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ASSESSMENT OF STRONTIUM (SR) DISTRIBUTION AND CONTAMINATION IN SOILS OF KIRKUK GOVERNORATE – IRAQ

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ABSTRACT

In this study, strontium (Sr) concentrations were measured, and the level of environmental contamination was evaluated in ten selected soil samples from Kirkuk Governorate, northeastern Iraq. Sr concentrations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following standard sample preparation procedures, including air-drying, grinding, and sieving. The average Sr concentration in the studied soils was 245.66 ppm, with values ranging from 222 to 289 ppm. The degree of contamination was assessed using geochemical indices, including the Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Index (I-geo). Results indicated that Sr in the studied soils is predominantly derived from natural geological sources, with negligible anthropogenic input. Moderate EF values suggested slight localized enrichment, whereas low CF and I-geo values confirmed the absence of significant environmental risk. Overall, these findings provide a geochemical baseline for Sr in Kirkuk soils and offer valuable reference data for future environmental monitoring and geochemical studies in the region.

Keywords: Strontium (Sr); Soil Contamination; Geochemical Assessment; ICP-MS; Kirkuk Governorate

INTRODUCTION

Strontium (Sr) is a natural alkaline-earth element widely distributed in the Earth's crust, and it mainly appears in four stable isotopic forms (^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr). Strontium commonly occurs with mineral companions such as celestite ($SrSO_4$) and strontianite (SrCO3), while its crustal average abundance is around 333 mg/kg (Peng *et al.,* 2021; Gupta & Walther, 2018; Mirzaee *et al.,* 2020). During natural weathering and mineral dissolution, strontium is mobilized into soils and other environmental compartments where it enters geochemical cycles by virtue of its strong chemical resemblance to calcium (Wedepohl, 1995; Zhang *et al.,* 2018; Ru *et al.,* 2024).

While stable strontium is not highly toxic, its compounds are sometimes radioactive and constitute a health hazard. The activity of the radionuclide ^{90}Sr is particularly significant because of its similar chemical properties to calcium, which assists adaptation into biological systems and more clearly retention in soils (Ammar *et al.,* 2024; Jovanović *et al.,* 2021; Chernysh *et al.,* 2024; Dubchak, 2017).

The behavior and mobility of strontium in soils are controlled by several physicochemical factors, including soil texture, clay content, and organic matter (OM) content, pH value, cation exchange capacity (CEC), and alkaline-earth element competition (mainly calcium and magnesium) (Sasmaz & Sasmaz, 2009; Sun *et al.,* 2025). Soils containing more clay or organics can act as sinks for strontium as they have higher retention capacity for screening out strontium from being mobile, while sandy and low retention soils may be weaker retainers for strontium movement in the soil profile. These features underline the importance of local soil conditions and source rock of strontium in fate, retention, and bioavailability of this element in terrestrial ecosystems (Wang *et al.,* 2017; Abass *et al.,* 2024).

The current work attempts to fill the blank in knowledge of strontium distribution in soils of the Kirkuk Governorate, NE-Iraq, by measuring its contents at ten sites. Furthermore, the potential enrichment and contamination are also assessed by the adopted commonly used geochemical indexes: Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Index (I-geo). These results are designed to act as a robust geochemical baseline, an indicator for environmental monitoring, and reference data for further investigation of strontium fate within semi-arid soils.

MATERIALS AND METHODS

Study Area

The study area is situated in the Kirkuk Governorate, NE-Iraq, which has a semi-arid climate that has long hot and dry summers and mild to moderately cold winters with low seasonal precipitation. These climatic conditions affect soil moisture regime and geochemical reactions which drive the mobility and distribution of trace elements within soils.

In geological terms, Kirkuk is considered as part of the Low Folded Zone, a zone of intensive down warping on the Iraqi Stable Shelf and consists mostly of sedimentary rocks (Limestone, Sandstone, Claystone, and Marl). Miocene deposits, such as Fatha and Injana formations, are of special interest; these contain high carbonate mineral content and alkaline-earth elements. Soils at the study sites are generally loamy to clay loamy, and vary markedly in carbonate content and cation-exchange capacity (CEC). These characteristics are important for the retention, mobility, and bioavailability of strontium to the soil matrix (Kareem *et al.,* 2020; Ismail *et al.,* 2024).

