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Fractional dynamics and predictive modelling of soil sulphur in relation to physicochemical properties under calcareous soil condition of North Bihar

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Abstract

This study aimed to evaluate the variability, interrelationships, and predictive modelling of different sulphur fractions in soils exhibiting a wide range of physicochemical characteristics. A total of twelve soil parameters, were analysed alongside five sulphur fractions: water-soluble (H_2O-S), inorganic sulphate (INORG-S), organic (ORG-S), residual (RES-S), and total sulphur (TOT-S). Descriptive statistics revealed that soils were predominantly alkaline (pH 8.11) and medium in organic carbon (0.70), with wide variability in nutrient content. ORG-S and RES-S constituted the dominant pools, while H_2O-S and INORG-S forms represented the readily available fractions. Pearson correlation analysis showed strong positive associations of sulphur fractions with organic carbon (OC), nitrogen (N), and micronutrients, and significant negative correlations with pH and $CaCO_3$. Stepwise multiple regression (SMR) model identified TOT-S, ORG-S, and RES-S as key predictors, with high coefficients of determination (R^2 ranging from 0.739 to 0.995), indicating robust inter-fractional relationships. The findings highlight the critical role of organic matter and soil reaction in regulating sulphur availability and partitioning.

Keywords: Calcareous, physicochemical, sulphur fraction, stepwise regression

Introduction

Sulphur (S) is an essential secondary nutrient that plays a pivotal role in plant growth and metabolism, particularly in the synthesis of amino acids, proteins, vitamins, and chlorophyll. Despite its critical function, S has often been overlooked in traditional nutrient management strategies, especially in calcareous and intensively cultivated soils where its deficiency is becoming increasingly prevalent^[1]. In soil systems, sulphur exists in various fractions - such as H_2O-S , adsorbed, ORG-S, RES-S and TOT-S forms, each contributing differently to its availability for plant uptake^[2, 3]. These fractions are influenced by a complex interplay of physicochemical properties of the soil, including pH, OC content, cation exchange capacity (CEC), texture, and $CaCO_3$ levels^[4, 5]. Understanding the dynamics of these fractions is essential, as they dictate both the mobility and bioavailability of S under different agroecological conditions^[1, 6]. Recent research indicates that the transformation and stabilization of S fractions are closely linked with soil properties, which vary significantly across land uses and depths^[7]. However, the comprehensive study of S fractionation in relation to soil physicochemical characteristics remains underexplored in many regions, particularly in soils affected by alkaline and calcareous conditions.

The increasing demand for sustainable agriculture necessitates precise nutrient management based on a deeper understanding of nutrient-soil interactions. This study aims to bridge the knowledge gap by exploring, a) the physicochemical parameters of soil that has influence on the bioavailability of S fractions, b) different S fractions of calcareous soil and its correlational study to explore the association with soil parameters and c) to find the suited predictors that is playing significant role in dynamics of S pools by stepwise multiple regression (SMR) analysis. The findings are expected to contribute significantly in understanding the distribution and

complicated relationship of S pools in calcareous soils that are being cultivated under different cropping system and landuse management and to develop site-specific nutrient recommendations and improving S use efficiency.

Materials and Methods

Sampling sites and soil sample collection

The study was conducted during the 2021-2022 period in the Samastipur and Muzaffarpur districts of North Bihar, India. Sampling sites within these districts were systematically selected based on previously documented occurrences of calcareous soil conditions. The soil samples were collected in the month of April, when 75 to 80% of cultivated land are in harvested condition. A total of 80 surface soil samples (0 -15 cm depth) were collected- 40 from each district and georeferenced using a handheld Global Positioning System (GPS) device (Figure 1c). The collected samples were air-dried at room temperature, manually cleaned to remove debris, and homogenized. Each sample was then reduced to approximately 500 g using the quartering method, passed through a 2 mm stainless steel sieve, and stored in labeled polyethylene bags for subsequent physicochemical characterization and S fractionation analysis.

