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Characterization of Soil Properties and Their Relationship with Various Sulphur Fractions in Groundnut Farming Regions of Bikaner District, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

An exploratory survey was conducted in Bikaner district during the 2015-16 kharif season to study the sulphur fractions and other soil properties in groundnut growing areas. 40 farmers from four tehsils (Lunkaransar, Shri Dungargarh, Nokha, and Kolayat) were selected for the study. Soil samples were collected and analyzed for pH, EC, $CaCO_3$, organic carbon, soil texture, available nutrients (N, P_2O_5, K_2O, S), and sulphur fractions. The results showed that the soils were sandy, loamy sand, and sandy loam in texture and alkaline in -pH. The majority of soils were calcareous with low organic carbon content. The available nitrogen was found to be low while available P_2O_5 and K_2O were medium. The distribution of different forms of sulphur in soil was found to be strongly dependent on soil characteristics such as clay content, silt and organic carbon content. It is noted that for more productive growth of groundnut better fertilizer practices along with organic manure should be practiced so as to improve OC status as well as compensate for lower water holding capacity of sandy soils.

Keywords: Sulphur; fraction; pH; survey; soil quality.

1. INTRODUCTION

Sulphur is considered the fourth most important plant nutrient after nitrogen, phosphorus, and potassium. It plays a crucial role in quality crop production. The intensification of agriculture, including the use of high-yielding varieties, multiple cropping, and increased irrigation, along with the increased use of chemical fertilizers low in sulphur and reduced sulphur dioxide emissions from industries [1,2], has created a significant gap between the amount of sulphur added to soils and the demand for sulphur by crops. This situation is further exacerbated by the loss of sulphur or its adsorption in soils. Coarse-textured soils, which are highly permeable, are particularly susceptible to sulphur deficiency [3].

With the improvement of crop productivity through the adoption of high-yielding varieties and multiple cropping systems, fertilizer use has become more and more important to increase crops yield and quality. S is an essential plant nutrient for crop production. For oil crop producers, S fertilizer is especially important because oil crops require more S than cereal grains. For example, the amount of S required to produce one ton of seed is about 3-4 kg S for cereals (range 1-6); 8 kg S for legume crops (range 5-13); and 12 kg S for oil crops (range 5-20). In general, oil crops require about the same amount of S as, or more than, phosphorus for high yield and product quality. In intensive crop rotations including oil crops, S uptake can be very high, especially when the crop residue is removed from the field along with the product. This leads to considerable S depletion in soil if the corresponding amount of S is not applied through fertilizer. S is increasingly being recognized as the fourth major plant nutrient after nitrogen, phosphorus and potassium. The importance of S in agriculture is being increasingly emphasized and its role in crop production is well recognized [4,5,6,7,8,9] (Jamal et al. 2010).

The positive response of crops to sulphur application is a clear indication of its deficiency in soils [10]. To maintain high levels of soil fertility and crop productivity, the amount of sulphur removed by crops and lost through leaching must be replenished through sulphur application [11]. Otherwise, sulphur deficiencies may pose an immediate threat to targeted food production. The increasing prevalence of sulphur deficiency in crops across different soils in the country, and the positive response to sulphur application from various sources, highlights the importance of this nutrient in crop production [12].

Sulphur plays a crucial role in the formation of amino acids such as cystine, cysteine, and methionine, as well as in the oil content of oilseeds and the nutritive quality of forages. It is involved in the synthesis of certain vitamins (B1, biotin, and thiamine), the metabolism of carbohydrates, proteins, and oils, and the formation of flavour compounds in crucifers. Sulphur also contributes to the market quality of produce from several crops [13,14,15].

Sulphur is also a constituent of glutathione, a compound that plays a crucial role in plant respiration. Additionally, sulphur is essential for chlorophyll formation and the synthesis of protein building blocks [16]. Research has shown that sulphur promotes nodulation in legumes and is responsible for the development of large grains in oilseeds. In the absence of sufficient sulphur, essential enzymatic activities and physiological functions are inhibited, leading to reduced crop quantity and quality. Sulphur deficiency in soil results in weak, stunted plants with pale green to yellow coloration, weak stems, and delayed maturity, leading to significant economic losses [17]. Sulphur deficiency has been shown to reduce crop yields by up to 35% [18].

In India, it is estimated that growing crops remove 1.8 million tonnes of sulphur per year, while only 0.8 million tonnes are added through fertilizers, resulting in an annual deficit of 1.0 million tonnes [19]. In intensive cropping systems, sulphur removal ranges from 30 to 70 kg ha-1 per annum. Therefore, maintaining optimal levels of sulphur in soil relative to other nutrients is crucial for achieving maximum crop production and quality [20].

Sulphur exists in soil in various forms, including free and adsorbed sulphate, as well as diverse organic and inorganic compounds. In humid regions, sulphur is predominantly present in organic form, while in arid soils, sulphate salts of calcium, magnesium, sodium, and potassium predominate [21]. Organically bound sulphur can be divided into two groups: carbon-bonded sulphur, which includes the sulphur of amino acids, and non-carbon-bonded sulphur, which includes phenolic and choline sulphates as well as lipids. The inorganic forms of sulphur in soil consist mainly of SO_4-S.

In soil, sulphur can be broadly grouped into five forms: total-S, organic-S, non-sulphate-S, available-S, and water-soluble-S. The term “available sulphur” refers to water-soluble sulphur, adsorbed sulphur, and easily hydrolysable organic sulphur compounds. The amount and availability of various forms of sulphur vary depending on soil physicochemical characteristics such as texture, pH, calcium carbonate content, and organic matter content. The distribution of different forms of sulphur and their relationship with important soil characteristics determine the sulphur-supplying power of soil by influencing its release and dynamics [22,23]. Therefore, assessing the status of different forms of sulphur in soil is essential for improving crop sulphur nutrition.

