



Integrated Sequential Extraction and Trace Element Geochemistry for Assessing Element Mobility and Fractionation in the Ikole–Itapaji Basement Complex, Southwestern Nigeria

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ABSTRACT

This study integrates sequential extraction and trace element geochemistry to assess the mobility, fractionation, and environmental behaviour of trace elements within the Ikole–Itapaji Basement Complex, Southwestern Nigeria. Representative samples were analysed using a modified seven-step sequential extraction procedure, while correlation and factor analyses were employed to determine elemental associations and the principal controls on trace element distribution. The results show that Fe and Mn dominate all geochemical fractions, with the highest concentrations occurring in the Fe–Mn oxide, sulfide/strongly bound, and residual fractions, indicating strong lithological control and low mobility. Conversely, only minor proportions of the analysed trace elements occur in the water-soluble and exchangeable fractions, suggesting limited bioavailability under the prevailing environmental conditions. Correlation analysis reveals a strong Cu–Ni–Co–Fe–Zn association controlled primarily by lithology, whereas the Pb–Ag–Th association reflects localized hydrothermal enrichment. Factor analysis extracted two significant components that account for 92.04% of the total variance, representing the dominant lithological factor and a subordinate hydrothermal pathfinder factor. Overall, the integrated results indicate that trace element distribution in the study area is governed predominantly by basement lithology, with localized hydrothermal processes contributing to elemental enrichment. The predominance of trace elements in stable geochemical fractions indicates low environmental mobility and minimal immediate ecological, groundwater contamination, and human health risks, although future weathering or mining activities could enhance trace element release. The study demonstrates the effectiveness of integrating sequential extraction with trace element geochemistry for evaluating element mobility, environmental risk, and mineralization potential in crystalline basement terrains.

Keywords: Sequential extraction; Trace element geochemistry; Element mobility; Fractionation; Ikole–Itapaji; Southwestern Nigeria.

INTRODUCTION

Trace element geochemistry is a fundamental tool for understanding the origin, evolution, and mineralization potential of crystalline basement rocks. The distribution and concentration of trace elements are controlled by lithology, mineral composition, weathering, hydrothermal alteration, and tectonic processes. In addition to their significance in petrogenetic studies and mineral exploration, trace elements are increasingly used to evaluate environmental quality because some potentially toxic elements may become mobile under changing physicochemical conditions (Rollinson, 1993; Rollinson & Pease, 2021; Alloway, 2013).

Although whole-rock geochemical analyses provide information on the total abundance of trace elements, they do not reveal the forms in which these elements occur or their potential mobility. Sequential extraction techniques overcome this limitation by partitioning trace elements into operationally defined geochemical fractions, thereby providing insights into their fractionation, mobility, and environmental availability. This approach has become widely applied in environmental geochemistry and mineral exploration for evaluating element speciation and assessing the potential release of trace elements under varying environmental



conditions (Tessier et al., 1979; Davidson et al., 1998; Filgueiras et al., 2002; Bouazizi et al., 2023; Abule & Ekpete, 2025).

The Ikole–Itapaji area is situated within the Precambrian Basement Complex of southwestern Nigeria, which comprises migmatite-gneiss, schist, quartzite, Older Granite, and pegmatitic rocks formed during the Pan-African Orogeny. Previous studies have focused primarily on the geology, structural framework, and mineral potential of the area using integrated geological, geophysical, and remote sensing techniques, demonstrating favourable conditions for mineralization (Rahaman, 1988; Oyinloye, 2011; Adetunla et al., 2025; Ogah & Abubakar, 2024; Ojo et al., 2024). However, information on the geochemical fractionation and mobility of trace elements within the basement rocks remains limited.

Therefore, this study integrates sequential extraction and trace element geochemistry to evaluate the distribution, fractionation, and mobility of trace elements in the Ikole–Itapaji Basement Complex, Southwestern Nigeria. The study provides baseline information that is valuable for understanding geochemical processes, assessing element mobility, and supporting future mineral exploration and environmental management in the area.

The specific objectives of this study are to:

1. determine the concentrations and distribution of trace elements in representative basement rock samples from the Ikole–Itapaji area;
2. characterize the geochemical fractionation of trace elements using the sequential extraction technique;
3. evaluate the mobility and relative availability of trace elements among different geochemical fractions; and
4. assess the implications of trace element fractionation and mobility for geochemical processes, mineral exploration, and environmental management within the Ikole–Itapaji Basement Complex.

The Study Area

Figure 1 shows the location of the Ikole–Itapaji–Ake-Ako area in Ekiti State, southwestern Nigeria. The area is situated within the Precambrian Basement Complex of southwestern Nigeria, which forms part of the Pan-African mobile belt. The basement terrain comprises migmatite–gneiss complexes, Pan-African granitoids, charnockites, pegmatites, and minor metasedimentary rocks that have experienced multiple episodes of deformation, metamorphism, and magmatism (Rahaman, 1988; Oyinloye, 2011).

The study area extends approximately between latitudes 7°47'N and 8°05'N and longitudes 5°26'E and 5°34'E, covering about 590 km². The terrain is rugged and undulating, with hills, ridges, and valleys characteristic of crystalline basement environments. The topographic variations primarily reflect differences in lithology, weathering resistance, and structural deformation of the basement rocks (Ojo et al., 2024).

The drainage pattern is predominantly dendritic, although local changes in stream orientation suggest structural control by fractures, joints, and faults. These structural discontinuities commonly influence surface drainage and provide pathways for groundwater flow and hydrothermal fluid migration within basement terrains (Adetunla et al., 2025).

The study area is readily accessible through a network of major and minor roads connecting Ikole-Ekiti, Itapaji, and Ake-Ako, facilitating geological investigations and field observations. Overall, the geological setting, topography, and structural characteristics make the area suitable for aeromagnetic investigation and structural interpretation aimed at improving the understanding of the basement framework and its mineral exploration potential.