Soil samples physicochemical analysis

Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water^[8] suspension using a 3-point (4, 7, 9.2 pH) calibrated pH meter and EC meter, respectively. OC was estimated by the Walkley and Black^[9] rapid titration method. Available nitrogen (N) was analyzed using the alkaline KMnO₄ method^[10]. Available phosphorus (P) and potassium (K) were extracted using Olsen's^[11] and 1N ammonium acetate methods^[12], respectively, and quantified colorimetrically and by flame photometry. Available S was extracted with 0.15% CaCl₂^[13] and turbidity was measured at 420 nm^[14]. CaCO₃ content was determined by rapid titration method^[15]. Soil texture was assessed by the hydrometer method and classified using the USDA textural triangle^[16]. To determine the micronutrients Iron(Fe), Zinc(Zn), Copper (Cu) and Manganese (Mn) in soil, the DTPA extraction method was used^[17] and analysed using atomic absorption spectrophotometer (240 FS AA).

Sulphur fractions determination

The S fractions, namely H₂O-S, INORG-S, ORG-S, RES-S, and TOT-S, were quantified using a sequential extraction protocol. To determine the H₂O-S, 10 g of air-dried soil was shaken with distilled water (1:5 w/v) for 30 minutes using a horizontal shaker at a constant speed. The resulting suspension was centrifuged at 5000 rpm for 10 minutes, and the supernatant was filtered through Whatman No. 42 filter paper. The same filtrate was then treated with dilute HCl to extract the INORG-S fraction, following the same centrifugation and filtration steps. For the ORG-S fraction, the residue from the inorganic extraction was oxidized with H₂O₂ under controlled conditions^[18, 19]. Subsequently, the RES-S was determined by digesting the remaining soil residue with a mixture of nitric acid and perchloric acid (HNO₃:HClO₄ in a 9:4 ratio) until a clear, jelly-like consistency was achieved. TOT-S was calculated as the sum of all extracted fractions. S concentrations in each extract were measured turbidimetrically at a wavelength of 420 nm using a spectrophotometer.

$$\text{TOT-S} = \text{H}_2\text{O-S} + \text{INORG-S} + \text{ORG-S} + \text{RES-S}$$

Statistical Analyses

Descriptive statistical analyses, including measures of central tendency and dispersion (mean, standard deviation, minimum, and maximum), were performed to summarize the variability of soil physicochemical properties and S fractions across the sampled sites. Pearson's correlation coefficients were computed to assess the strength and direction of linear relationships among the studied variables. To identify the most influential soil properties affecting various S fractions, SMR analysis was conducted. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 26. Microsoft Office Excel 2019 was employed for data organization, preliminary calculations.

Results

Soil Physicochemical Properties

The descriptive statistics of the soil samples collected from the study area are presented in Table 1. The results revealed considerable variability in soil properties, reflecting the heterogeneity of the landscape and management practices.

The particle size distribution of the soil samples revealed considerable variability across sand, silt, and clay fractions. Sand content ranged from 13.66 to 79.98%, with a mean of 60.43 and a standard deviation of 14.76%, indicating a predominance of sandy textures in the study area. Silt content varied between 8.86 and 49.29%, with a mean of 17.92 (±9.18), while clay content ranged from 2.73 to 57.04%, averaging 21.74 (±10.69). The wide range in clay and silt fractions suggests significant heterogeneity in depositional environments and weathering intensity across sampling sites. Based on the USDA textural triangle, the soils predominantly fall within sandy loam to loam classes, which are generally favourable for root penetration, aeration, and moderate water-holding capacity. The observed variability in texture is likely to influence nutrient retention, water dynamics, and overall soil fertility. The soil pH ranged from 7.17 to 9.41, with a mean value of 8.11 and a standard deviation of 0.55, indicating that the soils are moderately to strongly alkaline. Such alkaline conditions can influence nutrient solubility, particularly of micronutrients like zinc and iron, and may affect microbial activity and crop nutrient uptake. The EC values varied from 0.15 to 3.05 dS m⁻¹, with a mean of 0.98. The relatively low mean EC suggests that the soils are generally non-saline, although the upper range indicates the presence of slightly saline patches that may require monitoring for salt accumulation. The OC content ranged from 0.20 to 2.45 %, with a mean of 0.70. The high average OC content reflects good organic matter status, which may enhance soil fertility, water retention, and biological activity. This underscores the little need for organic matter enrichment through residue recycling or organic amendments.