In arable soils, sulphur occurs mostly in organic forms and partially in inorganic forms. Organic sulphur must be mineralized to sulphate-S to become available to plants [24]. Thus, the supply of sulphur to plants from a given soil depends on the inorganic sulphate content of the soil and the rate of mineralization of organic sulphur. The fraction of inorganic sulphur present in soils depends on several soil properties and climatic conditions. Sulphur availability is influenced by various soil factors, resulting in wide variation in the status of different forms of sulphur across different soils [22].

The amount and forms of sulphur in soils are largely determined by the mineralogical composition of the parent material, the degree of weathering, and the mechanical composition of the soil. In the studied area, the north-western part of Rajasthan, soils are coarse-textured and low in organic matter content. Since most of the sulphur in soil is present in organic form, the total reserve of sulphur in such soils is deficient. This problem is further exacerbated by high temperatures, which result in rapid mineralization and subsequent leaching losses of sulphate due to the low retention capacity of alkaline, coarse-textured sandy soils. This current study was thus planned to evaluate the distribution of soil sulphur in the *Torripsamments* [25] of groundnut growing areas of Bikaner.

2. MATERIALS AND METHODS

An exploratory survey of groundnut growing areas in Bikaner district was conducted during the 2015-16 kharif season. 40 farmers, 10 from each tehsil (Lunkaransar, Shri Dungargarh, Nokha, and Kolayat), growing groundnut for 3+ years were selected. Initial composite soil samples were collected for analysis of sulphur fractions and other soil properties. Data on nutrient application, management practices, and average yield were also collected. Soil samples were analyzed for pH, EC, CaCO3, organic carbon,soil texture available nutrients (N, P2O5, K2O, S), and sulphur fractions using methods described in Table 1.

Correlation-regression analyses were conducted to determine the relationships between different soil sulphur fractions and important soil properties. The critical limit of sulphur in soil for groundnut in the studied area was determined using the Cate and Nelson technique (1972).

Table 1. The details of methods and the procedure for these standard methods

S. No.	Properties	Procedure	Reference
1	pH (1:2.5 Soil water)	Using glass electrode pH meter	Richards (1953)
2	EC (1:2.5 Soil water)	Using standard precision conductivity bridge	Richards (1953)
3	Organic carbon (%)	Wet digestion using normal solution of chromic acid and titration with 0.5 N FAS in the presence of ferroin indicator	Walkley and Black (1934)
4	Particle size analysis (mm)	Hydrometer method	Bouyoucos [26]
5	$CaCO_3$	Rapid titration method using EDTA	Bascomb, [27]
6	Available N	Alkaline $KMnO_4$ Method, in micro kjeldahl in the presence of NaOH (2.5%)	Subbaih and Asija [28]
7	Available P_2O_5	Extractant: 0.5 M NaHCO3 (pH 8.5), Estimation: Colorimetric	Olsen et al. [29]
8	Available K_2O	Using neutral normal ammonium acetate as extractant and measuring K using flame photometer	Jackson [30]
9	Available S	Extracted by 0.15% $CaCl_2$ and analysed using spectrometric method in the presence of $BaCl_2$	Chesnin and Yien [31]
10	Organic sulphur	Extracted by NaH_2PO_4 and 2N Acetic Acid Solution	Bardsley and Lancaster [32]
11	Water Soluble S	Extracted by shaking with distilled water	Freney [33]
12	Heat Soluble sulphur	Extracted with 1% NaCl	Williams and Steinbergs [34]
13	SO_4 sulphur	By 0.15% $CaCl_2$, by phosphate extraction (500 ppm P KH_2PO_4), Sulfur will be estimated by turbidimetric method.	Williams and Steinbergs [34], Ensminger [35], Chesnin and Yien [31]
14	Total sulphur	By Acid digestion method	Tabatabai [24]
15	Non SO_4 sulphur	Computed by subtracting the sum of organic S and SO_4-S from Total-S	

3. RESULTS

a. Textural classification:

Particle size analysis data (Table 1) showed that sand content in Kolayat tehsil soils ranged from 77.19% to 88.42%, with a mean of 83.77%. Silt content ranged from 4.22% to 9.66%, with a mean of 6.51%, and clay content ranged from 7.00% to 13.75%, with a mean of 9.56%. In Lunkaransar tehsil, sand, silt, and clay content varied from 83.65% to 91.70%, 2.25% to 7.10%, and 6.05% to 9.25%, with means of 87.96%, 4.41%, and 7.65%, respectively. In Nokha tehsil, sand, silt, and clay content varied from 86.95% to 91.81%, 2.86% to 5.83%, and 7.42% to 9.02%, with means of 88.54%, 4.03%, and 7.42%, respectively. In Shri Dungargarh tehsil, sand, silt, and clay content varied from 86.90% to 91.42%, 2.53% to 5.05%, and 5.85% to 9.28%, with means of 89.01%, 3.65%, and 7.34%, respectively. The data shows that there is variation in sand, silt, and clay content across the different tehsils of Bikaner district. Sand content is generally high, ranging from 77.19% to 91.81%, with mean values ranging from 83.77% to 89.01% across the four tehsils. Silt content is generally lower, ranging from 2.25% to 9.66%, with mean values ranging from 3.65% to 6.51%. Clay content is also relatively low, ranging from 5.85% to 13.75%, with mean values ranging from 7.34% to 9.56%. Overall, the soils in the studied area are predominantly sandy, with lower levels of silt and clay.

