-IntNM. Available S was highest under PB-InoNM (14.8 mg kg⁻¹ at surface) and SAI values were also elevated under IntNM (6.42 in HR-IntNM), indicating improved sulphur release potential. The SOC:OS ratio ranged from 22.1 to 42.4, with high values under UP-IntNM at surface indicating improved sequestration of sulphur. These results underscore the superior performance of IntNM, combining farmyard manure (FYM) with chemical fertilisers, in improving OS, SOC and SAI, particularly in surface soils. The IntNM also resulted in higher SOC:OS ratio, indicating sustained sulphur release and improved soil health in RWCS.

Keywords: Indo-Gangetic Plains; integrated nutrient management; rice-wheat cropping system; soil health; sulphur fractions; sulphur availability index

Introduction

Sustainable intensification of agricultural systems requires a paradigm shift from yield-centric to holistic approaches that balance productivity, environmental stewardship and long-term soil health (1, 2). The rice-wheat cropping system (RWCS), occupying 24 million hectares across the Indo-Gangetic Plains (IGP), represents one of the world's most intensive agricultural systems, feeding over 400 million people while facing unprecedented sustainability challenges (3, 4). In the context of intensive cropping systems like the rice-wheat system prevalent across South Asia, the balance between nutrient inputs and outputs is often disrupted, leading to nutrient depletion and soil degradation (5). Since the introduction of the Green Revolution in India, the continuous use of sulphur-free fertilisers, intensive multiple cropping, adoption of repeated rice-wheat cropping sequence by farmers and adoption of high-yielding varieties have gradually led to widespread sulphur (S) deficiency in agricultural soils (6). Nearly 58.6% of the soils in India are deficient in available sulphur (7). Understanding the dynamics of essential nutrients like sulphur becomes crucial, as it plays a vital role in plant metabolism, protein synthesis and overall crop yield (8, 9). The role of sulphur in plant nutrition and soil fertility is multifaceted (10, 11).

Sulphur exists in the soil in both organic and inorganic forms, each with distinct characteristics and implications for plant uptake and availability (12, 13). Organic sulphur (OS), which is bound to soil organic matter (SOM), serves as a slow-release reservoir that can be mineralised over time to replenish the plant-available inorganic sulphur pool (14, 15). In contrast, water-soluble inorganic sulphur, typically in the form of sulphate, is immediately accessible for plant uptake (16, 17). Understanding the balance and dynamics between these two sulphur fractions and the impact of various nutrient management practices on them, is crucial for developing effective fertilisation strategies and promoting environmentally responsible agriculture (13, 18). The cultivation of green manure crops in intensive cropping systems is important for enhancing crop productivity through soil quality improvement (19). Integrated nutrient management (IntNM) strategies, combining organic and inorganic nutrient sources, offer a promising approach to address these challenges by promoting nutrient use efficiency and soil health (20). Conversely, sole reliance on inorganic nutrient management (InoNM) may lead to soil imbalances and reduced long-term sustainability (21). Despite the recognised importance of sulphur, there remains a notable lack of comparative field data on sulphur fractions under long-term nutrient management practice in

RWCS soils of the Indo-Gangetic Plain. Most of the existing evidence on sulphur dynamics in the rice–wheat cropping system was derived from controlled long-term experiments conducted at research stations, where nutrient inputs and environmental factors are systematically managed. However, the actual management practices adopted by the farmers in the Indo-Gangetic Plains may not fully align with such controlled settings. In view of the extensive geographical spread and diversity of management practices in RWCS, field-based evaluation under real farming conditions is essential to generate on-farm sulphur management recommendations. Critical knowledge gaps therefore persist, particularly with respect to: (i) quantitative assessment of S in various soil fractions under contrasting long-term management practices, (ii) understanding of management impacts on carbon-sulphur coupling and soil health and (iii) the influence of management practices on sulphur availability index (SAI) in the IGP.

This study tests 2 primary hypotheses: (1) IntNM practices will enhance organic sulphur pools and carbon sequestration compared to InoNM; (2) IntNM will improve sulphur availability index. The objective of the study was: (i) to assess the various sulphur fractions in soils under varying nutrient management practices in IGP and (ii) to assess the SAI and soil organic carbon to organic sulphur (SOC:OS) ratio in the collected soils.