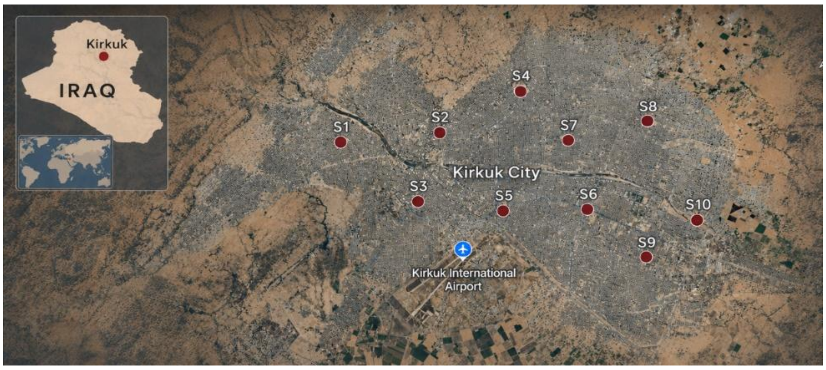

Figure 1: Location of Sampling Sites in Kirkuk Governorate

Soil Sampling

Ten sites were chosen in Kirkuk Governorate, from which soil samples were taken (Figure 1). Soil samples were collected from the surface layer (20 cm) at each site by stainless steel auger to avoid exogenous contamination. The samples were kept in labeled polyethylene bags, carried to the laboratory, and air-dried at room temperature for the next preparation and analysis. The dried soil samples were passed through a 2 mm sieve to exclude stones and other impurities. The samples were then homogenized and ground to pass through a 40 mesh using an agate mortar and pestle to a fine powder for uniform particle size, then placed in airtight containers until analysis.

Experimental Technique

Concentrations of strontium were measured by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). This extremely sensitive and accurate analytical method is widely used for the quantitative determination of trace elements in environmental samples. ICP-MS is performed by ionizing the sample in a high-temperature plasma, mass separating the ions, and detecting them with unprecedented sensitivity. This allows quantification of elements even when at extremely low concentrations, down to parts-per-billion (ppb) levels (Anh et al., 2025; Mazarakioti *et al.,* 2022; Zhang *et al.,* 2023).

Standard calibration procedures were applied to ensure quantitative accuracy, and reagent blanks as well as certified reference materials were analyzed alongside the soil samples to verify measurement reliability. These procedures ensured that the results were both accurate and reproducible, providing a robust dataset suitable for geochemical interpretation and environmental assessment.

Assessment of Soil Contamination

The degree of strontium enrichment and contamination in the soil samples was evaluated using three widely applied geochemical indices: the Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Index (I-geo).

i. Enrichment Factor (EF)

Enrichment factor was determined to reflect the relative enrichment of strontium in the soil with its natural abundance in the Earth's crust. EF is usually given as a double ratio between the target element and a reference element in the sample and crust. Reference elements like Al, Mg, Ca, Mn and Fe are frequently employed (Abderrahmane *et al.,* 2021). The reference element with which Al was standardized in this study, and results were calculated according to the Equations recommended by Sinex and Wright (Sinex & Wright, 1988):

$$\mathbf{EF} = \frac{(\mathbf{Cn/\ Al})\ \mathbf{sample}}{(\mathbf{Cn/\ Al})\ \mathbf{reference}} \qquad (1)$$

Where EF is the enrichment factor, (Cn/ Al) sample is the ratio of strontium and Al concentration of the sample and (Cn/ Al) reference is the ratio of strontium and Al concentration of a background (MalAmiri *et al.,* 2022). Five categories of enrichment were adopted based on EF values (Ma et al., 2020):

EF < 2: depletion to minimal enrichment
EF = 2–5: moderate enrichment
EF = 5–20: significant enrichment
EF = 20–40: very high enrichment
EF > 40: extremely high enrichment

ii. Contamination Factor (CF)

The contamination factor quantifies the level of contamination by comparing measured concentrations of strontium in soils to its natural geochemical background, and it is calculated as (Tomlinson *et al.,* 1980):

$$\mathbf{CF} = \frac{\boldsymbol{Cn}}{\boldsymbol{Bn}} \qquad (2)$$

Where Cn is a measured concentration of strontium in the soil, Bn is the geochemical background for the strontium (Sam-Uket *et al.,* 2023). Contamination levels are classified as follows (Hakanson, 1980):