The Table 3 shows that silt and clay content were positively and significantly correlated with all sulphur fractions, while sand content was negatively and significantly correlated with all sulphur fractions. The correlation coefficients between silt, clay, and sand content and different sulphur fractions vary across the different tehsils of Bikaner. In Kolayat tehsil, silt and clay content were positively and significantly correlated with all sulphur fractions, while sand content was negatively and significantly correlated with all sulphur fractions. In Lunkaransar tehsil, silt and clay content were also positively and significantly correlated with all sulphur fractions, while sand content was negatively and significantly correlated with all sulphur fractions. In Nokha tehsil, silt content showed a positive but non-significant correlation with all sulphur fractions, while clay content was positively and significantly correlated with all sulphur fractions. Sand content was negatively and significantly correlated with all sulphur fractions.

Overall, the data suggests that in all three tehsils, as the silt and clay content of the soil increases, the levels of different sulphur fractions also increase, while as sand content increases, the levels of different sulphur fractions decrease. However, the strength of these relationships varies across the different tehsils.

b. Calcium Carbonate: The Calcium carbonate content in overall sampling area (Table 6) is around 4.87 meq/lt. and it varies from 0.5 to 10 meq/lt. in terms of tehsil wise variation the data is presented in table. In tehsil Kolayat (Table 2), the calcium carbonate in soil was found to be in the range of 0.5 to 7 % with average values around 3.2%. the lowest value of $CaCO_3$ was observed in *Amaepura k-2* (0.5%) and highest was observed in *Akkasar K-7* (7%). As compared to *Lunkaransar* (Table 3) where the data varies from 3 to 8.5% and averaging around 5.6% this shows the higher concentration of salts in terms of lower and upper limits of $CaCO_3$ is concerned. The highest value was recorded in *Chak 277* and lowest was observed in *Chak 269* village. In *Nokha* (Table 4) the values of $CaCO_3$ were in the range of 0.5 and 10% with average values of 6.25% this tehsil saw the most variation in $CaCO_3$ concentration. The highest reading was observed in *Kakada* (10%), and least value was seen in *Berasar* (10%). Also, $CaCO_3$ in *Shri Dungargarh* (Table 5) varied from 1.5 to 8% averaging around 4.45%. the lowest value of $CaCO_3$ was seen in *Seruna D-10* while in *Derajsar D-6* the value was lowest.

The correlation coefficient of the $CaCO_3$ doesn't show significant correlation among the Sulphur fractions with calcium carbonate concentration. The values of correlation coefficient for different tehsils are presented in Tables (7-10).

c. pH: The pH of the sampling area (Table 6) averages out at 8.89 meaning the region falls under very high salinity, the range for the entire sampling area was observed to be 8.0 to 9.44 in *Chak 269* and *Akkasar k-10*, respectively. Tehsil wise data shows that highest pH was overserved in Nokha (Table 2) where the lowest value was observed in *Zhadeli* (8.05) and highest in *Sindhu* (9.34). In other tehsils the variation as depicted in table. Shows *Kolayat* (Table 3) having highest level of salinity with data ranging from 8.68 to 9.44 in *Amarpura K-2* and *Akkasar K-10*. *Lunkaransar* (Table 4) having pH ranging from 8.0 to 9.29 in *Chak 269* and *Nathyana 9LKD*, respectively.

The correlation among pH and different fraction of Sulphur shows high negative correlation coefficient ranging from -0.59 between pH and Sulphate sulphur of Nokha, whereas highest negative correlation was observed among pH and total sulphur fraction in soils of Kolayat. Shows that as the pH of a soil increases the total sulphur as well as other fractions of sulphur also show a decreasing trend Tables (7-10).

d. Electrical Conductivity: The data shows that average values of EC ranges (Table 6) from 0.07 dSm^{-1} in Goplsar D-4 to 0.20 dSm^{-1} in Akkasar K-10 with mean values of 0.14 dSm^{-1}. EC values show no constraint of salinity in sampling area. The highest variation was observed in Kolayat (Table 2) where EC fluctuated between 0.09 to 0.20 dSm^{-1}. Whereas least variation in EC was seen in Lunkaransar (Table 3) with range between 0.12 to 0.18 dSm^{-1}. In Nokha (Table 4) EC ranges from 0.10 to 0.19 dSm^{-1}. In Shri Dungargarh (Table 5) EC varied between 0.01 to 0.16 dSm^{-1}.

Correlation Coefficient between EC and Different fractions of Sulphur in surveyed area shows very high negative values with ranging from r=-0.712 with heat soluble fraction in Shri Dungargarh area samples to r= -0.99 among Sulphate sulphur and EC of Kolayat samples. The Data of EC with different fraction is given in Tables (7-10).

e. Organic Carbon:

The soil in four tehsils of Rajasthan – Kolayat (Table 2), Lunkaransar (Table 3), Nokha (Table

4), and Shri Dungargarh (Table 5) - was analyzed for its organic carbon content. In Kolayat, the organic carbon content ranged from 0.08% to 0.21%, with an average of 0.15%. Amarpura K-2 village had the highest content while Akkasar K-6 village had the lowest. In Lunkaransar, the range was 0.10% to 0.24%, with an average of 0.17%. Chak 269 village had the highest content and Chak 277 village had the lowest. In Nokha, the range was 0.09% to 0.25%, with an average of 0.15%. Zhadeli village had the highest content while Sindhu village had the lowest. In Shri Dungargarh, the range was 0.10% to 0.34%, with an average of 0.23%. Seruna D-9 village had the highest content while Gopalsar D-5 village had the lowest.