Materials and Methods

Study area

This study was designed to assess the impact of existing, long-term management practices on sulphur availability in soil under farmers' field condition. Before the selection of sites, a farmer's field survey was conducted in 3 states namely, Punjab, Haryana and Uttar Pradesh, to collect detailed information on cropping history, fertiliser application patterns, organic amendments and nutrient management practices. Based on the information obtained, representative sites with consistent long-term integrated and inorganic nutrient management practices were identified for soil sampling. Different nutrient management practices followed by the farmers were considered as treatments for comparative evaluation. Soil samples were collected from six representative sites in these 3

states (Table 1), with 3 sites following IntNM and 3 sites following InoNM.

The information on soil types in the study area was collected from ICAR– National Bureau of Soil Survey and Land Use Planning, Regional Centre, Delhi. Soils across all sites were Inceptisols (according to USDA Soil Taxonomy), with a similar sandy clay loam texture, which facilitates comparability for meaningful interpretation of management effects. Although the soils across the selected districts largely belonged to similar textural classes, variations were observed in their fertility status. The baseline important soil properties, including pH, electrical conductivity (EC), bulk density (BD), cation exchange capacity (CEC) and available nitrogen (N), phosphorus (P) and potassium (K) across the study area are presented in Table 2.

The RWCS are predominant in the upper and trans- IGP of Punjab, Haryana and Uttar Pradesh. Farmers in this region have been following inorganic and integrated nutrient management practices for a considerable period. Under inorganic nutrient management, farmers have been using only chemical fertilisers and in case of integrated nutrient management, farmers have been using chemical fertilisers along with organic manure or green manure. Detailed information about management practices with location is given in Table 1.

Soil sampling and processing

Composite soil samples were collected from three depths (0–15, 15–30 and 30–60 cm) with 3 replicates from the locations under different management practices. The total number of samples were 54 (6 locations × 3 depths × 3 replications). Soil sampling was carried out immediately after the harvesting of the wheat crop

Table 2. Important properties of soils (0–15 cm) in the study area

Parameters	Range in characteristics
pH	7.76–8.11 (±0.13)
EC (dS m ⁻¹)	0.14–0.43 (±0.09)
CEC (meq 100 g ⁻¹)	7.52–8.40 (±0.37)
Available N (kg ha ⁻¹)	226–281 (±20.3)
Available P (kg ha ⁻¹)	14.9–21.7 (±2.69)
Available K (kg ha ⁻¹)	139–313 (±68.8)
BD (Mgm ⁻³)	1.43–1.47 (±0.01)

Figures in parentheses indicate standard deviation.

Table 1. Soil sampling locations and treatment details in the rice–wheat cropping system

Treatment*	Treatment details		Management Practise	Location		Climatic conditions
	Rice	Wheat		Geographic Coordinates	Location	
PB-InoNM	NPK 129:0:27 kg ha ⁻¹ ; zinc 6 kg ha ⁻¹ ; sulphur 21 kg ha ⁻¹	NPK 144:52:0 kg ha ⁻¹	Inorganic (followed for more than 14 years)	N 31°09'23" E 75°58'29"	Shaheed Bhagat Singh Nagar, Punjab	Subtropical climate, mean annual rainfall 924 mm, predominantly received during monsoon months (July–September); Hot, humid summers and cold, dry winters.
PB-IntNM	NPK 124:52:0 kg ha ⁻¹ ; zinc 7 kg ha ⁻¹ ; sulphur 9 kg ha ⁻¹ ; FYM 22.5 tons ha ⁻¹ (once in 2 years)	NPK 124:52:0 kg ha ⁻¹	Integrated (followed for more than 14 years)	N 31°10'10" E 76°02'50"	Shaheed Bhagat Singh Nagar, Punjab	
HR-InoNM	NPK 165:26:68 kg ha ⁻¹	NPK 176:52:0 kg ha ⁻¹	Inorganic (followed for more than 10 years)	N 29°49'45" E 76°59'35"	Karnal, Haryana	Subtropical climate, mean annual rainfall 828 mm during the southwest monsoon (July–September); Hot, humid summers and cold, dry winters.
HR-IntNM	NPK 176:52:0 kg ha ⁻¹ ; zinc 7 kg ha ⁻¹ ; sulphur 9 kg ha ⁻¹ ; FYM 9.0 tons ha ⁻¹ (once in 2 years)	NPK 129:0:0 kg ha ⁻¹	Integrated (followed for more than 10 years)	N 29°50'20" E 76°59'52"	Karnal, Haryana	
UP-InoNM	NPK 201:52:0 kg ha ⁻¹ ; zinc 4 kg ha ⁻¹ ; sulphur 11 kg ha ⁻¹	NPK 124:52:0 kg ha ⁻¹	Inorganic (followed for more than 15 years)	N 28°31'18" E 77°42'16"	Bulandshahr, Uttar Pradesh	Subtropical climate, mean annual rainfall 794 mm peak rainfall in July–August; Hot, humid summers and cold, dry winters.
UP-IntNM	NPK 116:31:14 kg ha ⁻¹ ; zinc 4 kg ha ⁻¹ ; sulphur 2 kg ha ⁻¹ ; FYM 6 tons ha ⁻¹ (once in 2 years)	NPK 124:52:0 kg ha ⁻¹	Integrated (followed for more than 15 years)	N 28°32'44" E 77°42'00"	Bulandshahr, Uttar Pradesh	