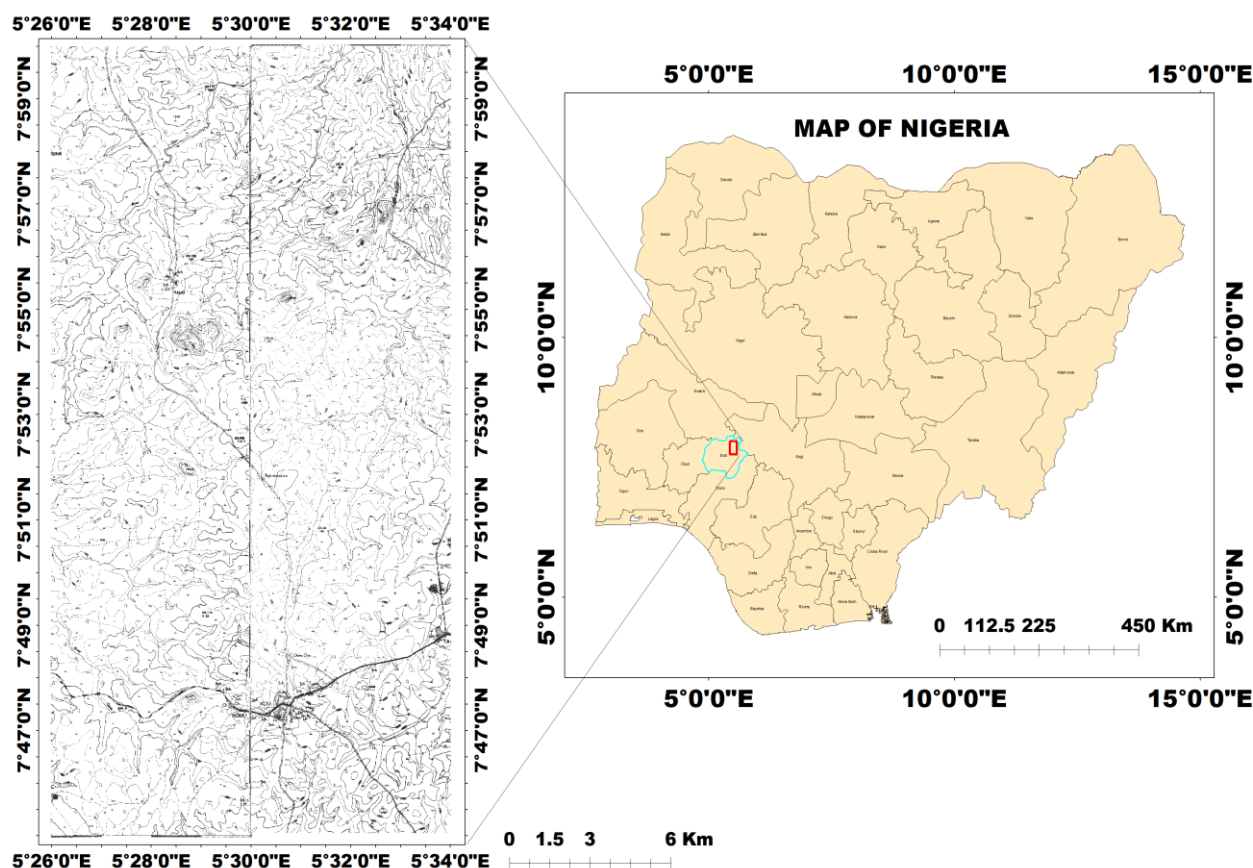


Figure 1. Location and topographic map of the Ikole–Itapaji–Ake-Ako area, Ekiti State, southwestern Nigeria, illustrating the geographical extent, drainage network, road accessibility, and topographic relief of the study area.

GEOLOGICAL SETTING

The study area is located within southwestern Nigeria, forming part of the Precambrian Basement Complex of the West African Craton. This crystalline basement terrain is distinct from the surrounding sedimentary basins, including the Sokoto Basin, Chad Basin, Bida Basin, and the Benue Trough, which are largely composed of Cretaceous-to-Tertiary sediments (Ojo et al., 2024). The southwestern region, including the Ikole–Itapaji axis, is dominated by crystalline rocks that have undergone extensive tectono-metamorphic evolution. The Nigerian Basement Complex evolved through multiple orogenic events, notably the Liberian, Eburnean, and Pan-African cycles, which resulted in widespread deformation, metamorphism, and granitoid emplacement (Adetunla et al., 2025). These processes led to the development of major lithological units, including the migmatite–gneiss complex, schist belts, and Pan-African granitoids.

In the study area, migmatite–gneiss and granitic rocks are predominant, with minor metasedimentary occurrences. Structurally, the area is characterized by well-developed faults, fractures, and foliations, predominantly trending NE–SW and NW–SE, reflecting the imprint of Pan-African deformation (Ogah & Abubakar, 2024). These structures are critical in controlling hydrothermal fluid flow and mineral deposition. Mineralization within the Basement Complex is commonly associated with quartz veins, pegmatites, and shear zones. The presence of granitic and pegmatitic intrusions within the Ikole–Itapaji area further suggests favourable conditions for mineralization. Recent studies have demonstrated the effectiveness of integrated geophysical methods in delineating such structurally controlled mineralized zones (Salako et al., 2024). The geological framework of the study area reflects a complex interplay of lithology and structure, providing a suitable environment for mineralization and justifying integrated geophysical and remote sensing investigations (Fig. 2)

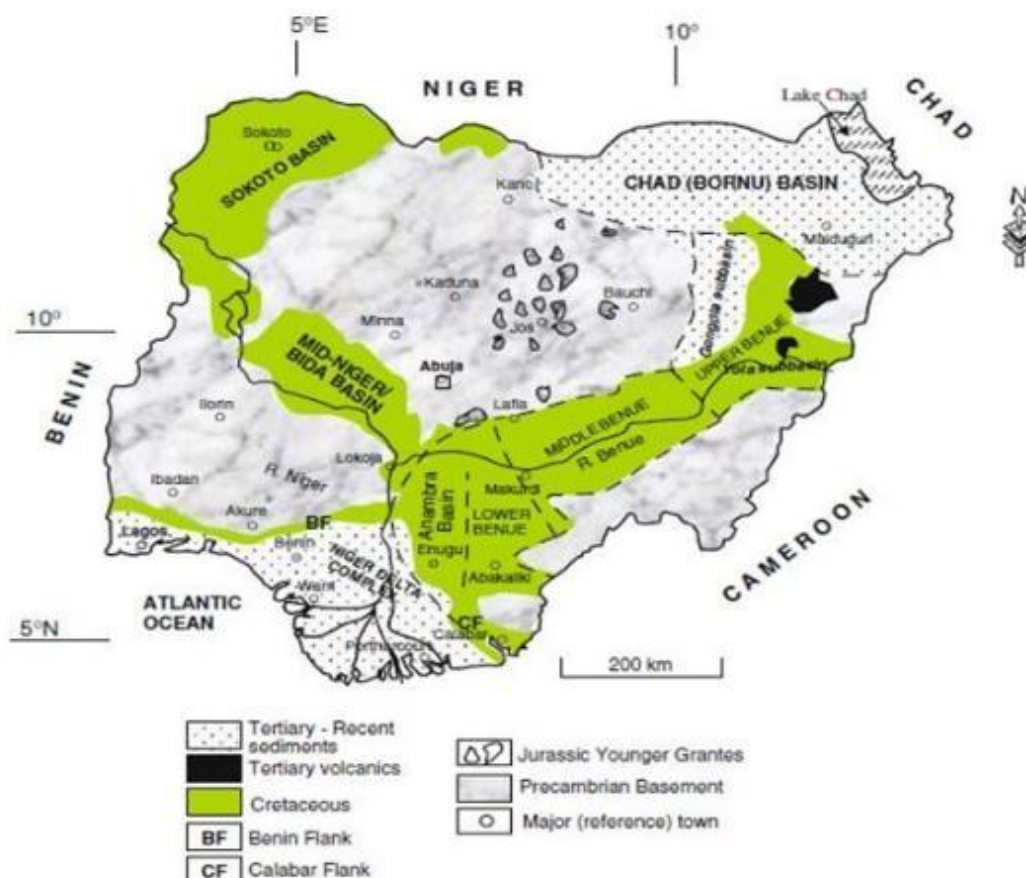


Figure 2: Geological map of Nigeria showing the distribution of major lithological units, including the Precambrian Basement Complex and surrounding sedimentary basins (Sokoto, Chad, Bida, and Benue Trough).