In four tehsils of Rajasthan - Shri Dungargarh, Nokha, Lunkaransar, and Kolayat - a strong positive correlation was observed between the organic carbon content of soil and various forms of sulphur. This suggests that the presence of sulphur in the soil is closely related to its organic carbon content. Tables (7-10).

f. Available Nitrogen: The available nitrogen content (Table 6) in soil was analyzed for villages in four tehsils of Rajasthan – Kolayat (Table 2), Lunkaransar (Table 3), Nokha (Table 4), and Shri Dungargarh (Table 5). In Kolayat, the available nitrogen content ranged from 100.10 to 221.10 kg/ha, with an average of 192.02 kg/ha. All villages in this tehsil belonged to the low category of soil available nitrogen. Amarpura K-2 village had the highest content while Angnaeu K-4 village had the lowest. In Lunkaransar, the range was 170.58 to 233.60 kg/ha, with an average of 205.35 kg/ha. All villages in this tehsil also belonged to the low category of soil available nitrogen. Chak 269 village had the highest content and Chak 277 village had the lowest. In Nokha, the range was 166.25 to 235.20 kg/ha, with an average of 202.03 kg/ha. All villages in this tehsil also belonged to the low category of soil available nitrogen. Zhadeli village had the highest content while Sindhu village had the lowest. In Shri Dungargarh, the range was 172.50 to 299.84 kg/ha, with an average of 223.04 kg/ha. Seruna D-9 village had the highest content while Gopalsar D-5 village had the lowest.

The correlation between available nitrogen and various forms of sulphur was analyzed for four different sets of data. In all four sets, a positive correlation was observed between available nitrogen and total sulphur, organic sulphur, available sulphur, non-sulphate sulphur, sulphate sulphur, water-soluble sulphur, and heat-soluble sulphur. The strength of the correlation varied between different sets of data (Tables 7-10).

This data suggests that there is a positive relationship between the available nitrogen content of soil and the presence of various forms of sulphur, with the strength of the correlation varying between different sets of data.

g. Available Phosphorus: The available phosphorus content in soil was analyzed for villages in four tehsils of Rajasthan – Kolayat (Table 2), Lunkaransar (Table 3), Nokha (Table 4), and Shri Dungargarh (Table 5). In all four tehsils, the villages belonged to the medium category of soil available phosphorus. In Kolayat, the available phosphorus content ranged from 12.45 to 27.17 kg/ha, with an average of 18.39 kg/ha. Amarpura K-2 village had the highest content while Akkasar K-10 village had the lowest. In Lunkaransar, the range was 13.07 to 27.49 kg/ha, with an average of 17.56 kg/ha. Chak 269 village had the highest content and Nathvana 9LKD village had the lowest. In Nokha, the range was 14.06 to 20.93 kg/ha, with an average of 17.38 kg/ha. Zhadeli village had the highest content while Sindhu village had the lowest. In Shri Dungargarh, the range was 11.21 to 20.62 kg/ha, with an average of 14.58 kg/ha. Seruna D-9 village had the highest content while Gopalsar D-5 village had the lowest.

The correlation between available phosphorus and various forms of sulphur was analyzed for four different sets of data. In all four sets, a significant positive correlation was observed between available phosphorus and total sulphur, organic sulphur, available sulphur, non-sulphate sulphur, sulphate sulphur, water-soluble sulphur, and heat-soluble sulphur. The strength of the correlation varied between different sets of data (Tables 7-10).

This data suggests that there is a strong positive relationship between the available phosphorus content of soil and the presence of various forms of sulphur.

h. Available potassium: The available potassium content in soil was analyzed for

Table 2. Physio-chemical properties of soils of Kolayat tehsil of groundnut growing areas of Bikaner district

Name of Village	Particle size analysis (%)			$CaCo_3$ (%)	EC (dSm^{-1})	pH	O.C. (%)	Available nutrients ($Kg\ ha^{-1}$)		
	Sand	Silt	Clay					N	P_2O_5	K_2O
Amarpura	86.93	6.02	7.05	2.00	0.16	9.11	0.11	190.10	17.18	169.00
Amarpura	77.19	8.06	13.75	0.50	0.09	8.68	0.21	221.10	27.17	214.20
Angnaeu	87.36	4.60	8.04	1.00	0.17	9.19	0.13	199.20	15.56	168.16
Angnaeu	81.99	7.56	10.45	1.50	0.14	8.92	0.15	100.10	20.62	204.72
Akkasar	79.22	7.27	13.51	6.00	0.10	8.75	0.19	217.20	23.03	211.00
Akkasar	88.42	4.53	7.05	2.50	0.18	9.24	0.08	170.85	15.47	166.60
Akkasar	77.24	9.66	12.12	7.00	0.11	8.82	0.18	216.70	20.62	206.90
Hadla	86.22	5.13	8.65	2.00	0.15	9.01	0.16	212.10	18.05	190.58
Hadla	87.78	4.22	8.00	4.00	0.19	9.33	0.16	210.90	13.70	153.80
Akkasar	84.95	8.05	7.00	5.50	0.20	9.44	0.10	181.90	12.45	124.90
Mean	83.73	6.51	9.56	3.20	0.15	9.05	0.15	192.02	18.39	180.99
Min	77.19	4.22	7.00	0.50	0.09	8.68	0.08	100.10	12.45	124.90
Max	88.42	9.66	13.75	7.00	0.20	9.44	0.21	221.10	27.17	214.20
SD	4.44	1.87	2.69	2.28	0.04	0.26	0.04	36.37	4.52	29.31
CV%	5.31	28.66	28.15	71.11	25.79	2.82	28.33	18.94	24.59	16.19

Table 3. Physio-chemical properties of soils of Lunkaransar tehsil of groundnut growing areas of Bikaner district