*Treatments consist of PB-InoNM- Inorganic nutrient management Punjab; PB-IntNM- Integrated nutrient management Punjab; HR-InoNM- Inorganic nutrient management Haryana; HR-IntNM- Integrated nutrient management Haryana; UP-InoNM - Inorganic nutrient management Uttar Pradesh; UP-IntNM- Integrated nutrient management Uttar Pradesh.

under relatively dry field conditions. At each site, composite samples were collected using a stainless-steel auger. The sampled area within each field covered approximately uniform management zones to ensure representativeness and reduce localised variability, following standard soil sampling protocols. The collected soil samples were air-dried, ground using a mortar and pestle, sieved through a 2.0 mm sieve and analysed for several important properties.

Analysis of soil samples

Soil pH and EC were determined in soil water suspension (soil:water :: 1:2.5). Soil bulk density was determined by the core method (22) and organic C was measured following Walkley and Black method (23). Sulphur was fractionated into various forms: Available S (CaCl_2 -extractable S) was determined by using 0.15 % CaCl_2 as per the standard procedure outlined by Williams and Steinbergs (24). Water-soluble S (WSS) was measured by shaking with distilled water (25). Organic sulphur was determined by oxidising soil with H_2O_2 to convert biomass organic sulphur to sulphate, which was then measured through the turbidimetric method in a Spectrophotometer (26). Sulphur availability index (6, 27) was calculated based on the available S and total organic matter content of soil (Equation 1). Soil organic matter concentration (g kg^{-1}) was calculated from the measured soil organic carbon (SOC) concentration (g kg^{-1}) using the conventional van Bemmelen factor of 1.724, if soil organic matter contains 58 % carbon (28).

$$\text{SAI} = (0.4 \times \text{CaCl}_2 \text{ extractable S in mg kg}^{-1}) + \text{Organic Matter (\%)} \quad (1)$$

Soil organic carbon to organic sulphur ratio was computed based on the SOC and organic sulphur (OS) content of soil (Equation 2).

$$\text{SOC:OS ratio} = \text{SOC (g kg}^{-1}) / \text{OS (g kg}^{-1}) \quad (2)$$

All chemical analyses were performed using analytical grade reagents following standard soil analytical procedures. Instruments were calibrated using appropriate standards and reagent blanks were included to ensure analytical accuracy. Selected samples were analysed in triplicate to verify reproducibility.

Statistical analysis

Analysis of variance (ANOVA) was carried out to compare the soil characteristics data between the treatments at a particular depth and to analyse the statistical significance of inorganic and integrated management practices in RWCS and their effect on various sulphur fractions. All statistical analyses were performed using R software (R Core Team, Vienna, Austria). To compare the differences between the treatments at 5% level of significance, Duncan's multiple comparison test was applied.