Available N content ranged from 117.73 to 401.08 kg ha⁻¹, with a mean of 257.29. The moderate nitrogen levels suggest nitrogen supplementation to meet crop demands. The available P levels ranged from 6.2 to 51.0 kg ha⁻¹, with a mean of 19.73. The wide range and relatively low mean available P indicate that P deficiency may be a concern in several locations, necessitating site-specific P management. The K content varied from 74.31 to 303.66 kg ha⁻¹, with a mean of 191.19. These values suggest generally good potassium availability, although variability across sites may influence crop response to potassium fertilization. CaCO₃ content ranged from 16.79 to 40.37 %, with a mean of 26.67. The high CaCO₃ levels are characteristic of calcareous soils and contribute to the prevailing alkaline pH. However, excessive CaCO₃ may reduce the availability of

micronutrients such as Fe and Zn. The available S concentrations ranged from 2.78 to 55.65 mg kg⁻¹, with a mean of 19.45. The high standard deviation (14.39) indicates substantial variability, suggesting that S deficiency may occur in certain areas, particularly in coarse-textured or intensively cropped soils.

Among the micronutrients, Zn ranged from 0.18 to 2.91 mg kg⁻¹, with a mean of 0.83. Several samples were below the critical threshold of 0.6 mg kg⁻¹, indicating widespread zinc deficiency. The Fe content ranged from 1.02 to 13.66 mg kg⁻¹, with a mean of 7.33. While the average Fe content is within the sufficiency range, the lower values suggest potential deficiency in some soils. The Cu levels ranged from 0.27 to 4.76 mg kg⁻¹, with a mean of 1.74, indicating generally sufficient availability. The Mn content ranged from 2.13 to 13.31 mg kg⁻¹, with a mean of 7.7, suggesting adequate Mn availability for most crops. Overall, the data highlight the spatial variability in soil fertility parameters, emphasizing the need for site-specific nutrient management strategies to enhance crop productivity and soil health.

Sulphur Fractions in Soil

The distribution of various S fractions in the soil samples is presented in Table 2. The data reveal substantial variability across different forms of S, reflecting the dynamic nature of S cycling in soils and the influence of organic matter, mineralization, and management practices.

H₂O-S ranged from 2.06 to 21.31 mg kg⁻¹, with a mean value of 5.72 and a standard deviation of 3.96. This fraction represents the most readily available form of S for plant uptake. Although the mean value suggests moderate availability, the wide range indicates that some soils may be deficient in immediately available S, particularly under intensive cropping systems. INORG-S content varied from 36.23 to 77.41 mg kg⁻¹, with an average of 49.36 and a standard deviation of 9.75. This fraction constitutes the major pool of plant-available S in most soils. The observed values suggest that the soils generally possess adequate levels of inorganic sulphate, although localized deficiencies may still occur depending on soil texture and leaching conditions.

ORG-S ranged from 137.84 to 320.19 mg kg⁻¹, with a mean of 223.17 and a standard deviation of 48.43. This fraction represents the largest pool of S in the soil, primarily associated with soil organic matter. The high variability in organic S content reflects differences in organic matter inputs, decomposition rates, and microbial activity across the study area. RES-S, which includes S bound in resistant organic and mineral forms, ranged from 30.55 to 133.68 mg kg⁻¹, with a mean of 59.67 and a standard deviation of 25.46. Although not immediately available to plants, this fraction serves as a long-term reservoir that can contribute to S supply through slow mineralization.

TOT-S content ranged from 208.10 to 523.97 mg kg⁻¹, with a mean of 337.92 and a standard deviation of 81.35. The total S pool integrates all forms of S present in the soil and provides a comprehensive measure of the soil's S status. These findings highlight the importance of evaluating not only total S but also its individual fractions to better understand S dynamics and availability in soils. Such information is critical for developing effective S management strategies, particularly in S-deficient regions or under high-yielding cropping systems.