Name of Village	Particle size analysis (%)			Textural class	$CaCo_3$ (%)	EC (dSm^{-1})	pH	O.C. (%)	Available nutrients (Kg ha^{-1})		
	Sand	Silt	Clay						N	P_2O_5	K_2O
Kasturiya	90.41	2.86	6.73	Sandy	7.50	0.16	8.85	0.14	192.50	13.70	164.51
Chak 277,600 RD	86.43	4.75	8.82	Loamy Sand	8.50	0.13	8.17	0.21	218.90	18.90	228.50
Chak 277,600 RD	91.70	2.25	6.05	Sandy	7.50	0.18	8.98	0.10	170.58	13.70	161.30
Chak 273	88.22	4.92	6.86	Sandy	5.00	0.15	8.68	0.15	200.70	16.19	180.16
Chak 269	83.65	7.10	9.25	Loamy Sand	3.00	0.12	8.00	0.24	233.60	27.49	322.60
Bhadera	88.43	3.75	7.82	Sandy	5.50	0.15	8.60	0.18	210.50	16.81	180.16
Nathvana, 9LKD	86.61	4.93	8.55	Loamy Sand	3.50	0.14	8.25	0.20	215.71	18.68	194.90
Nathvana 9LKD	89.96	3.84	6.20	Sandy	5.00	0.18	9.29	0.13	180.82	13.07	155.90
10 LKD	89.46	3.52	7.02	Sandy	6.00	0.15	8.48	0.17	209.10	17.43	186.30
10 LKD	84.70	6.15	9.15	Loamy Sand	4.50	0.12	8.15	0.22	221.10	19.61	239.20
Mean	87.96	4.41	7.65	Loamy Sand	5.60	0.15	8.55	0.17	205.35	17.56	201.35
Min	83.65	2.25	6.05	Loamy Sand	3.00	0.12	8.00	0.10	170.58	13.07	155.90
Max	91.70	7.10	9.25	Sandy	8.50	0.18	9.29	0.24	233.60	27.49	322.60
SD	2.58	1.47	1.23		1.79	0.02	0.41	0.04	19.37	4.19	50.62
CV%	2.93	33.43	16.05		32.00	14.53	4.85	25.44	9.43	23.88	25.14

Table 4. Physio-chemical properties of soils of Nokha tehsil of groundnut growing areas of Bikaner district

Name of Village	Particle size analysis (%)			Textural Class	$CaCo_3$ (%)	EC (dSm^{-1})	pH	O.C.(%)	Available nutrients (Kg ha^{-1})		
	Sand	Silt	Clay						N	P_2O_5	K_2O
Sindhu	91.81	2.86	5.33	Sandy	8.00	0.19	9.34	0.09	166.25	14.06	142.57
Berasar	86.95	5.83	7.22	Loamy Sand	0.50	0.16	9.15	0.11	172.50	17.18	164.51
Kakada	87.10	5.04	7.86	Loamy Sand	5.00	0.15	9.14	0.15	200.70	17.94	192.20
Kakada	89.32	3.25	7.43	Sandy	10.00	0.16	9.14	0.13	199.10	16.19	160.85
Uadsar	87.20	4.85	7.95	Loamy Sand	4.50	0.13	8.98	0.15	214.80	18.05	208.39
Uadsar	88.12	3.83	8.05	Loamy Sand	9.50	0.12	8.95	0.17	220.30	18.81	270.52
Zhadeli	87.14	3.84	9.02	Loamy Sand	6.00	0.10	8.06	0.25	235.20	20.93	409.44
Zhadeli	88.60	4.32	7.08	Loamy Sand	4.50	0.17	9.15	0.10	203.80	16.19	160.50
Jasrasar	88.05	3.00	8.95	Loamy Sand	4.50	0.11	8.66	0.23	226.80	18.90	298.40
Sadhasar	91.13	3.52	5.35	Sandy	10.00	0.18	9.19	0.10	180.80	15.56	157.19
Mean	88.54	4.03	7.42	Loamy Sand	6.25	0.15	8.98	0.15	202.03	17.38	216.46
Min	86.95	2.86	5.33	Loamy Sand	0.50	0.10	8.06	0.09	166.25	14.06	142.57
Max	91.81	5.83	9.02	Sandy	10.00	0.19	9.34	0.25	235.20	20.93	409.44
SD	1.73	0.97	1.27		3.08	0.03	0.37	0.06	23.16	1.97	85.26
CV%	1.95	23.94	17.14		49.35	20.80	4.12	37.25	11.46	11.33	39.39

Table 5. Physio-chemical properties of soils of Shri Dungargarh tehsil of groundnut growing areas of Bikaner district

Name of Village	Particle size analysis (%)			Textural Class	$CaCo_3$ (%)	EC (dSm^{-1})	pH	O.C.(%)	Available nutrients (Kg ha^{-1})		
	Sand	Silt	Clay						N	P_2O_5	K_2O
Benisar	91.42	2.53	6.05	Sandy	2.50	0.12	9.11	0.21	200.10	13.07	120.64
Lakhasar	89.56	3.30	7.14	Sandy	6.00	0.08	8.99	0.24	222.70	14.32	149.88
Gajpura	88.42	2.76	8.82	Loamy Sand	3.50	0.08	8.92	0.29	235.26	15.56	197.41
Gopalsar	88.94	4.21	6.85	Loamy Sand	5.50	0.10	9.10	0.22	202.27	13.70	131.60
Gopalsar	91.11	3.04	5.85	Sandy	4.50	0.16	9.14	0.10	172.50	11.21	113.37
Derajsar	88.95	4.12	6.93	Loamy Sand	8.00	0.09	9.05	0.23	207.35	13.78	142.57
Derajsar	89.02	5.05	5.93	Sandy	6.00	0.15	9.12	0.13	199.70	13.07	116.98
Seruna	88.18	3.82	8.00	Loamy Sand	3.50	0.08	8.95	0.26	230.80	14.94	150.27
Seruna	86.90	3.82	9.28	Loamy Sand	3.50	0.07	8.65	0.34	299.84	20.62	571.50
Seruna	87.61	3.83	8.56	Loamy Sand	1.50	0.08	8.93	0.29	259.91	15.56	182.78
Mean	89.01	3.65	7.34	Sandy	4.45	0.10	9.00	0.23	223.04	14.58	187.70
Min	86.90	2.53	5.85	Loamy Sand	1.50	0.07	8.65	0.10	172.50	11.21	113.37
Max	91.42	5.05	9.28	Sandy	8.00	0.16	9.14	0.34	299.84	20.62	571.50
SD	1.41	0.75	1.26		1.94	0.03	0.15	0.07	36.16	2.49	137.62
CV%	1.59	20.69	17.11		43.50	31.47	1.64	31.51	16.21	17.09	73.32