Results and Discussion

Available sulphur

Available S concentrations differed significantly across nutrient management practices, soil depths and locations (Table 3), showing a marked decline with increasing depth, consistent with earlier findings on sulphate mobility in soil (8, 29). At 0–15 cm, PB-InoNM recorded the highest available S (14.8 mg kg^{-1}), followed by HR-IntNM (13.5 mg kg^{-1}) and PB-IntNM (12.1 mg kg^{-1}), all significantly higher than HR-InoNM (6.67 mg kg^{-1}) and UP-IntNM (8.34 mg kg^{-1}). The higher sulphur availability under PB-InoNM may be attributed to continued sulphur fertilisation and favourable soil texture supporting sulphate retention (27). In the 15–30 cm layer, the trend remained similar. PB-InoNM (8.21 mg kg^{-1}), UP-InoNM (7.23 mg kg^{-1}) and HR-IntNM (7.19 mg kg^{-1}) exhibited significantly higher available S than HR-InoNM (3.16 mg kg^{-1}) and UP-IntNM (3.38 mg kg^{-1}), highlighting the contribution of integrated and balanced fertilisation to sulphur retention in subsurface soils (30). At 30–60 cm, available S declined markedly across all treatments. PB-InoNM (3.31 mg kg^{-1}), HR-IntNM (2.82 mg kg^{-1}) and UP-InoNM (2.64 mg kg^{-1}) showed relatively higher values, while UP-IntNM registered the lowest (0.9 mg kg^{-1}). The lowest available S level (6.67 mg kg^{-1}) was observed at the HR-InoNM site, which received no sulphur fertiliser. In Haryana, the IntNM practice, which included 9 kg ha^{-1} of sulphur fertiliser, resulted in significantly higher WSS and available S compared to its inorganic counterpart. This demonstrates that for ensuring immediate sulphur availability for crops, direct fertilisation with sulphate-containing fertilisers is the most dominant factor. The significantly higher content of water-soluble sulphur fraction observed with the integrated use of fertiliser and manure may be attributed to higher microbial activity under IntNM practices, which might have resulted in mineralisation of OS thereby increasing the S availability (31, 27).

Water-soluble sulphur

The WSS varied significantly with management practices and soil depth (Table 3). A consistent decline in WSS with increasing depth was observed across all treatments. At 0–15 cm, the highest WSS was recorded under PB-InoNM (17.0 mg kg^{-1}), followed by HR-IntNM (15.1 mg kg^{-1}), while the lowest WSS was observed in HR-InoNM (7.58 mg kg^{-1}). Integrated management generally resulted in lower WSS compared to inorganic treatments, particularly in UP and HR. At 15–30 cm, PB-InoNM and HR-IntNM maintained higher WSS (10.7 and 9.46 mg kg^{-1} , respectively), while HR-InoNM and UP-IntNM showed significantly reduced values (4.14 and 4.45 mg kg^{-1} , respectively). At 30–60 cm, WSS further declined, with PB-InoNM showing the highest value (6.02 mg kg^{-1}) and UP-IntNM showing the lowest (1.63 mg kg^{-1}). In PB-InoNM, a high sulphur fertiliser input of 21 kg ha^{-1} maintained a larger pool of sulphate in the surface soil.

Table 3. Forms of sulphur as influenced by the different nutrient management practices

Treatment*	WSS (mg kg^{-1})			OS (mg kg^{-1})			Available S (mg kg^{-1})		
	0-15 cm	15-30 cm	30-60 cm	0-15 cm	15-30 cm	30-60 cm	0-15 cm	15-30 cm	30-60 cm
HR-InoNM	7.58 ^c	4.14 ^b	2.26 ^{bc}	130 ^c	83.3 ^c	49.9 ^b	6.67 ^c	3.16 ^b	1.25 ^{bc}
HR-IntNM	15.1 ^a	9.46 ^a	5.08 ^a	235 ^a	150 ^a	61.8 ^a	13.5 ^{ab}	7.19 ^a	2.82 ^a
PB-InoNM	17.0 ^a	10.7 ^a	6.02 ^a	209 ^{ab}	133 ^{ab}	54.8 ^{ab}	14.8 ^a	8.21 ^a	3.31 ^a
PB-IntNM	13.9 ^a	8.83 ^a	4.45 ^{ab}	182 ^b	116 ^b	53.6 ^{ab}	12.1 ^{ab}	6.71 ^a	2.42 ^{ab}
UP-InoNM	12.9 ^{ab}	9.46 ^a	4.76 ^a	151 ^c	96.7 ^c	53.2 ^{ab}	11.4 ^b	7.23 ^a	2.64 ^a
UP-IntNM	9.15 ^{bc}	4.45 ^b	1.63 ^c	146 ^c	93.4 ^c	56.1 ^{ab}	8.34 ^c	3.38 ^b	0.90 ^c

* Treatments consist of PB-InoNM- Inorganic nutrient management Punjab; PB-IntNM- Integrated nutrient management Punjab; HR-InoNM- Inorganic nutrient management Haryana; HR-IntNM- Integrated nutrient management Haryana; UP-InoNM - Inorganic nutrient management Uttar Pradesh; UP-IntNM- Integrated nutrient management Uttar Pradesh. Data with common lowercase letters indicate no significant difference between the treatments for a particular soil depth at 5% probability level.