The geological cross-section along A–B in Fig. 3 illustrates the subsurface relationships between the major lithological units. Granite gneiss occupies most of the intermediate crustal section and overlies a broad migmatitic basement. The undulating contact between granite gneiss and migmatite suggests an irregular basement surface produced by differential melting, metamorphic segregation, and prolonged crustal evolution. The continuity of the migmatite beneath much of the section indicates that it forms the oldest exposed basement unit within the area.

The cross-section further demonstrates that the granodiorite intrusion cuts the surrounding granite gneiss in the northeastern segment of the profile. This intrusive relationship indicates that the granodiorite is younger than the host granite gneiss. The pegmatite body shown within the granodiorite represents a later magmatic phase formed by crystallization of residual silica-rich melts. Such pegmatitic intrusions are common products of highly evolved granitic systems and frequently host economically important rare-element minerals (Adetunla et al., 2025).

From a geological evolution perspective, the study area records multiple stages of crustal development. The migmatites represent the oldest basement components formed through high-grade metamorphism and partial melting. These were subsequently reworked and transformed into granite gneiss during regional metamorphic events. Charnockitic bodies were emplaced or developed under high-temperature conditions, while granodioritic magmatism and pegmatitic intrusions represent younger intrusive phases associated with crustal melting and magmatic differentiation. Collectively, these lithological relationships indicate prolonged Precambrian crustal evolution culminating in widespread Pan-African tectono-metamorphism (Rahaman, 1988; Oyinloye, 2011).

The geological architecture depicted by the map and cross-section demonstrates that the Ikole–Itapaji–Ake-Ako area forms part of a deeply reworked basement terrane characterized by extensive migmatization, granitoid emplacement, and localized charnockitic development. The intimate association of these lithologies provides evidence of repeated episodes of metamorphism, partial melting, magmatism, and crustal stabilization within the southwestern Nigerian Basement Complex.

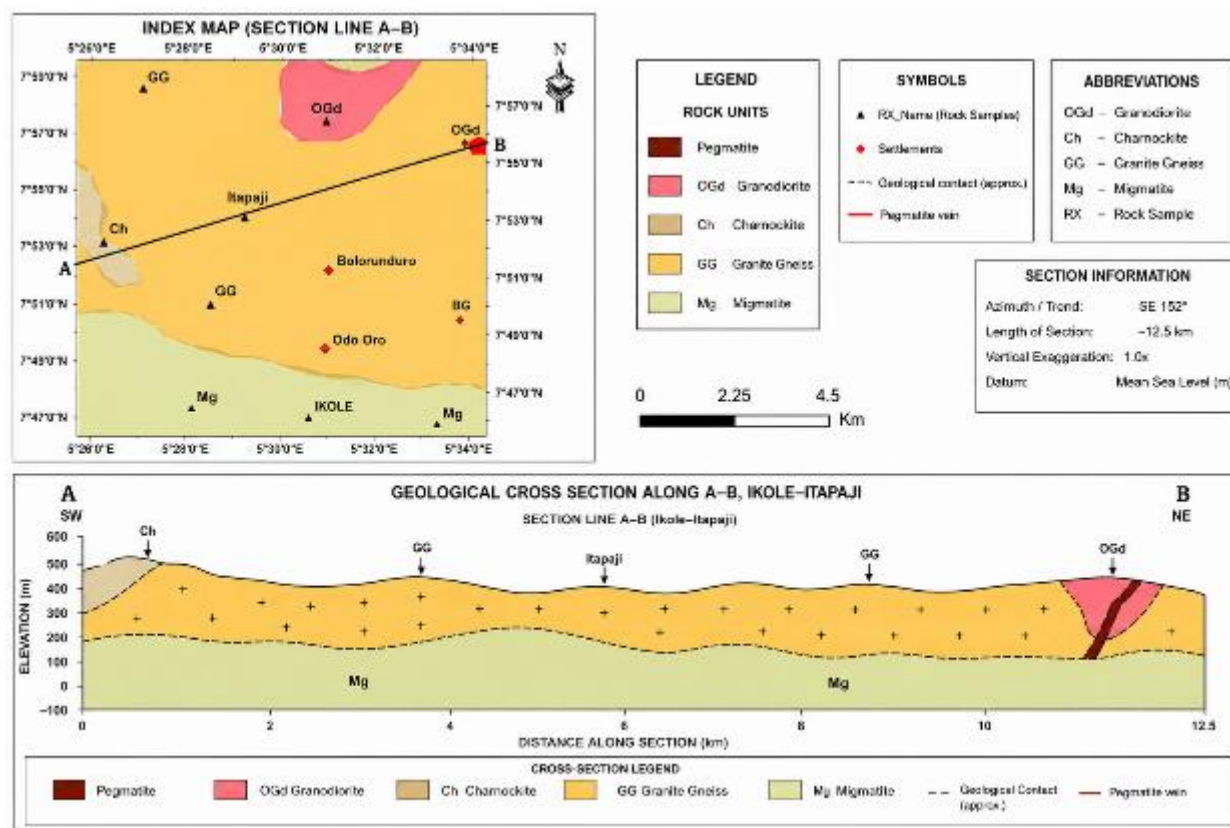


Figure 3. Geological cross-section along A–B across the Ikole–Itapaji area, showing the subsurface relationships between migmatite, granite gneiss, charnockite, granodiorite, and pegmatite units.

MATERIALS AND METHODS

Materials

The materials used for this study comprised field and laboratory equipment required for geological mapping, rock sample collection, sample preparation, trace element determination, and sequential extraction analyses. Field equipment included a 1:25,000-scale topographic map of the Ikole–Itapaji–Ake-Ako area, a Brunton compass clinometer, a Garmin GPSMAP 64s handheld Global Positioning System (GPS), a geological hammer, chisel, hand lens, sample bags, permanent markers, a field notebook, digital camera, and appropriate personal protective equipment. These materials facilitated geological observations, location referencing, and the collection of representative weathered rock materials from the major lithological units within the study area.