Table 6. Range and mean values of physio-chemical properties of groundnut growing areas of Bikaner district

Properties	Min.	Max.	Mean	SD	CV%
Sand	77.19	91.81	87.31	3.43	3.93
Silt	2.25	9.66	4.65	1.71	3.93
Clay	5.33	13.75	7.99	1.90	23.78
$CaCo_3$	0.50	10.00	4.88	2.53	51.82
EC	0.07	0.20	0.14	0.04	26.68
pH	8.00	9.44	8.89	0.36	4.10
Organic carbon	0.08	0.34	0.18	0.06	36.00
Available N	100.10	299.84	205.61	30.76	14.96
Available P_2O_5	11.21	27.49	16.98	3.63	21.41
Available K_2O	113.37	571.50	196.62	83.83	42.64

Table 7. Coefficient of correlation (r) between different forms of sulphur and physico-chemical properties of groundnut growing areas of Kolayat tehsil of Bikaner district

Kolayat tehsil	Sand	Silt	Clay	$CaCo_3$	EC	pH	OC	Available N	Available P_2O_5	Available K_2O
Total Sulphur	-0.808*	0.528*	0.881*	-0.065	-0.970*	-0.989*	0.794*	0.160	0.945*	0.961*
Organic S	-0.818*	0.522*	0.904*	-0.056	-0.978*	-0.986*	0.795*	0.202	0.961*	0.939*
Available S	-0.819*	0.498	0.921*	-0.045	-0.980*	-0.987*	0.841*	0.231	0.963*	0.944*
Non Sulphate S	-0.785*	0.515*	0.853*	-0.080	-0.952*	-0.979*	0.784*	0.137	0.922*	0.963*
Sulphate S	-0.877*	0.597*	0.941*	0.036	-0.989*	-0.985*	0.790*	0.178	0.976*	0.927*
Water SS	-0.726*	0.455	0.797*	-0.157	-0.933*	-0.960*	0.629*	0.088	0.917*	0.953*
Heat SS	-0.570*	0.271	0.681*	-0.308	-0.858*	-0.908*	0.569*	0.074	0.861*	0.932*

** Significant at 5 % level of significance*
*** Significant at 1 % level of significance*

Table 8. Coefficient of correlation (r) between different forms of sulphur and physico-chemical properties of groundnut growing areas of Lunkaransar tehsil of Bikaner district

Lunkaransar tehsil	Sand	Silt	Clay	$CaCo_3$	EC	pH	OC	Available N	Available P_2O_5	Available K_2O
Total Sulphur	-0.937*	0.880*	0.916*	-0.521*	-0.963*	-0.896*	0.967*	0.974*	0.872*	0.850*
Organic S	-0.792*	0.766*	0.749*	-0.494	-0.812*	-0.686*	0.850*	0.877*	0.648*	0.613*
Available S	-0.843*	0.730*	0.900*	-0.296	-0.965*	-0.976*	0.900*	0.937*	0.828*	0.788*
Non Sulphate S	-0.922*	0.852*	0.918*	-0.479	-0.943*	-0.931*	0.922*	0.908*	0.931*	0.926*
Sulphate S	-0.844*	0.732*	0.899*	-0.297	-0.965*	-0.976*	0.899*	0.936*	0.828*	0.788*
Water SS	-0.840*	0.721*	0.905*	-0.293	-0.962*	-0.976*	0.904*	0.938*	0.829*	0.789*
Heat SS	-0.838*	0.725*	0.890*	-0.127	-0.941*	-0.933*	0.861*	0.852*	0.808*	0.845*

** Significant at 5 % level of significance*
*** Significant at 1 % level of significance*

Table 9. Coefficient of correlation (r) between different forms of sulphur and physico-chemical properties of groundnut growing areas of Nokha tehsil of Bikaner district

Nokha tehsil	Sand	Silt	Clay	$CaCo_3$	EC	pH	OC	Available N	Available P_2O_5	Available K_2O
Total Sulphur	-0.832*	0.206	0.971*	-0.253	-0.945*	-0.758*	0.852*	0.891*	0.947*	0.787*
Organic S	-0.855*	0.255	0.966*	-0.308	-0.934*	-0.753*	0.836*	0.860*	0.947*	0.777*
Available S	-0.805*	0.175	0.958*	-0.239	-0.959*	-0.764*	0.876*	0.841*	0.940*	0.806*
Non Sulphate S	-0.811*	0.171	0.970*	-0.224	-0.950*	-0.771*	0.863*	0.914*	0.949*	0.802*
Sulphate S	-0.858*	0.316	0.922*	-0.289	-0.854*	-0.594*	0.746*	0.727*	0.858*	0.629*
Water SS	-0.637*	-0.061	0.911*	-0.075	-0.988*	-0.857*	0.950*	0.917*	0.941*	0.926*
Heat SS	-0.421	-0.045	0.605*	-0.071	-0.712*	-0.953*	0.789*	0.659*	0.785*	0.903*

** Significant at 5 % level of significance*
*** Significant at 1 % level of significance*

Table 10. Coefficient of correlation (r) between different forms of sulphur and physico-chemical properties of groundnut growing areas of Shri Dungargarh tehsil of Bikaner district