Integrated treatments consistently showed lower WSS at deeper depths as compared to inorganic treatments. However, the benefits of IntNM on S availability could be availed in the long run, which was also reported by previous researchers (14). In their findings they reported that IntNM might contribute towards more stable organic forms of sulphur, especially when combined with farmyard manure (FYM) applications over multiple years.

Organic sulphur

Organic sulphur concentrations showed significant variation across nutrient management practices, soil depths and locations (Table 3), exhibiting a general decline with increasing depth, consistent with prior findings (8, 29). At 0–15 cm, the highest OS was observed under HR-IntNM (235 mg kg⁻¹), which is significantly higher than other treatments and likely due to the regular addition of FYM, enhancing organic S pools (32). PB-InoNM (209 mg kg⁻¹) and PB-IntNM (182 mg kg⁻¹) also maintained relatively high OS, while the lowest values were noted under HR-InoNM (130 mg kg⁻¹), UP-InoNM (151 mg kg⁻¹) and UP-IntNM (146 mg kg⁻¹). In the 15–30 cm layer, HR-IntNM again recorded the highest OS (150 mg kg⁻¹), followed by PB-InoNM (133 mg kg⁻¹). Treatments from HR and UP under inorganic management exhibited significantly lower OS concentrations (83.3– and 96.7 mg kg⁻¹ respectively), which is in line with earlier reports that exclusive chemical fertilisation can limit accumulation of OS in soils (30). At 30–60 cm, OS declined further but remained highest under HR-IntNM (61.8 mg kg⁻¹), while HR-InoNM showed the lowest (49.9 mg kg⁻¹). Other treatments showed marginal differences. These results highlight the positive role of IntNM in maintaining higher organic S, particularly in Haryana, due to improved organic matter turnover and sulphur immobilisation (27).

Sulphur availability index

The sulphur availability index (SAI), which integrates both available S and soil organic matter, varied notably among treatments and depths (Fig. 1.). Across depths, PB-InoNM exhibited the highest SAI values, suggesting improved sulphur bioavailability due to enhanced organic S contributions and mineralisation dynamics. At the surface layer (0–15 cm), PB-InoNM recorded the highest SAI (6.72), followed by HR-IntNM (6.42) and PB-IntNM (5.90), indicating greater S release potential under integrated and organic-based inputs. In contrast, HR-InoNM recorded the lowest SAI (3.45), reflecting limited S supply capacity under inorganic-only inputs. In the subsurface layer (15–30 cm), SAI remained relatively high under PB-InoNM (3.86) and UP-InoNM (3.46), while HR-InoNM exhibited a significant decline (1.82), highlighting reduced sulphur mobility and availability in the absence of organic amendments. At 30–60 cm, SAI values declined across all treatments, with the highest observed in PB-InoNM (1.67), followed closely by HR-IntNM and UP-InoNM. Notably, UP-IntNM exhibited the lowest SAI (0.75), implying minimal sulphur contribution in deeper layers under integrated management. Higher SAI values were found in the upper soil depth, which decreased with increasing depth in case of both the integrated and inorganic management practices. Such trends underscore the impact of nutrient management on S availability mainly in the surface soil, which may be attributed to the mineralisation of organic S and organic matter–sulphur interaction (27, 33).

Soil organic carbon

Soil organic carbon content varied significantly with nutrient management, soil depth and location (Table 4). In general, higher SOC was observed under IntNM across all locations, particularly in

Table 4. Soil organic carbon content as influenced by the different management practices at different soil depths

Treatment*	Soil organic carbon g kg ⁻¹		
	0–15 cm	15–30 cm	30–60 cm
HR-InoNM	4.51 ^b	3.25 ^c	1.93 ^b
HR-IntNM	5.92 ^a	3.64 ^{ab}	2.25 ^a
PB-InoNM	4.62 ^b	3.34 ^{abc}	2.03 ^b
PB-IntNM	6.13 ^a	3.71 ^a	2.27 ^a
UP-InoNM	4.69 ^b	3.31 ^{bc}	1.96 ^b
UP-IntNM	5.77 ^a	3.59 ^{abc}	2.24 ^a