Laboratory equipment included a drying oven, porcelain mortar and pestle, stainless-steel sieve (63 μ m), analytical balance, centrifuge, mechanical shaker, hot plate, digestion vessels, polypropylene centrifuge tubes, pipettes, volumetric flasks, and laboratory glassware required for sequential extraction. Analytical-grade reagents, including deionized water, magnesium chloride (MgCl_2), sodium acetate (NaOAc), hydroxylamine hydrochloride ($\text{NH}_2\text{OH}\cdot\text{HCl}$), hydrogen peroxide (H_2O_2), ammonium acetate (NH_4OAc), nitric acid (HNO_3), and perchloric acid (HClO_4), were used throughout the extraction procedure. Trace element analyses of all extracts were carried out at ACME Analytical Laboratories (Bureau Veritas Commodities Canada Ltd.), Vancouver, Canada, using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS).



Methods

Field Sampling and Sample Preparation

A reconnaissance survey preceded detailed field investigations to identify accessible outcrops and representative weathered profiles developed on the major lithological units of the Ikole–Itapaji Basement Complex. Geological observations were integrated with existing lithological information to ensure representative spatial coverage of the study area.

A total of thirty-five (35) representative weathered rock samples were collected from different locations covering migmatite, granite gneiss, coarse porphyroblastic gneiss, granite, pegmatite, and charnockite. 20 samples were selected to adequately represent the lithological variability and weathering characteristics of the study area. In the laboratory, samples were air-dried at room temperature, gently disaggregated using a porcelain mortar and pestle, and sieved through a 63 μm mesh. The <63 μm fraction was retained because of its relatively high surface area and greater capacity for trace element retention and adsorption (Kabata-Pendias, 2011; Alloway, 2013). Approximately 1.0 g of each prepared sample was weighed into clean polypropylene centrifuge tubes for sequential extraction.

Sequential Extraction Procedure

Trace element fractionation was determined using a seven-step sequential extraction procedure modified from Tessier et al. (1979). The procedure partitions trace elements into operationally defined geochemical fractions according to their binding strength and provides information on their mobility, stability, and potential environmental availability. The modified protocol adopted in this study has been widely applied in environmental geochemistry to distinguish mobile fractions from structurally bound residual phases (Filgueiras et al., 2002; Davidson et al., 1998; Bouazizi et al., 2023; De Matteis et al., 2023; Firmino et al., 2025).

The extraction sequence consisted of the following fractions:

- Phase I: Water-soluble fraction.
- Phase II: Exchangeable fraction.
- Phase III: Carbonate-bound fraction.
- Phase IV: Fe–Mn oxide-bound (reducible) fraction.
- Phase V: Organic matter-bound (oxidizable) fraction.
- Phase VI: Sulfide/strongly bound fraction.
- Phase VII: Residual fraction.

For each extraction stage, the residue obtained from the preceding step was treated with the appropriate extracting reagent under controlled experimental conditions. Following agitation, the suspension was centrifuged, and the supernatant was carefully separated and preserved for elemental determination before proceeding to the subsequent extraction stage. The residual fraction was finally subjected to complete acid digestion using a mixture of HF–HClO₄–HNO₃ to release trace elements incorporated within silicate minerals (Tessier et al., 1979; Abule & Ekpeta, 2025; Delina, 2024).

Trace Element Analysis

The extracts obtained from each sequential extraction stage were analysed for selected trace elements using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) at ACME Analytical Laboratories (Bureau Veritas Commodities Canada Ltd.), Vancouver, Canada. Quality assurance and quality control (QA/QC) procedures

included the analysis of certified reference materials, reagent blanks, duplicate samples, and internal laboratory standards to ensure analytical accuracy, precision, and reproducibility.

Data Analysis

Trace element concentrations obtained from the sequential extraction procedure were used to evaluate element fractionation and mobility within the different geochemical phases. The percentage distribution of each trace element among the seven operationally defined fractions was calculated to determine its dominant host phase and relative mobility. Statistical analyses, including descriptive statistics, Pearson correlation analysis, and factor analysis, were employed to identify elemental associations and infer the geochemical processes controlling trace element distribution. The integration of sequential extraction data with trace element geochemistry provided a comprehensive assessment of trace element mobility, fractionation, and geochemical behaviour within the Ikole–Itapaji Basement Complex.

RESULTS AND DISCUSSION

Sequential Extraction

Water-Soluble Phase

The water-soluble fraction represents the most readily mobile and bioavailable form of trace elements in geological materials and typically contains only a small proportion of the total metal inventory because most elements remain incorporated within stable mineral phases (Kabata-Pendias, 2011; Alloway, 2013). As presented in Table 1, all analysed trace elements exhibit consistently low concentrations across samples (SQ1–SQ17), indicating limited dissolution into the aqueous phase. Iron (Fe) recorded the highest concentrations (2.873–7.427 mg/kg), followed by manganese (Mn) (1.742–3.128 mg/kg), whereas Cu, Zn, Pb, Cd, Ni, Co, and Cr occurred at comparatively lower concentrations, suggesting that these elements are largely retained within less mobile geochemical fractions and are predominantly derived from natural lithogenic sources (Reimann & de Caritat, 2012; Abule & Ekpete, 2025).

The spatial distribution shown in Figure 4 further confirms the predominance of Fe and Mn throughout the study area, with no marked enrichment of the remaining trace elements. This pattern indicates that trace element distribution is primarily controlled by the weathering of the basement rocks rather than by significant anthropogenic inputs. The generally low concentrations of trace elements in the water-soluble fraction further suggest limited immediate mobility and bioavailability under the prevailing geochemical conditions, thereby reducing the likelihood of groundwater contamination or plant uptake. Although the current concentrations indicate minimal ecological and human health concerns, changes in environmental conditions, such as acidification or mining-related disturbances, may enhance trace element release from more stable fractions, underscoring the need for periodic environmental monitoring (Alloway, 2013; De Matteis et al., 2023; Abule & Ekpete, 2025).