Shri Dungargarh tehsil	Sand	Silt	Clay	$CaCo_3$	EC	pH	OC	Available N	Available P_2O_5	Available K_2O
Total Sulphur	-0.771	-0.164	0.966*	-0.385	-0.854*	-0.914*	0.949*	0.901*	0.905*	0.744*
Organic S	-0.783	-0.087	0.933*	-0.376	-0.956*	-0.800*	0.974*	0.847*	0.800*	0.540*
Available S	-0.771	-0.084	0.919*	-0.332	-0.848*	-0.977*	0.936*	0.959*	0.966*	0.860*
Non Sulphate S	-0.662*	-0.230	0.883*	-0.357	-0.659*	-0.882*	0.811*	0.819*	0.866*	0.800*
Sulphate S	-0.774*	-0.082	0.921*	-0.336	-0.852*	-0.976*	0.937*	0.957*	0.964*	0.853*
Water SS	-0.778*	-0.080	0.924*	-0.345	-0.832*	-0.979*	0.934*	0.962*	0.972*	0.872*
Heat SS	-0.819*	-0.107	0.985*	-0.437	-0.845*	-0.871*	0.913*	0.886*	0.827*	0.621*

** Significant at 5 % level of significance*
*** Significant at 1 % level of significance*

Table 11. Coefficient of correlation (r) between different forms of sulphur and physico-chemical properties of groundnut growing areas of all four tehsil of Bikaner district

All tehsils of Bikaner district	Sand	Silt	Clay	$CaCo_3$	EC	pH	OC	Available N	Available P_2O_5	Available K_2O
Total Sulphur	-0.387**	0.149	0.534**	-0.037	-0.257	-0.164	0.166	0.353*	0.691**	0.604**
Organic S	-0.467**	0.205	0.619**	-0.092	-0.327**	-0.246	0.241	0.441**	0.734**	0.663**
Available S	-0.299*	0.095	0.417**	-0.054	-0.219	0.069	0.097	0.248	0.493**	0.395**
Non Sulphate S	-0.407**	0.168	0.551**	-0.047	-0.277**	-0.192	0.178	0.361*	0.717**	0.619**
Sulphate S	-0.241	0.027	0.393**	-0.031	-0.295*	0.049	0.165	0.298*	0.458**	0.368**
Water SS	-0.389**	0.120	0.536**	0.059	-0.202	-0.572**	0.227	0.385**	0.758**	0.815**
Heat SS	-0.471**	0.070	0.715**	-0.079	-0.597**	-0.719**	0.595**	0.714**	0.787**	0.860**

** Significant at 5 % level of significance*
*** Significant at 1 % level of significance*

villages in four tehsils of Rajasthan (Table 6) – Kolayat (Table 2), Lunkaransar (Table 3), Nokha (Table 4), and Shri Dungargarh (Table 5). In Kolayat, the available potassium content ranged from 124.90 to 214.20 kg/ha, with an average of 180.99 kg/ha. All villages in this tehsil belonged to the medium category of soil available potassium. Amarpura K-2 village had the highest content while Akkasar K-10 village had the lowest. In Lunkaransar, the range was 155.90 to 322.60 kg/ha, with an average of 201.35 kg/ha. Chak 269 village had the highest content and Nathvana 9LKD village had the lowest. In Nokha, the range was 142.57 to 409.44 kg/ha, with an average of 216.46 kg/ha. Zhadeli village had the highest content while Sindhu village had the lowest. In Shri Dungargarh, the range was 113.37 to 571.50 kg/ha, with an average of 187.70 kg/ha. Seruna D-9 village had the highest content while Gopalsar D-5 village had the lowest.

The correlation between available potassium and various forms of sulphur was analyzed for four different sets of data. In all four sets, a significant positive correlation was observed between available potassium and total sulphur, organic s sulphur, available sulphur, non-sulphate sulphur, sulphate sulphur, water-soluble sulphur, and heat-soluble sulphur. The strength of the correlation varied between different sets of data (Table 7-10).

This data suggests that there is a strong positive relationship between the available potassium content of soil and the presence of various forms of sulphur.

4. DISCUSSION

Soil Textural Classes:

The data on particle size analysis of soils revealed that the majority of soils belonged to the loamy sand category, indicating that they were formed mostly from alluvial material and characterized by a coarse texture. The variation in soil texture might be due to factors such as topographic position, nature of parent material, in-situ weathering, and age of the soils.

Silt and clay content were found to be positively and significantly correlated with various forms of sulphur, indicating that a significant quantity of sulphur is adsorbed on the finer fractions of soil and that the availability of sulphur may increase with an increase in fineness of texture. Sand, on the other hand, showed a significant negative relationship with all forms of sulphur, suggesting that the value of all forms of sulphur decreases with an increase in sand particles in the soil. This may be attributed to less organic carbon accumulation and high leaching.

These findings are consistent with previous research by Trivedi et al. [36], Singh et al. [37], Athokpam et al. [38], and Singh et al. [39].

$CaCO_3$:

The calcium carbonate ($CaCO_3$) content of soil samples from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed as a useful parameter to assess nutrient availability and release behavior. The CaCO3 content varied between 0.50% to 7.00% in Kolayat, 3.00% to 8.50% in Lunkaransar, 0.50% to 10.00% in Nokha, and 1.50% to 8.00% in Shri Dungargarh. The majority of soils in the area were found to be calcareous ($CaCO_3$ content > 5%) according to the classification given by F.A.O. [40].

The accumulation of CaCO3 in these soils might be due to the semi-arid climatic conditions, where rainfall is less than annual evapo-transpiration, resulting in less water available for leaching of insoluble carbonates and bicarbonates of calcium. The correlation coefficients indicate that CaCO3 content was negatively correlated with all forms of sulphur fractions, suggesting that non-calcareousness in soil enriches sulphur content.