Relationship between Sulphur Fractions and Soil Properties

The Pearson correlation coefficients between various S fractions and selected soil physicochemical properties are presented in

Table 3. The results reveal several significant relationships, indicating the influence of soil characteristics on the distribution and dynamics of S in the soil system.

Soil pH exhibited a significant negative correlation with all S fractions, including H₂O-S ($r = -0.347^{**}$), INORG-S ($r = -0.452^{**}$), ORG-S ($r = -0.270^{*}$), RES-S ($r = -0.386^{**}$), and TOT-S ($r = -0.353^{**}$). These negative correlations suggest that increasing alkalinity may reduce the availability and retention of S in various forms, likely due to reduced solubility and microbial activity under high pH conditions. EC showed a significant positive correlation with all S fractions, with the strongest association observed for RES-S ($r = 0.530^{**}$) and TOT-S ($r = 0.507^{**}$). This indicates that higher salt concentrations may enhance S retention or reflect the accumulation of sulphate salts in saline environments.

OC was positively and significantly correlated with all S fractions, particularly with INORG-S ($r = 0.752^{**}$) and RES-S ($r = 0.700^{**}$). These strong correlations highlight the role of organic matter in S retention and transformation, as organic residues serve as both a source and sink for S in soil. Significant correlations were observed between soil texture components and S fractions. Sand content showed a consistent negative correlation with all S forms, including H₂O-S ($r = -0.304^{**}$), INORG-S ($r = -0.302^{**}$), ORG-S ($r = -0.257^{*}$), RES-S ($r = -0.273^{*}$), and TOT-S ($r = -0.289^{**}$), indicating reduced S retention in coarser-textured soils. In contrast, silt content was positively correlated with all S fractions, particularly ORG-S ($r = 0.330^{**}$) and TOT-S ($r = 0.325^{**}$), suggesting enhanced S retention in finer-textured soils. Clay content showed weak and non-significant correlations with S fractions. These results highlight the role of sand and silt in influencing S dynamics, with implications for nutrient management in texturally diverse soils.

Available N also showed significant positive correlations with all S fractions, with the highest correlation observed for INORG-S ($r = 0.696^{**}$). This suggests a close association between nitrogen and S cycling, likely due to their mutual dependence on microbial mineralization processes. Available P did not exhibit significant correlations with any S fractions, indicating that phosphorus availability may be governed by different soil processes and is less directly linked to S dynamics in the studied soils. Available K showed weak to moderate positive correlations with S fractions, with significant associations observed for INORG-S ($r = 0.273^{*}$), ORG-S ($r = 0.294^{**}$), RES-S ($r = 0.227^{*}$), and TOT-S ($r = 0.285^{*}$). These relationships may reflect the influence of soil mineralogy and cation exchange capacity on both potassium and S retention.

CaCO₃ content was negatively correlated with all S fractions, with a significant correlation observed for INORG-S ($r = -0.305^{**}$). This suggests that calcareous conditions may limit S availability, possibly due to precipitation or reduced microbial activity in high CaCO₃ soils.

Among the micronutrients, Zn, Fe, and Cu, all showed significant positive correlations with most S fractions. Notably, copper exhibited the strongest correlation with ORG-S ($r = 0.433^{**}$) and TOT-S ($r = 0.413^{**}$), indicating a potential synergistic relationship between organic matter-associated micronutrients and S. Mn, however, showed no significant correlation with most S fractions and was negatively correlated with ORG-S ($r = -0.286^{*}$), suggesting a more complex or independent behaviour in the soil matrix. Overall, the correlation analysis underscores the strong interdependence between S fractions and key soil properties such as pH, OC, N, and micronutrient content. These findings emphasize the need for

integrated nutrient management strategies that consider the interactions among multiple soil parameters to optimize S availability and crop nutrition.

Stepwise multiple regression analysis of sulphur fractions

To better understand the interrelationships among different S fractions and their dependence on soil properties, SMR analysis was performed. The regression models identified the most significant predictors for each S fraction, and the corresponding coefficients of determination (R^2) are presented in Table 4.