Table 1. Heavy metal concentrations in the water-soluble phase (mg/kg) of sediments/soils from the Ikole–Itapaji area, Southwestern Nigeria. This fraction represents the most mobile and immediately bioavailable portion of trace metals, reflecting their potential short-term environmental availability and mobility in the near-surface environment.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	6.321	2.087	0.077	0.681	0.572	0.054	0.062	0.023	0.004
SQ 2	6.128	2.063	0.072	0.631	0.509	0.059	0.063	0.021	0.003
SQ 3	7.427	3.108	0.083	0.724	0.592	0.063	0.069	0.028	0.005
SQ 4	7.129	3.099	0.081	0.711	0.579	0.061	0.066	0.025	0.005
SQ 6	5.873	2.145	0.094	0.742	0.582	0.063	0.067	0.029	0.006

SQ7	4.568	1.958	0.064	0.465	0.368	0.043	0.048	0.016	0.003
SQ 8	6.409	2.056	0.076	0.641	0.539	0.052	0.063	0.022	0.004
SQ 10	2.873	1.742	0.049	0.163	0.126	0.034	0.037	0.013	0.002
SQ 11	3.208	1.839	0.056	0.218	0.189	0.041	0.045	0.015	0.003
SQ 12	5.175	2.094	0.086	0.598	0.565	0.061	0.057	0.024	0.005
SQ 13	5.387	2.109	0.087	0.605	0.591	0.063	0.054	0.026	0.005
SQ 14	6.125	2.135	0.092	0.676	0.608	0.067	0.061	0.029	0.006
SQ 15	7.105	3.128	0.091	0.624	0.573	0.056	0.054	0.031	0.006
SQ 16	5.891	2.207	0.095	0.673	0.606	0.065	0.059	0.034	0.007
SQ 17	5.006	1.876	0.098	0.659	0.627	0.064	0.062	0.033	0.007

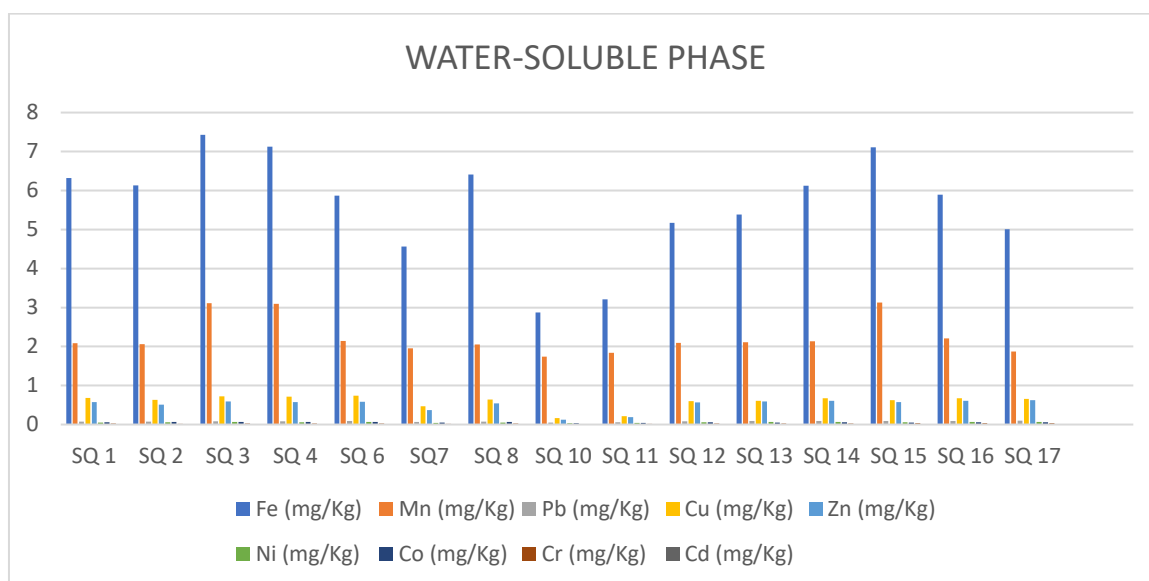


Figure 4. Cluster column chart of heavy metal concentrations in the water-soluble phase (mg/kg).

Exchangeable Phase

The exchangeable fraction comprises trace elements weakly adsorbed onto mineral surfaces through electrostatic interactions and represents one of the most environmentally sensitive geochemical fractions because these elements can be readily released by changes in pH, ionic strength, or ion-exchange processes (Kabata-Pendias, 2011; Alloway, 2013). As presented in Table 2, the exchangeable fraction exhibits generally higher trace element concentrations than the water-soluble fraction, indicating that a proportion of the elements is reversibly retained on mineral exchange sites rather than remaining in solution. Iron (Fe) recorded the highest concentrations (5.731–10.742 mg/kg), followed by manganese (Mn) (1.342–3.127 mg/kg), whereas Cu, Zn, Pb, Ni, Co, Cr, and Cd occurred at comparatively lower concentrations.

The spatial distribution illustrated in Figure 5 further demonstrates the predominance of Fe and Mn throughout the study area, reflecting their strong association with clay minerals and Fe–Mn oxide coatings developed during weathering of the basement rocks (Abule & Ekpote, 2025). The generally low concentrations of the remaining trace elements suggest limited enrichment within the exchangeable phase and indicate that most are retained in more stable geochemical fractions.

Overall, the exchangeable fraction indicates low to moderate trace element mobility under the prevailing geochemical conditions in the Ikole–Itapaji Basement Complex. Although Pb and Cd occur at relatively low concentrations, their occurrence within this readily exchangeable fraction implies that changes in environmental conditions, particularly soil acidification or anthropogenic disturbances, could increase their mobility and bioavailability. Nevertheless, the present concentrations indicate minimal ecological and human

health risks, while highlighting the importance of periodic monitoring to detect any future changes in trace element mobility (Alloway, 2013; De Matteis et al., 2023).

Table 2: Exchangeable phase of the heavy metal concentrations in soil samples (mg/kg). The table presents the distribution of Fe, Mn, Pb, Cu, Zn, Ni, Co, Cr, and Cd across all sampling locations, reflecting metals weakly bound to soil exchange sites and their potential environmental mobility.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	8.084	1.875	0.098	0.789	0.701	0.072	0.071	0.031	0.007
SQ 2	8.005	1.802	0.097	0.712	0.685	0.073	0.069	0.032	0.005
SQ 3	10.742	2.085	0.102	0.826	0.732	0.081	0.075	0.037	0.029
SQ 4	10.488	2.016	0.108	0.813	0.735	0.085	0.076	0.037	0.028
SQ 6	6.402	2.073	0.112	0.839	0.784	0.082	0.073	0.042	0.009
SQ7	6.023	1.762	0.082	0.619	0.586	0.065	0.059	0.025	0.005
SQ 8	8.787	1.904	0.126	0.804	0.721	0.075	0.073	0.034	0.026
SQ 10	5.731	1.342	0.085	0.279	0.261	0.067	0.072	0.026	0.004
SQ 11	6.174	1.563	0.096	0.351	0.31	0.071	0.072	0.029	0.005
SQ 12	7.787	2.012	0.113	0.801	0.721	0.094	0.087	0.038	0.009
SQ 13	7.819	2.105	0.109	0.799	0.726	0.097	0.085	0.042	0.01
SQ 14	8.534	3.083	0.138	0.902	0.846	0.102	0.095	0.051	0.017
SQ 15	10.231	3.127	0.146	0.927	0.872	0.117	0.102	0.054	0.021
SQ 16	7.118	2.105	0.128	0.942	0.839	0.112	0.11	0.059	0.028
SQ 17	6.104	2.098	0.131	0.967	0.886	0.132	0.121	0.061	0.026