These findings are consistent with previous research by Trivedi et al. [36], Chaudhary and Shukla [41], Deshmukh et al. [42], Kara and Ceylan, [43], and Sharma and Gangwar [44].

pH:

The pH of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed. The minimum pH value was recorded in Lunkaransar while the maximum was observed in Kolayat. The pH of soils in all four tehsils indicated that they were alkaline in reaction, likely due to medium to high base saturation, high amounts of carbonate and bicarbonate, and insufficient rainfall or irrigation to leach down bases.

The pH was found to be negatively and significantly correlated with different forms of sulphur. This may be due to the presence of H+ and OH- ions on the soil complex, where H+ ions attract SO4-2 ions. These findings are consistent with previous research by Singh et al. [45], Singh et al. [39], Lal and Singh [46], Bhargava and Sharma (1982), More et al. (1988), Sharma and Gangwar [44], Singh et al. [37], Jat and Yadav [47], and Chaudhary and Shukla [41].

EC:

The electrical conductivity (EC) of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed as an indicator of total soluble salts. The minimum EC value was recorded in Kolayat while the maximum was observed in Shri Dungargarh. The EC values indicated that the soils had low to moderate salinity, with all soils being non-saline. The lower EC values may be due to high leaching of soils due to their light texture and high permeability, while higher EC values may be due to irrigation with poor quality water and low-lying areas.

The EC of soil was found to be significantly and negatively related to all forms of sulphur fractions, suggesting that under high salinity conditions, SO4-2 may be leached down due to the presence of salts in soluble forms. These findings are consistent with previous research by Vyas et al. [48], Kaushik and Shukla [49], Tiwari et al. [50], Sharma and Gangawar [44], Gupta et al. [51], Roy et al. [52], Tiwari and Pandey [53], Sadrasania [54], Sharma and Gangwar [44], and Chaudhary and Shukla [41].

OC:

The organic carbon content of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed. The minimum organic carbon value was recorded in Kolayat while the maximum was observed in Shri Dungargarh. The low organic carbon content in sandy soils might be due to factors such as the absence of stable aggregates, severe wind erosion, high microbial decay, high temperature, and good aeration.

A positive and significant relationship was observed between different forms of sulphur and organic carbon, suggesting that the levels of sulphur forms in the soil are dependent on the amount of organic carbon present. These findings are consistent with previous research by Roy et al. [52], Babu et al. [55], Mishra and Singh [56], Srinivas et al. (2011), Singh et al. [57], Reddy and Mehta [58], Marsonia et al. (1986), Bhan and Tripathi (1973), Ruhal and Paliwal [59], Singh and Sharma (1983), Sharma and Gangwar [44], Athokpam et al. [38], and Singh et al. [39].

Available N:

The available nitrogen content of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed. The minimum available nitrogen value was recorded in Kolayat while the maximum was observed in Shri Dungargarh. The data suggested that the majority of soil samples were low in available nitrogen content, likely due to factors such as hot and dry climate, low organic matter and total nitrogen reserve, and low or no application of organic manures and crop residues.

These findings are consistent with previous research by Revathi et al. [60], Srinivas et al. (2011), Prasad et al. [61], and Polara and Kabaria [62].

A positive and significant relationship was observed between available nitrogen and different forms of sulphur. These findings are consistent with previous research by Desmukh et al. [42], Singh et al. [37], and Athokpam et al. [38].

Available P:

The available phosphorus content of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed. The highest available phosphorus value was recorded in Kolayat while the lowest was observed in Shri Dungargarh. The soils in the study area were found to be medium in available P_2O_5, with a large range that might be due to variation in soil properties and management practices. The medium to high values of available phosphorus might be attributed to regular application of inorganic phosphatic fertilizers.

A positive significant relationship was observed between different forms of sulphur and available phosphorus, suggesting that all forms of sulphur increased with an increase in the availability of phosphorus in soil. These findings are consistent with previous research by Swarnkar and Verma [63], Deshmukh et al. [42], Babu et al. [55], Jamuna et al. [64], Srinivas et al. (2011), and Tisdale et al. [65].

Available K:

The available potassium content of soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - was analyzed. The highest and lowest available potassium values were both recorded in Shri Dungargarh. The soils in all villages of the four tehsils were found to be medium in available K2O content. Since potassium fertilizer application is not common in semi-arid and arid regions of Rajasthan, crops are dependent on the native stock of potassium. Depletion of soil potassium due to inadequate fertilization and intensive cultivation in sandy soil has been reported, while medium to high available potassium status could be due to factors such as weathering of potassium-bearing minerals and release of potassium from decomposing organic matter.

A positive correlation was observed between available potassium and all forms of sulphur, consistent with previous research by Ramesh and Rao [66], Mishra and Singh [56], Surendra et al. (2003), and Revathi et al. [60,67-70].

5. CONCLUSION

In conclusion, an analysis of the soils from four tehsils in Bikaner district - Kolayat, Lunkaransar, Nokha, and Shri Dungargarh - revealed that they were sandy, loamy sand, and sandy loam in texture and alkaline in reaction. The majority of soils were calcareous, with pH values ranging from 8.00 to 9.44 and electrical conductivity varying from 0.07 to 0.20 dSm-1. From the point of view of soil fertility status, the organic carbon content of soil was generally low, ranging from 0.08 to 0.34%, while the available nitrogen, phosphorus, and potassium ranged from 100.10 to 299.84 kg/ha, 11.21 to 27.49 kg/ha, and 113.37 to 571.50 kg/ha, respectively. Thus, the soils of the study area were found to be low in available nitrogen and medium in available P2O5 and K2O content.

Furthermore, the distribution of different forms of sulphur in soil was found to be strongly dependent on soil characteristics and their relationships with each other. Among different soil properties, clay content was found to be the dominant factor explaining variation in sulphur forms in soil, followed by silt and organic carbon content.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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