The regression model for H_2O -S included TOT-S and ORG-S as significant predictors. The model equation explained 73.9% of the variation ($R^2 = 0.739$), indicating that while total S positively influences the water-soluble fraction, organic S contributes negatively, possibly due to its slower mineralization rate. For INORG-S, the best-fit model included total S, organic S, and available N as significant variables. This model accounted for 82.3% of the variation ($R^2 = 0.823$), highlighting the combined influence of total S reserves, organic matter mineralization, and nitrogen availability on the inorganic sulphate pool. The regression model for ORG-S was highly robust, with an R^2 of 0.989.

The model suggests that organic S is strongly influenced by total S content, while residual S has a negative effect, possibly reflecting competition between stable and labile S pools. RES-S was also well predicted ($R^2 = 0.972$) by total S and organic. This model indicates that while total S contributes positively to the residual pool, higher levels of organic S may reduce the residual fraction, likely due to shifts in S partitioning. Finally, TOT-S itself was best explained by organic and residual S with an exceptionally high R^2 of 0.995, confirming that these two fractions together constitute the bulk of the total S pool in the studied soils. These regression models collectively underscore the strong interdependence among S fractions and the central role of organic and residual S in governing total S dynamics. The high R^2 values across models reflect the internal consistency of S partitioning in soil and provide a predictive framework for assessing S availability based on measurable fractions.

Discussion

Soil physicochemical properties

The descriptive analysis of soil samples from the study area revealed considerable variability in textural composition and nutrient status, reflecting the heterogeneity of parent material, land use, and management practices. Soils were predominantly sandy in texture, with sand (mean of 60.43%), while silt and clay averaged 17.92% and 21.74%, respectively. The dominance of sandy textures suggests lower water and nutrient retention capacity, which can influence crop productivity and nutrient dynamics [20]. Soil pH with a mean of 8.11, indicating moderately to strongly alkaline conditions. Such alkalinity is typical of calcareous soils and can adversely affect the availability of micronutrients like Zn, Fe, and Mn [21]. The EC values were generally low (mean 0.98), suggesting non-saline to slightly saline conditions, although the upper range (3.05 dS m^{-1}) indicates localized salinity concerns that may require monitoring [22].

OC content was relatively medium, reflecting moderate organic matter inputs and less decomposition under warm climatic conditions. This aligns with earlier findings in similar agroecological zones [23, 24]. Available N ranged widely, indicating moderate fertility but also highlighting the need for site-specific nitrogen management. P and K levels also showed substantial variability. Available P, with several samples likely

falling below the critical threshold for optimal crop growth²⁵. Potassium levels were generally adequate, though the wide range suggests spatial heterogeneity in K reserves.

$CaCO_3$ content confirming the calcareous nature of the soils. High $CaCO_3$ levels contribute to pH buffering but may also reduce the solubility of micronutrients [26]. S content varied widely, indicating that S deficiency may be a concern in some areas, particularly in sandy soils with low organic matter [27].

Micronutrient analysis revealed that Zn, Fe, Cu, and Mn were present in varying concentrations. Mean values were 0.83, 7.33, 1.74, and 7.75, respectively. While average levels were within sufficiency ranges [28], the lower extremes suggest potential deficiencies, especially for Zn and Fe, which are commonly limited in alkaline and calcareous soils [29, 30]. Overall, the data underscore the need for integrated nutrient management strategies that consider the spatial variability in soil fertility parameters. Emphasis should be placed on long term maintenance of organic matter content, correcting micronutrient deficiencies, and managing pH and salinity to enhance nutrient availability and crop productivity.

Sulphur Fractions

The distribution of S fractions in the studied soils revealed a clear dominance of organic and residual forms, with comparatively lower concentrations of H_2O and INORG-S. This pattern is consistent with the established understanding that a significant portion of soil S is organically bound and becomes available to plants through mineralization [31]. H_2O and INORG-S, which represent the immediately available forms, were present in modest amounts, suggesting that while total S reserves are adequate, plant-available S may be limited in some soils. This reinforces the importance of monitoring labile S pools, particularly in coarse-textured or low-organic matter soils where leaching losses are more likely [32].