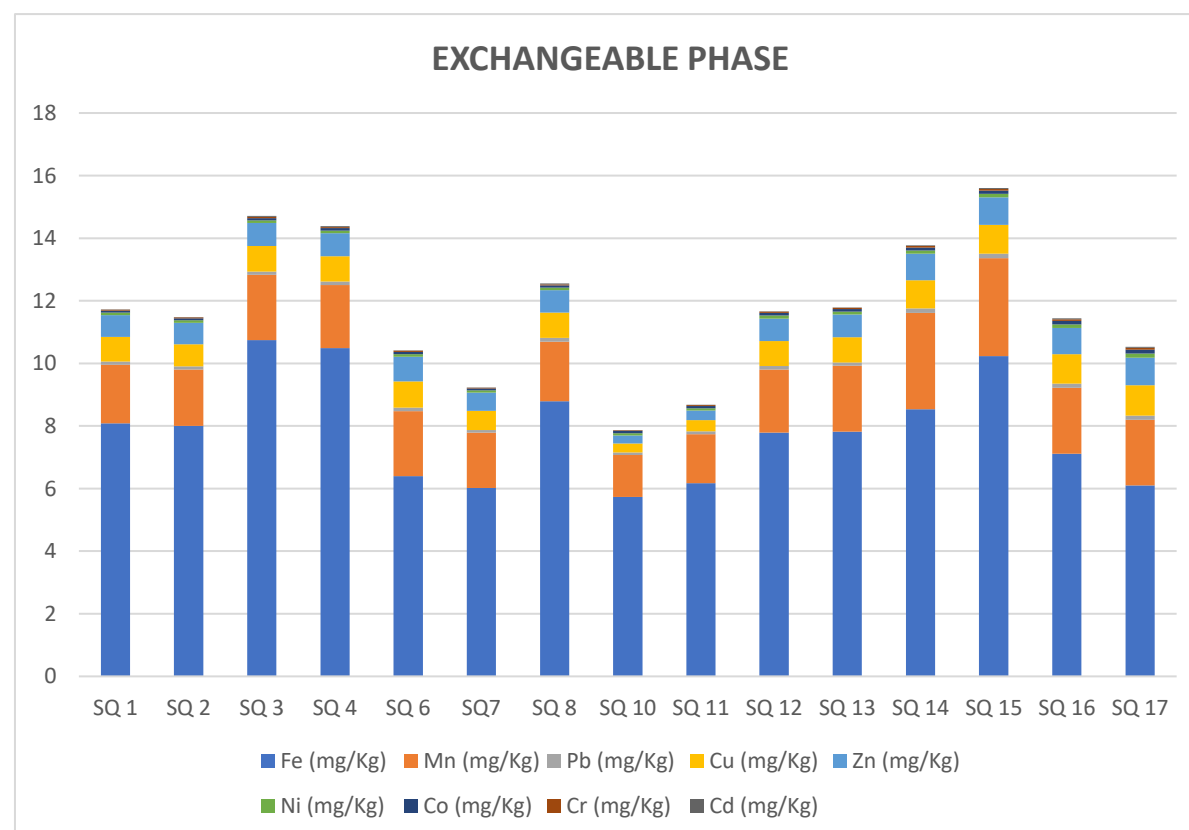


Figure 5. Exchangeable phase of the heavy metal concentrations in soil samples (mg/kg).

Carbonate-Bound Phase

The carbonate-bound fraction consists of trace elements associated with carbonate minerals and represents a potentially mobile geochemical phase because these elements may be released under acidic conditions through carbonate dissolution (Kabata-Pendias, 2011; Alloway, 2013). As shown in Table 3, trace element concentrations in this fraction are generally higher than those observed in the water-soluble and exchangeable phases, indicating stronger retention within carbonate minerals. Iron (Fe) recorded the highest concentrations (36.325–66.488 mg/kg), followed by manganese (Mn) (23.728–38.019 mg/kg), whereas Zn, Cu, Pb, Ni, Co, Cr, and Cd occurred at comparatively lower concentrations.

The spatial distribution presented in Figure 6 reveals relatively elevated concentrations at sampling locations SQ3, SQ4, and SQ15, while comparatively lower values were observed at SQ10. This variation is attributed primarily to differences in lithology and weathering intensity across the study area rather than to anthropogenic contamination (Abule & Ekpote, 2025; Delina, 2024). The predominance of Fe and Mn further suggests that these elements are preferentially associated with carbonate-bearing weathering products developed from the underlying basement rocks.

Overall, the carbonate-bound fraction indicates that most trace elements remain relatively stable under the prevailing geochemical conditions but could become more mobile if environmental acidification promotes carbonate dissolution. Therefore, the current trace element concentrations suggest low immediate ecological and human health risks within the Ikole–Itapaji area. Nevertheless, periodic monitoring is recommended, particularly in areas where future mining activities or land-use changes may modify soil chemistry and enhance trace element mobility (Alloway, 2013; De Matteis et al., 2023).

Table 3. Heavy metal concentrations in the carbonate-bound phase (mg/kg). The table shows the distribution of metals associated with carbonate minerals across all samples, reflecting their relative stability and potential release under acidic environmental conditions.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	40.129	25.207	2.279	2.439	13.226	2.147	1.701	0.531	0.069
SQ 2	41.052	25.422	2.142	2.197	13.055	2.132	1.626	0.625	0.065
SQ 3	65.246	37.529	3.217	2.826	18.614	2.704	2.002	0.954	0.089
SQ 4	66.488	38.019	3.832	3.213	18.901	3.125	2.106	1.005	0.103
SQ 6	38.615	24.234	1.715	2.327	13.178	2.362	1.448	0.603	0.059
SQ7	38.247	24.127	1.665	2.401	13.218	2.295	1.353	0.616	0.055
SQ 8	41.271	25.431	3.102	2.424	13.286	2.149	1.747	1.103	0.072
SQ 10	36.325	23.728	1.025	1.112	12.521	1.891	0.829	0.518	0.054
SQ 11	37.623	24.061	2.611	2.103	12.101	2.047	1.521	0.556	0.055
SQ 12	39.114	25.716	3.112	2.518	12.224	2.104	1.687	0.738	0.069
SQ 13	38.864	24.612	3.109	2.429	12.138	2.049	1.716	0.742	0.071
SQ 14	41.451	26.128	2.234	2.657	13.441	2.162	1.392	0.671	0.077
SQ 15	46.539	37.423	3.627	2.985	19.807	3.127	2.108	1.054	0.121
SQ 16	41.318	25.035	2.512	2.548	13.033	2.102	1.711	1.005	0.098
SQ 17	38.712	24.291	2.271	2.462	12.987	1.937	1.491	0.657	0.097