CF < 1: low contamination
1 ≤ CF < 3: moderate contamination
3 ≤ CF < 6: considerable contamination
CF ≥ 6: very high contamination

iii. Geo-Accumulation Index (I-geo)

The geo-accumulation index (I-geo) was originally proposed by Muller to assess soil contamination by comparing current element concentrations to pre-industrial levels, and it is calculated as (Muller, 1969):

$$\text{I-geo} = \log_2 \left(\frac{\boldsymbol{Cn}}{\mathbf{1.5}\boldsymbol{Bn}}\right) \qquad (3)$$

Where I-geo is the geo-accumulation index, Cn is a measured concentration of strontium in the soil, Bn is the geochemical background for the strontium, and 1.5 is the background matrix correction factor due to Lithogeny effects (Al-Taani *et al.,* 2021). The I-geo is classified into seven categories (Muller, 1969):

I-geo < 0: practically uncontaminated
0 ≤ I-geo < 1: uncontaminated to moderately contaminated
1 ≤ I-geo < 2: moderately contaminated
2 ≤ I-geo < 3: moderately to heavily contaminated
3 ≤ I-geo < 4: heavily contaminated
4 ≤ I-geo < 5: heavily to extremely contaminated
I-geo ≥ 5: extremely contaminated

These indices provide a comprehensive framework for evaluating strontium enrichment and contamination in soils and are widely used in environmental and geochemical studies.

RESULTS AND DISCUSSION

The concentrations and contamination indices (EF, CF, and I-geo) of strontium in the soil samples from the study area are summarized in Table 1. The levels of strontium (Sr) in the soils collected from ten sites across Kirkuk Governorate ranged from 222 ppm in samples S4 and S9 to 289 ppm in sample S8, with an average of 245.66 ppm and a standard deviation of 21.71.

Table 1: Strontium Concentrations and Contamination Indices (Enrichment Factor EF, Contamination Factor CF, and Geo-Accumulation Index I-geo) in the Soil Samples

Sample Code	Sr (ppm)	EF	CF	I-geo
S1	238	3.728	0.643	0.379
S2	243	3.580	0.657	0.409
S3	237	3.336	0.641	0.373
S4	222	2.871	0.600	0.279
S5	230	3.344	0.622	0.33
S6	224	2.984	0.605	0.292
S7	260	4.252	0.703	0.507
S8	289	3.849	0.781	0.659
S9	222	4.115	0.600	0.279
S10	272	4.879	0.735	0.572
Max	289	4.879	0.781	0.659
Min	222	2.871	0.6	0.279
Av	245.66	3.724	0.664	0.418
St	21.71	0.579	0.058	0.124

The spatial variation of strontium concentrations among the investigated sites is illustrated in Figure 2. The figure clearly shows higher concentrations at sites S8 and S10, whereas lower concentrations were observed at S4 and S9. This variation highlights the heterogeneous nature of local soils in this region, suggesting that local geological factors probably control strontium distribution. When comparing our results with other regional studies, it is evident that strontium concentrations in soils are strongly influenced by local geology. In Baghdad, Iraq, reported concentrations ranged from 211 to 361 ppm, slightly higher than in Kirkuk, which may reflect differences in underlying bedrock and soil mineral composition (Mohammad & Awadh, 2023). In Turkey, soil strontium levels showed a much wider variation, from 73 to 4320 ppm, indicating the presence of mineral-rich parent rocks and, in some areas, localized anthropogenic contributions (Horasan & Arık, 2019). Soils in India exhibited concentrations between 134 and 438 ppm, moderately higher than Kirkuk, likely due to natural geogenic sources combined with soil properties such as clay content and carbonate levels that favor Sr retention (Machender *et al.*, 2013). Overall, these comparisons highlight that the distribution of strontium in soils is primarily governed by geological and pedological factors rather than human activity. Variations in strontium content among different regions can be attributed to differences in bedrock composition, soil texture, carbonate and organic matter content, and historical soil formation processes, all of which influence the mobility and retention of strontium within the soil matrix.