The substantial contribution of ORG-S highlights the role of soil organic matter in S cycling. RES-S, though not readily available, serves as a long-term reserve and reflects the soil's buffering capacity. The observed variability among fractions suggests that S availability is influenced by both biological activity and soil mineral composition [33]. Overall, the findings underscore the need for fraction-specific S assessment in soil fertility evaluations. Reliance on TOT-S alone may overlook potential deficiencies in plant-available forms, particularly under intensive cropping systems or in soils with limited organic inputs.

Correlation of sulphur fractions with soil properties

The correlation analysis revealed that S fractions were significantly influenced by key soil physicochemical properties, particularly OC, EC, and soil texture. OC showed strong positive correlations with all S forms, underscoring its central role in S retention and mineralization. This aligns with earlier findings that organic matter serves as both a reservoir and a regulator of S availability in soils [34, 35]. EC was also positively associated with all S fractions, suggesting that higher ionic strength in the soil solution may enhance S solubility or reflect the accumulation of sulphate salts under certain conditions. Soil pH, on the other hand, exhibited significant negative correlations with most S forms, indicating reduced S availability in more alkaline soils, likely due to decreased microbial activity and increased sulphate adsorption [36]. Textural components influenced S dynamics as well. Sand content was negatively correlated with S fractions, while silt showed positive associations, suggesting that finer-textured soils are more

effective in retaining S. Clay content showed weak and non-significant relationships, possibly due to the overriding influence of organic matter and pH in these soils.

Among nutrients, nitrogen exhibited strong positive correlations with all S forms, reflecting their coupled cycling through organic matter decomposition. Micronutrients such as Zn, Fe, and Cu also showed consistent positive associations, indicating potential synergistic interactions in soil processes that govern their availability [37]. These findings highlight the complex interplay between soil properties and S behaviour, emphasizing the need for integrated soil fertility assessments that consider both chemical and physical attributes.

Stepwise multiple regression analysis

Stepwise regression analysis provided valuable insights into the interdependence of S fractions and their predictive relationships with soil parameters. TOT-S emerged as a consistent and significant predictor across all models, underscoring its foundational role in governing the distribution of individual S pools. ORG-S and RES-S were also key contributors, particularly in models predicting TOT-S and each other,

reflecting their dominance in the soil S continuum.

The model for H₂O-S indicated a positive influence of TOT-S and a negative influence of ORG-S, suggesting that while overall S reserves enhance solubility, organic-bound forms may limit immediate availability due to slower mineralization rates. INORG-S was best explained by a combination of TOT-S, ORG-S, and available N, highlighting the role of both organic matter and nitrogen-driven microbial activity in sulphate release [38].

ORG-S was strongly predicted by TOT-S and RES-S, indicating a dynamic equilibrium between stable and labile pools. Similarly, RES-S was influenced by TOT-S and ORG-S, suggesting reciprocal interactions in long-term S stabilization. The exceptionally high R² values across models reflect the internal consistency of S partitioning in these soils. These findings reinforce the importance of evaluating S fractions collectively rather than in isolation [39]. Understanding their interrelationships can improve S diagnostics and inform more precise nutrient management strategies, particularly in soils with complex organic and mineral interactions.

Table 1: Descriptive statistics of physicochemical parameters, sand, silt, clay, pH, EC, OC, N, P, K, CaCO₃, S, Zn, Fe, Cu, and Mn of collected soil samples

	Sand (%)	Silt (%)	Clay (%)	pH	EC (dS m ⁻¹)	OC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	CaCO ₃ (%)	S (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Mn (mg kg ⁻¹)
Minimum	13.66	8.86	2.73	7.17	0.15	0.2	117.73	6.2	74.31	16.79	2.78	0.18	1.02	0.27	2.13
Maximum	79.98	49.29	57.04	9.41	3.05	2.45	401.08	51	303.66	40.37	55.65	2.91	13.66	4.76	13.31
Mean	60.43	17.92	21.74	8.11	0.98	0.70	257.29	19.73	191.19	26.67	19.45	0.83	7.33	1.74	7.75
Sd	14.76	9.18	10.69	0.55	0.72	0.47	53.45	8.68	59.78	5.04	14.39	0.51	3.11	0.80	2.73

n=80, Sd = standard deviation, all the observation of each parameter were taken in triplicate