* Treatments consist of PB-InoNM- Inorganic nutrient management Punjab; PB-IntNM- Integrated nutrient management Punjab; HR-InoNM- Inorganic nutrient management Haryana; HR-IntNM- Integrated nutrient management Haryana; UP-InoNM - Inorganic nutrient management Uttar Pradesh; UP-IntNM- Integrated nutrient management Uttar Pradesh. Data with common lowercase letters indicate no significant difference between the treatments for a particular soil depth at 5% probability level.

surface soils, consistent with earlier findings that combined organic and inorganic inputs enhance soil carbon stocks (34, 35). At 0–15 cm, PB-IntNM recorded the highest SOC (6.13 g kg⁻¹), followed by HR-IntNM (5.92 g kg⁻¹) and UP-IntNM (5.77 g kg⁻¹). These values were significantly higher than those under InoNM, which ranged from 4.51 to 4.69 g kg⁻¹. The enhanced SOC under IntNM may be attributed to regular FYM application, high microbial activity and carbon sequestration (36). In the 15–30 cm layer, SOC levels declined, yet PB-IntNM (3.71 g kg⁻¹) and HR-IntNM (3.64 g kg⁻¹) remained significantly higher than HR-InoNM (3.25 g kg⁻¹), reflecting the downward movement and partial stabilisation of organic residues over time. At 30–60 cm, no significant difference in SOC content was observed between PB-IntNM (2.27 g kg⁻¹), HR-IntNM (2.25 g kg⁻¹) and UP-IntNM (2.24 g kg⁻¹). The IntNM has been reported to improve growth and root biomass of rice-wheat crops stimulated by balanced nutrition (37). The subsequent decomposition of this increased root material and crop residue contributes substantially to the accrual of new and stabilised organic carbon in the soil profile (38).

Soil organic carbon to organic sulphur ratio

The SOC:OS ratio exhibited considerable variation across treatments, depths and locations, reflecting the differences in organic matter quality and nutrient management strategies (Fig. 2). Across all depths, the ratio ranged from 22.1 to 42.4, indicating differing rates of carbon to sulphur association and potential mineralisation dynamics. InoNM in Punjab showed lowest SOC:OS ratio (22.1) at the surface layer (0–15 cm), whereas IntNM in Uttar Pradesh recorded the highest SOC:OS ratio (39.5). This wide range of SOC:OS ratio implies a management-induced difference in organic matter composition and microbial activity. In the 15–30 cm layer, the lowest SOC:OS ratio was observed under IntNM in Haryana (24.3) whereas the highest value was observed under IntNM in Uttar Pradesh (38.4) which was at par with InoNM in Haryana (39.0), reflecting a possible slower turnover of organic matter and reduced sulphur mineralisation due to the absence of S application under solely chemical inputs of NPK in HR-InoNM. In 30–60 cm depth, there was no significant impact of management practices on the SOC:OS ratio. In the present study, the findings suggest that IntNM promotes a more balanced and stable SOC:OS relationship, contributing to sustained sulphur availability and organic matter stability in the RWCS (27). It has been reported