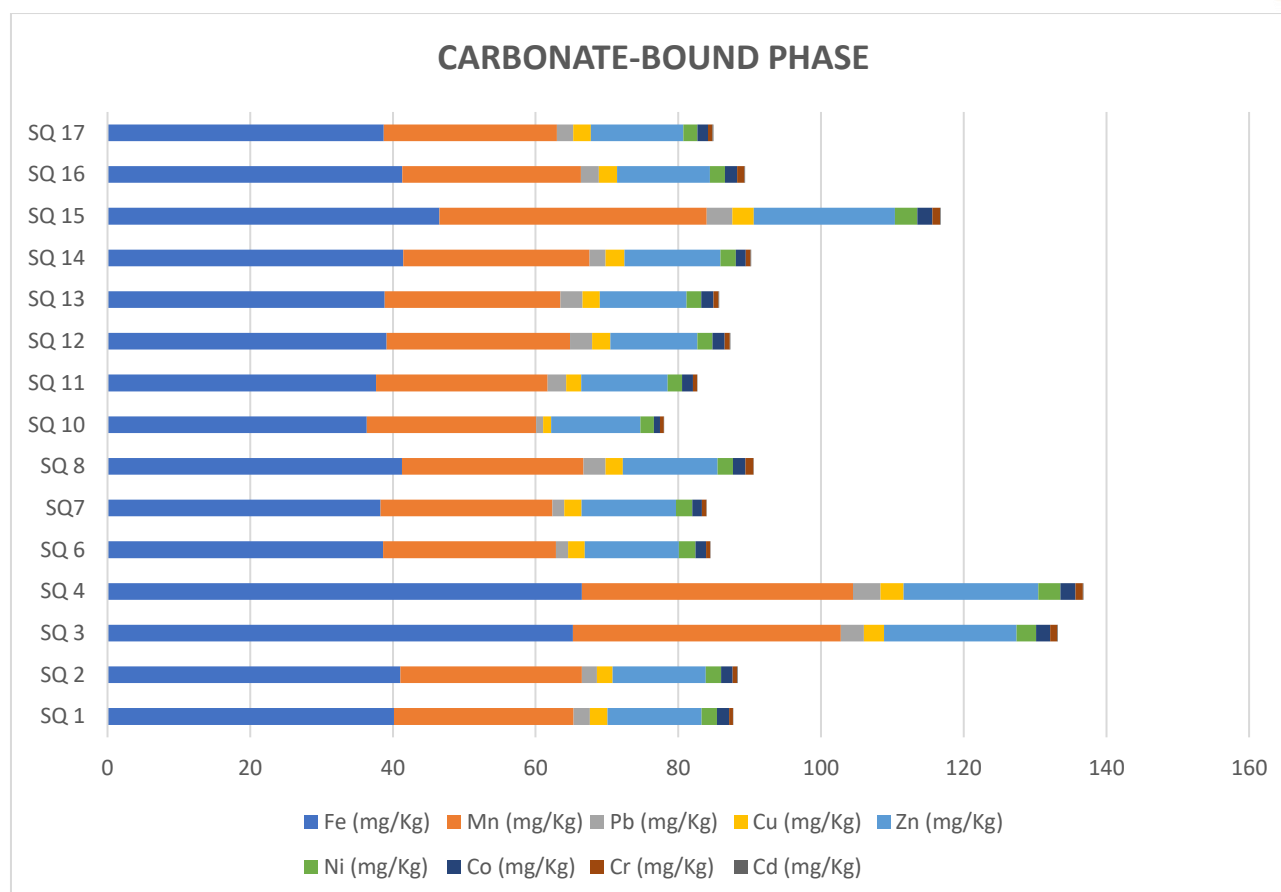


Table 6. Statistical summary of the heavy metals in the carbonate-bound phase (mg/kg).

Fe–Mn Oxide Phase

Table 4 presents the distribution of trace elements associated with the Fe–Mn oxide fraction, which represents one of the most important geochemical sinks for trace elements because iron and manganese oxides possess high adsorption capacities and effectively scavenge metals from the surrounding environment (Kabata-Pendias, 2011; Alloway, 2013). Iron (Fe) recorded the highest concentrations (303.187–476.031 mg/kg), followed by manganese (Mn) (139.204–267.163 mg/kg), confirming the dominance of these oxide phases in trace element retention. Among the remaining trace elements, Zn (54.584–77.129 mg/kg) exhibited the highest concentrations, followed by Pb, Ni, Cu, Co, Cr, and Cd.

The spatial distribution shown in Figure 7 reveals relatively elevated concentrations at sampling locations SQ3, SQ4, and SQ15, whereas comparatively lower concentrations were observed at SQ10. These spatial variations are interpreted to reflect differences in lithology, weathering intensity, and the abundance of Fe–Mn oxide minerals, rather than significant anthropogenic contributions (Abule & Ekpote, 2025; Delina, 2024). The preferential enrichment of Zn and other trace elements within this fraction further indicates the important role of Fe–Mn oxides in controlling trace element distribution and limiting their mobility within the weathered basement terrain.

Overall, the Fe–Mn oxide fraction constitutes a major reservoir for trace elements in the Ikole–Itapaji Basement Complex. Under the prevailing oxidizing conditions, these elements remain largely immobilized through adsorption and co-precipitation with Fe–Mn oxides, resulting in low immediate ecological and human health risks. However, changes to reducing conditions, such as prolonged waterlogging, mining activities, or other environmental disturbances, may dissolve these oxide phases and promote the release of associated trace elements, thereby increasing their mobility and potential environmental impact (De Matteis et al., 2023; Firmino et al., 2025).

Table 4: Heavy metal concentrations in the Fe–Mn oxide phase (mg/kg). The table presents the distribution of metals associated with iron and manganese oxides across all samples, reflecting their strong adsorption capacity and role as key geochemical sinks for trace elements.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	354.813	152.227	25.711	13.403	63.866	19.181	10.271	6.361	0.621
SQ 2	361.558	175.129	22.019	15.019	63.545	20.196	11.287	6.185	0.657
SQ 3	435.209	237.214	33.277	20.236	74.091	22.573	14.263	9.159	1.872
SQ 4	446.513	241.116	35.332	21.873	77.129	26.103	14.742	10.015	1.983
SQ 6	362.145	154.434	26.072	12.615	63.071	20.032	10.481	5.235	0.598
SQ7	358.903	149.828	21.612	13.211	63.242	18.269	9.593	6.062	0.615
SQ 8	371.874	185.401	26.128	14.029	70.008	20.542	11.792	8.187	1.328
SQ 10	303.187	139.204	16.623	11.197	54.584	16.352	6.282	4.815	0.574
SQ 11	337.217	144.436	18.217	12.018	58.611	19.142	8.027	5.251	0.591
SQ 12	349.812	147.164	23.712	16.182	62.202	20.017	10.019	6.131	0.691
SQ 13	345.875	147.119	23.389	16.429	62.138	20.049	9.948	5.782	0.711
SQ 14	360.158	176.524	25.304	15.173	63.493	21.366	11.097	7.176	0.877
SQ 15	476.031	267.163	36.125	22.957	75.937	25.183	13.162	10.254	2.021
SQ 16	361.521	155.003	22.574	14.348	64.113	19.179	11.201	7.012	0.798
SQ 17	338.019	142.401	17.753	12.967	59.285	18.331	10.096	8.954	0.917