Table 2: Descriptive statistics different soil sulphur fractions

	H ₂ O-S (mg kg ⁻¹)	INORG-S (mg kg ⁻¹)	ORG-S (mg kg ⁻¹)	RES-S (mg kg ⁻¹)	TOT-S (mg kg ⁻¹)
Minimum	2.06	36.23	137.84	30.55	208.1
Maximum	21.31	77.41	320.19	133.68	523.97
Mean	5.72	49.36	223.17	59.67	337.92
Sd	3.96	9.75	48.43	25.46	81.35

n=80, Sd = standard deviation, all the observation of each sulphur fractions were taken in triplicate

Table 3: Pearson correlation coefficients (r) between various sulphur fractions and different soil physicochemical properties

Physicochemical Parameters	H ₂ O-S	INORG-S	ORG-S	RES-S	TOT-S
pH	-0.347**	-0.452**	-0.270*	-0.386**	-0.353**
EC	0.489**	0.472**	0.438**	0.530**	0.507**
OC	0.635**	0.752**	0.533**	0.700**	0.657**
Sand	-0.304**	-0.302**	-0.257*	-0.273*	-0.289**
Silt	0.285*	0.252*	0.330**	0.268*	0.325**
Clay	0.203	0.215	0.082	0.163	0.136
N	0.523**	0.696**	0.559**	0.551**	0.614**
P	-0.103	0.076	0.112	-0.039	0.058
K	0.135	0.273*	0.294**	0.227*	0.285*
CaCO ₃	-0.147	-0.305**	-0.173	-0.196	-0.208
S	0.522**	0.522**	0.326**	0.527**	0.447**
Zn	0.389**	0.325**	0.325**	0.346**	0.360**
Fe	0.384**	0.370**	0.309**	0.366**	0.361**
Cu	0.319**	0.316**	0.433**	0.327**	0.413**
Mn	0.032	0.001	-0.286*	-0.001	-0.169

** Pearson correlation is significant at the 0.01 level, * Pearson correlation is significant at 0.05 level.

Table 4: Stepwise multiple regression analysis of sulphur fractions with different soil physicochemical properties and sulphur fractions [$R^2(n)$, n is selected model]

Sulphur fraction	Stepwise regression model	R^2 (model)
H ₂ O-S	-5.923 + .08(TOT-S) - .069(ORG-S)	0.739(2)
INORG-S	13.627 + 0.07(TOT-S) + 5.281(ORG-S) + 0.032(N)	0.823(3)
ORG-S	-9.709 + 0.882(TOT-S) – 1.091(RES-S)	0.989(2)
RES-S	-13.032 + 0.727(TOT-S) – 0.776(ORG-S)	0.972(2)
TOT-S	15.111 + 1.104(ORG-S) + 1.281(RES-S)	0.995(2)