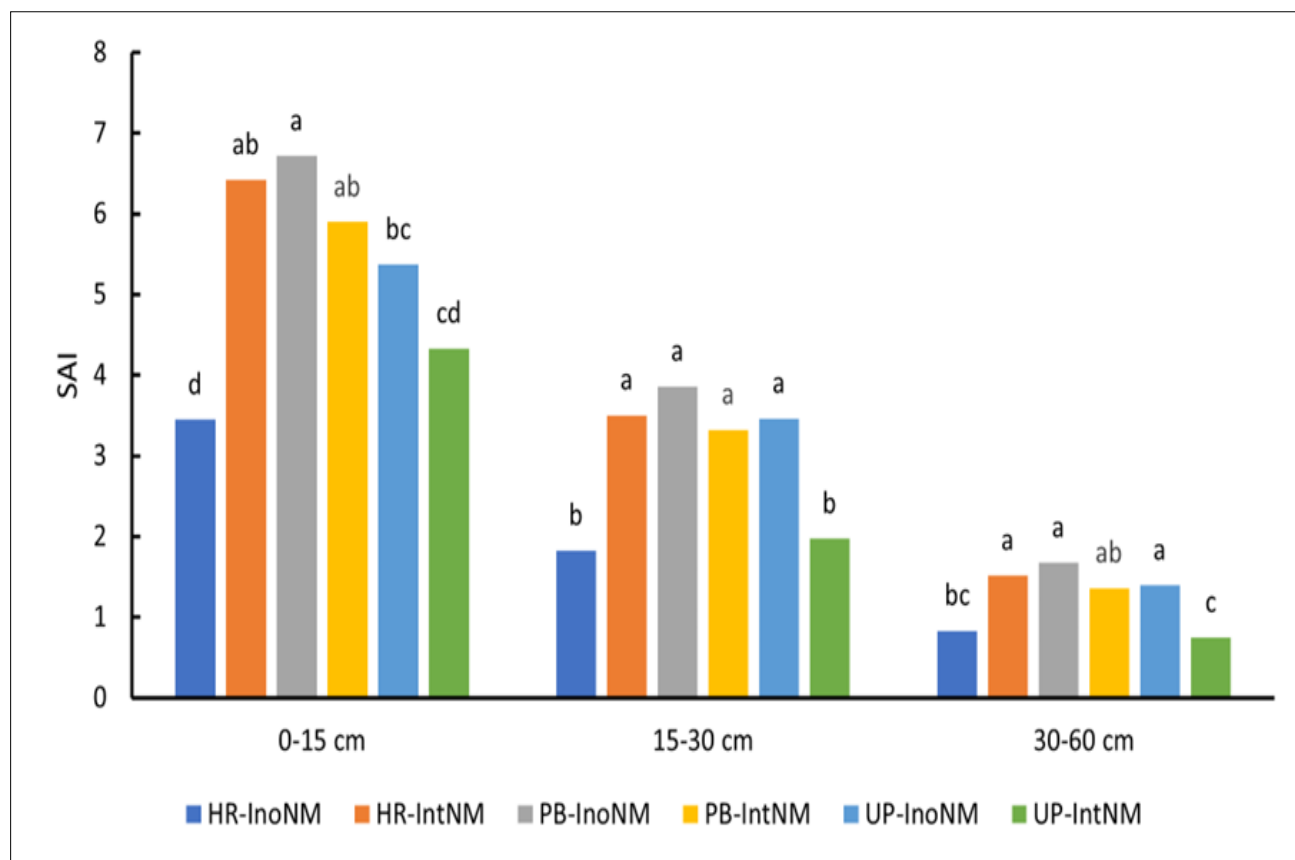


Fig. 1. Impact of nutrient management practices on SAI in soils under rice-wheat cropping system. Data with common lowercase letters indicate no significant difference between the treatments for a particular soil depth at 5 % probability level. PB-InoNM: Inorganic nutrient management Punjab; PB-IntNM: Integrated nutrient management Punjab; HR-InoNM: Inorganic nutrient management Haryana; HR-IntNM: Integrated nutrient management Haryana; UP-InoNM: Inorganic nutrient management Uttar Pradesh; UP-IntNM: Integrated nutrient management Uttar Pradesh.