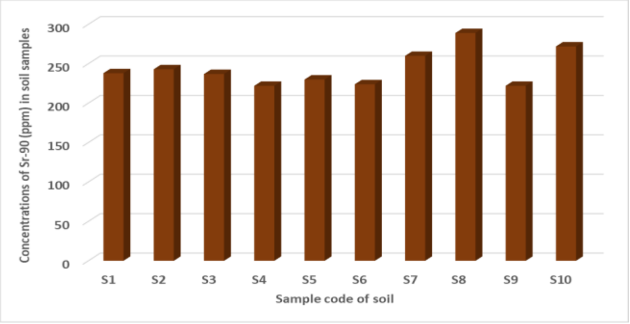

Figure 2: Strontium Concentrations in Soil Samples

Figure 3 presents the pollution assessment indices including Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Index (I-geo) for the studied samples. Enrichment Factor (EF) values ranged from 2.871 to 4.879, indicating moderate enrichment at the sites. S10 showed the maximum value, indicating slight enrichment at a small scale that could be related to natural variability in the matrix geology. The Contamination Factor (CF) ranged from 0.600 to 0.781, placing the soils in the low-moderate contamination category. The sample S8, containing the highest strontium concentration, also exhibited the highest CF (0.781), while the samples S9 and S4 were less contaminated. Also, the Geo-accumulation Index (I-geo) ranged from 0.279 to 0.659, suggesting that soils were essentially unpolluted or moderately polluted.

Taken together, these indices show that strontium in Kirkuk soils is mostly derived from natural geological source with little effect of anthropogenic contribution. Moderate EF values indicate the obvious natural enrichment to some extent in localized areas, and low CF and I-geo from most sites confirm that environmental risk related to strontium is unlikely.

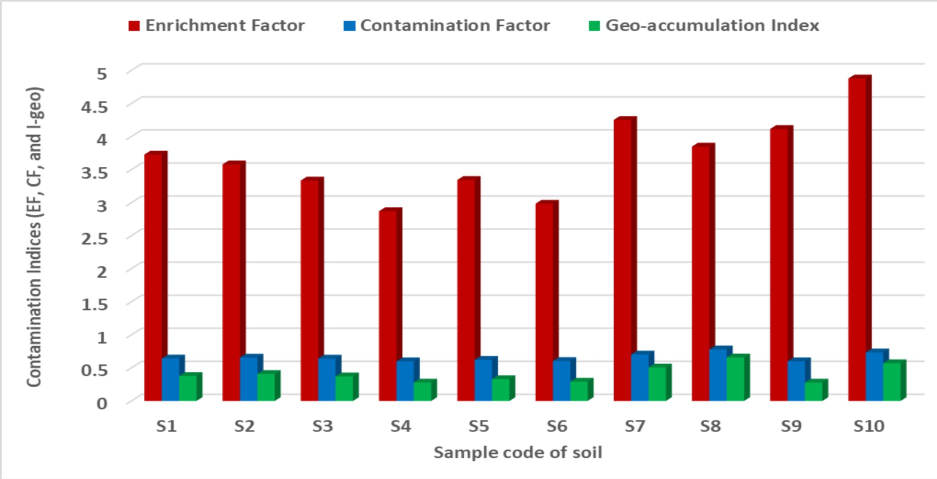

Figure 3: Pollution Assessment Indices (EF, Igeo, and CF) for Strontium Across the Studied Area

The spatial strontium concentration variability in the soils points out that local geological conditions are more important for an element distribution than a general regional tendency. Underlying bedrock, in terms of composition or mineral content, the process of historical soil formation clearly explains this difference. Interpretation of the result is in reasonable agreement with previous observations of alkaline-earth elements for semi-arid areas, which are helpful to estimate strontium behavior in the study area.

In general, the current results provide a geochemical background level of strontium in Kirkuk soils and could be useful for the environmental baseline information needed in environmental monitoring programs, risk assessment studies, as well as for other hydrogeochemical investigations. The present results serve as a foundation for further research and expand the knowledge base on strontium distribution in a semi-arid soil environment.

CONCLUSION

This work presents an assessment of strontium (Sr) levels in soils from ten sites located in Kirkuk Governorate, northeastern Iraq. The dataset revealed clear site-dependent variation which represents soil heterogeneity of the area and local geological conditions affecting strontium distribution. Assessment using the Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Index (I-geo) indicated that strontium is mostly of natural geological origin, with minimal anthropogenic activities. Moderate EF values show weak localized enrichment in some sites, while low CF and I-geo indicate that ecological risk due to strontium pollutants is evidently low. The study provided a baseline value of Kirkuk soils for strontium, which is necessary for future environmental control and risk assessment. These results offer a valuable reference for researchers, environmental managers and decision-makers in making appropriate decisions about soil quality and trace element management in northeastern Iraq.

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