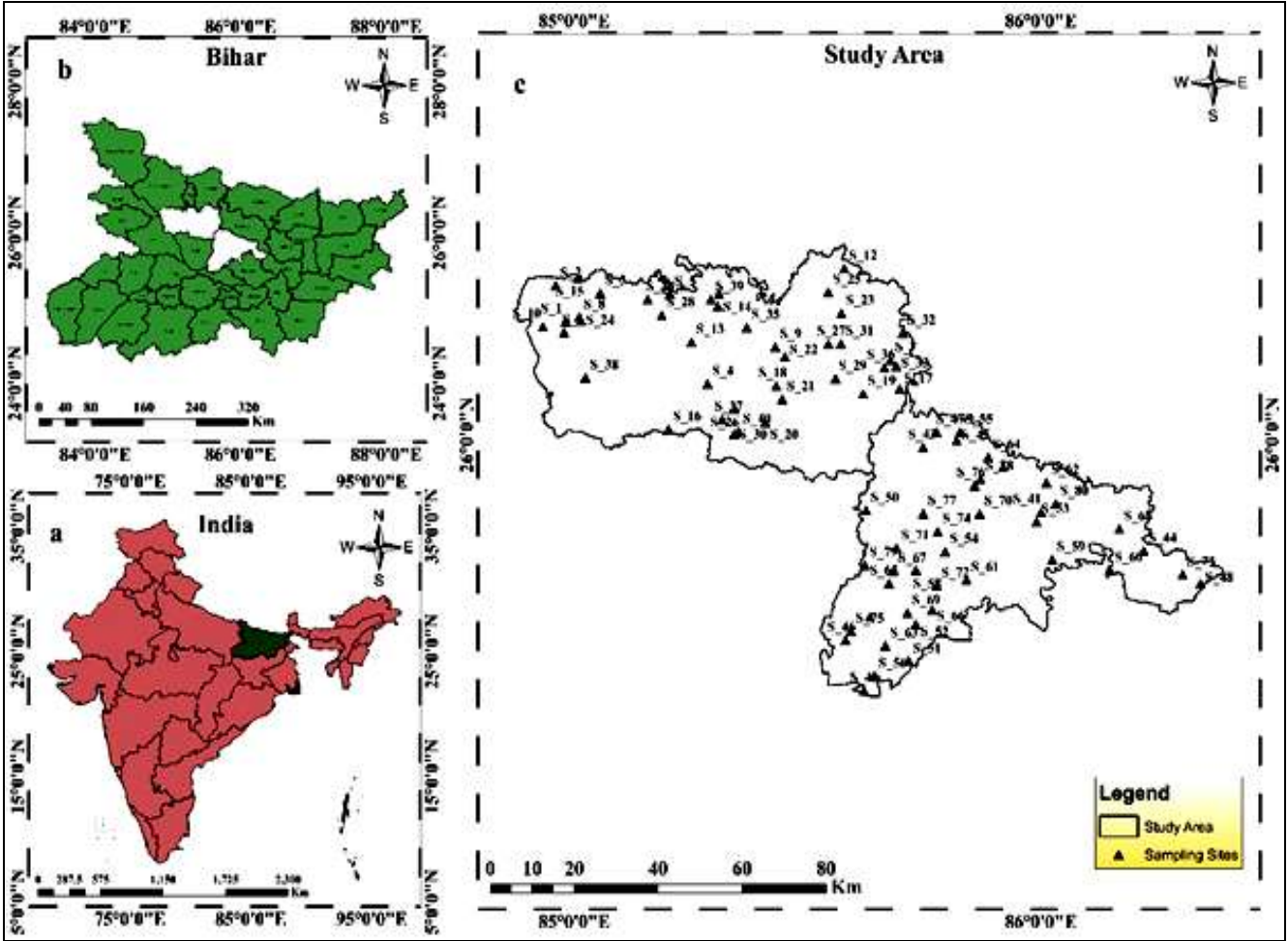


Fig 1: Study area a) India with Bihar state b) Bihar with Samastipur and Muzaffarpur districts c) Study area with different soil sampling sites

Conclusion

The study revealed significant variability in soil physicochemical properties and S fractions across the sampled sites, reflecting diverse soil fertility conditions. Soils were predominantly alkaline and medium in organic carbon, with moderate to high variability in macro and micronutrient availability. Among S fractions, ORG-S and RES-S constituted the major pools, while H₂O and INORG-S forms represented the plant-available component. Correlation analysis demonstrated strong positive associations of S fractions with OC, N, and micronutrients such as Zn, Fe, and Cu, while pH, sand and CaCO₃ showed significant negative correlations. SMR highlighted TOT-S, ORG-S and RES-S as key predictors influencing the distribution of other S forms, with high coefficients of determination indicating robust inter-fractional relationships. These findings underscore the importance of integrated assessment of S fractions and soil properties for accurate diagnosis of S fertility. The results provide a scientific basis for site-specific S management strategies aimed at enhancing nutrient use efficiency and sustaining crop productivity in alkaline and organic matter-deficient soils.

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