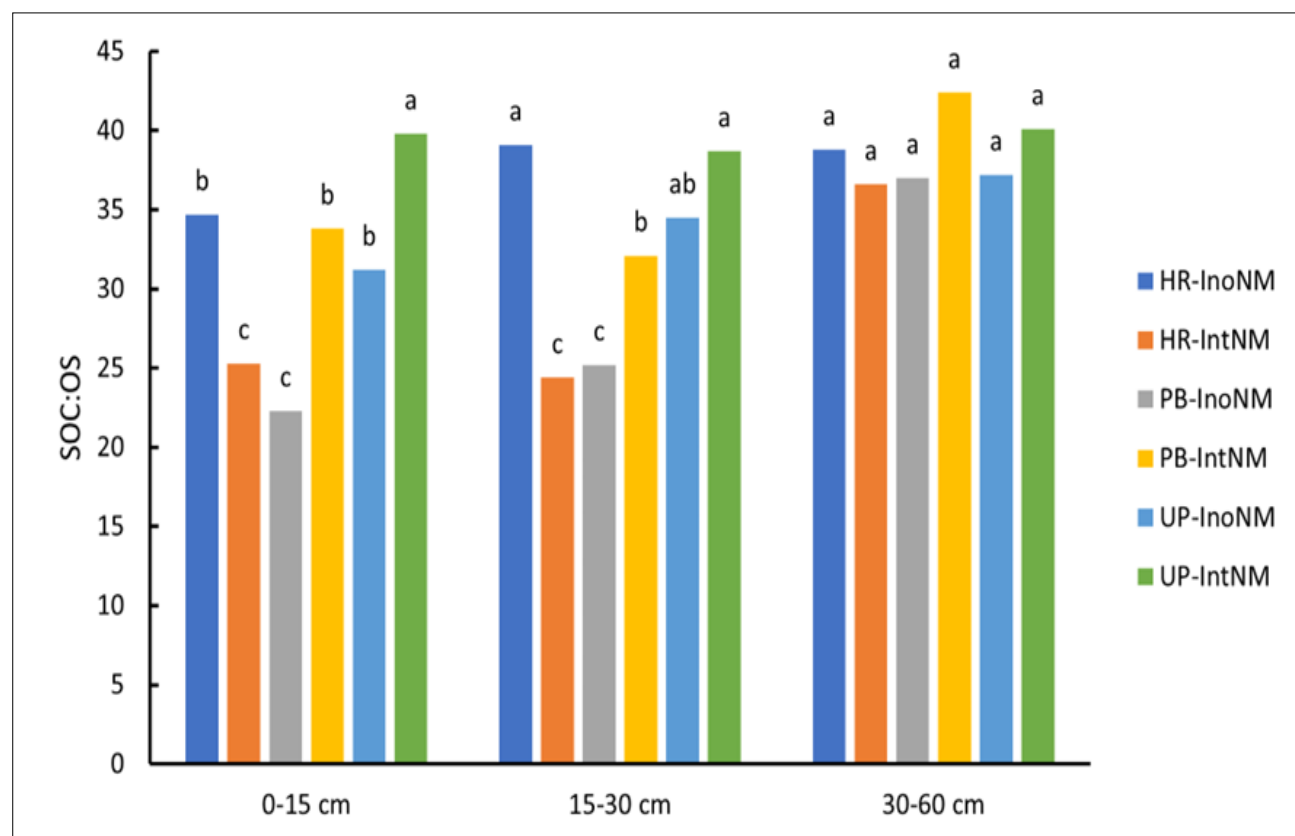


Fig. 2. Impact of nutrient management practices on SOC:OS ratio in soils under rice-wheat cropping system. Data with common lowercase letters indicate no significant difference between the treatments for a particular soil depth at 5 % probability level. PB-InoNM: Inorganic nutrient management Punjab; PB-IntNM: Integrated nutrient management Punjab; HR-InoNM: Inorganic nutrient management Haryana; HR-IntNM: Integrated nutrient management Haryana; UP-InoNM: Inorganic nutrient management Uttar Pradesh; UP-IntNM: Integrated nutrient management Uttar Pradesh.

that the SOC:OS ratio is useful for understanding sulphur mineralisation, immobilisation, oxidation, reduction and stability of organically bound nutrients in soils such as nitrogen, phosphorus and sulphur (39). It was also reported that higher carbon: sulphur ratio indicated stabilisation of sulphate S in organic forms through immobilisation, whereas mineralisation might take place with a lower carbon: sulphur ratio with increased sulphate S concentration in soil solution (27).

Conclusion

This study demonstrates that nutrient management practices significantly influence soil sulphur fractions in the rice–wheat cropping system across the Indo-Gangetic Plains. The InoNM treatments maintained higher water-soluble sulphur and available S, particularly in surface layers, due to consistent sulphate fertilisation. However, integrated nutrient management, combining farmyard manure with chemical fertilisers, enhanced organic sulphur (OS), soil organic carbon (SOC) and the sulphur availability index, especially in the surface soil layer. The IntNM treatments also supported more favourable SOC:OS ratio, indicating the potential of soil for sustained S release. It can be concluded that integrated nutrient management followed by the farmers in Punjab with the application of NPK at 124:52:0 kg ha⁻¹ along with zinc at the rate of 7 kg ha⁻¹, sulphur at the rate of 3 kg ha⁻¹ and FYM at 22.5 tons ha⁻¹ (once in two year) in rice and NPK at 124:52:0 kg ha⁻¹ in wheat is a viable option for long-term sulphur availability under the rice–wheat cropping system in Indo-Gangetic Plains for sustained productivity. Future research should involve large number of samples from the study area for validation of the findings in the IGP.

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Authors' contributions

BS conceptualised the research and BS, PR, NA and TJP collaboratively developed the methodology. BS, SB, JNS and AD, conducted the formal analysis and investigation. BS took the lead in preparing the original draft and contributed to the review and editing process. MS and PKU provided supervision and guidance under the leadership of NA. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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