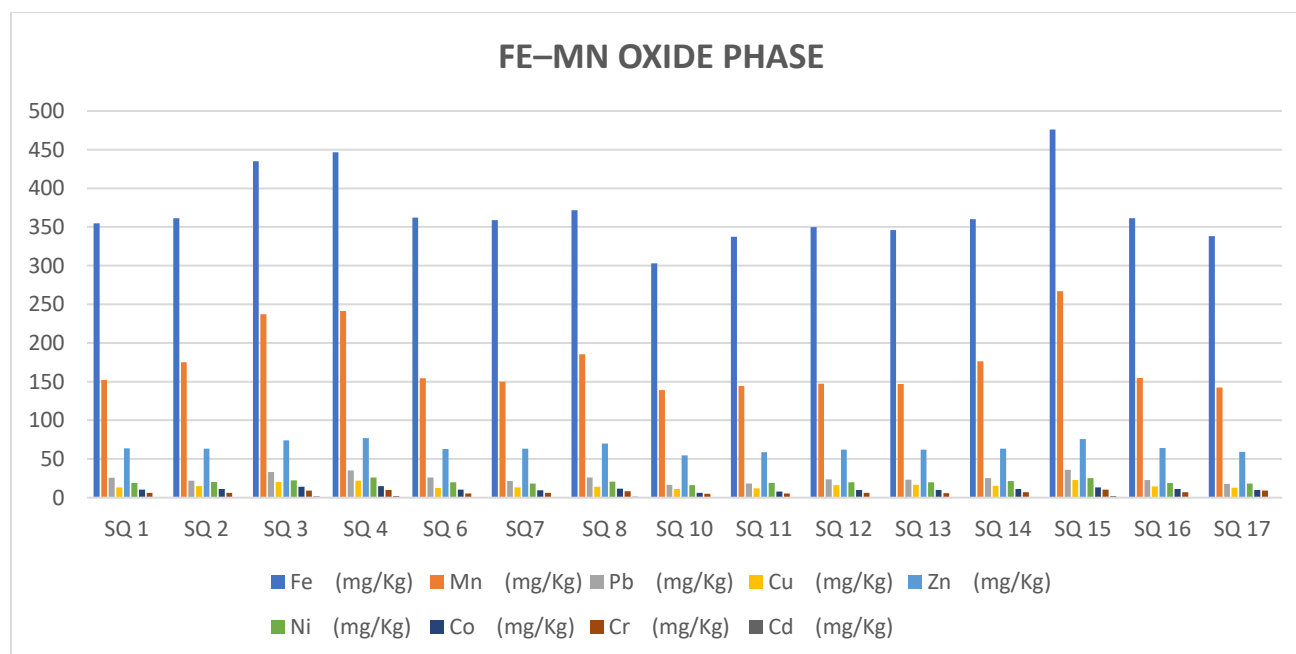


Figure 7. Cluster column chart of the heavy metal concentrations in the Fe–Mn oxide phase (mg/kg).

Organic Matter–Bound Phase

The organic matter-bound fraction comprises trace elements complexed with humic substances and decomposed organic materials, representing an important geochemical reservoir that regulates trace element retention and their gradual release during organic matter decomposition (Kaiser & Kalbitz, 2012; Liu et al., 2022). As presented in Table 5, iron (Fe) recorded the highest concentrations (148.854–356.163 mg/kg), followed by manganese (Mn) (55.772–89.112 mg/kg). Among the remaining trace elements, Zn and Cu

exhibited relatively higher concentrations, reflecting their strong affinity for organic ligands, whereas Pb, Ni, Co, Cr, and Cd occurred at comparatively lower concentrations.

The spatial distribution illustrated in Figure 8 shows relatively elevated concentrations at sampling locations SQ3, SQ4, and SQ15, while lower concentrations were observed at SQ10. These variations are attributed primarily to lithological differences and variations in organic matter content across the study area rather than to anthropogenic contamination (Abule & Ekpete, 2025; Delina, 2024). The enrichment of Zn and Cu within this fraction further suggests preferential complexation with organic matter, thereby reducing their immediate mobility under the prevailing environmental conditions.

Overall, the organic matter-bound fraction indicates that most trace elements are presently retained in relatively stable organometallic complexes and therefore pose low immediate ecological and human health risks within the Ikole–Itapaji area. However, decomposition of organic matter or changes in redox conditions may destabilize these complexes and release the associated trace elements into more mobile forms, thereby increasing their bioavailability and potential environmental impact (De Matteis et al., 2023; Firmino et al., 2025).

Table 5: Heavy metals concentrations in the organic matter–bound phase (mg/kg). The table shows the distribution of metals associated with organic matter across all samples, reflecting their affinity for organic complexation and potential release during organic matter decomposition.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	182.012	75.224	12.172	20.032	33.213	12.817	6.915	5.503	0.453
SQ 2	181.654	78.127	13.181	20.215	33.158	13.102	6.429	6.232	0.485
SQ 3	335.147	87.225	14.137	22.864	37.685	16.214	8.105	6.954	0.981
SQ 4	341.401	89.112	16.562	23.509	40.021	18.121	9.012	7.051	1.128
SQ 6	164.319	64.435	10.345	15.861	27.183	10.129	4.971	4.672	0.429
SQ7	168.247	64.247	10.631	15.539	28.011	10.216	5.056	4.956	0.433
SQ 8	189.074	81.236	13.123	20.421	33.786	13.014	6.747	6.143	0.472
SQ 10	148.854	55.772	9.926	14.158	24.128	8.997	4.635	4.329	0.414
SQ 11	152.627	57.201	10.011	15.141	25.091	9.089	4.921	4.457	0.425
SQ 12	169.612	65.236	11.162	16.214	25.274	10.176	5.068	4.781	0.446
SQ 13	169.881	64.837	11.134	16.452	25.181	10.089	5.112	8.714	0.451
SQ 14	180.575	76.294	12.634	21.052	32.846	12.763	6.557	5.773	0.472
SQ 15	356.163	87.826	15.663	24.486	40.372	18.522	9.138	7.074	1.221
SQ 16	185.052	75.135	12.246	20.415	33.325	13.012	6.751	6.028	0.482
SQ 17	168.176	65.095	10.773	15.404	28.197	10.332	6.904	6.193	0.462

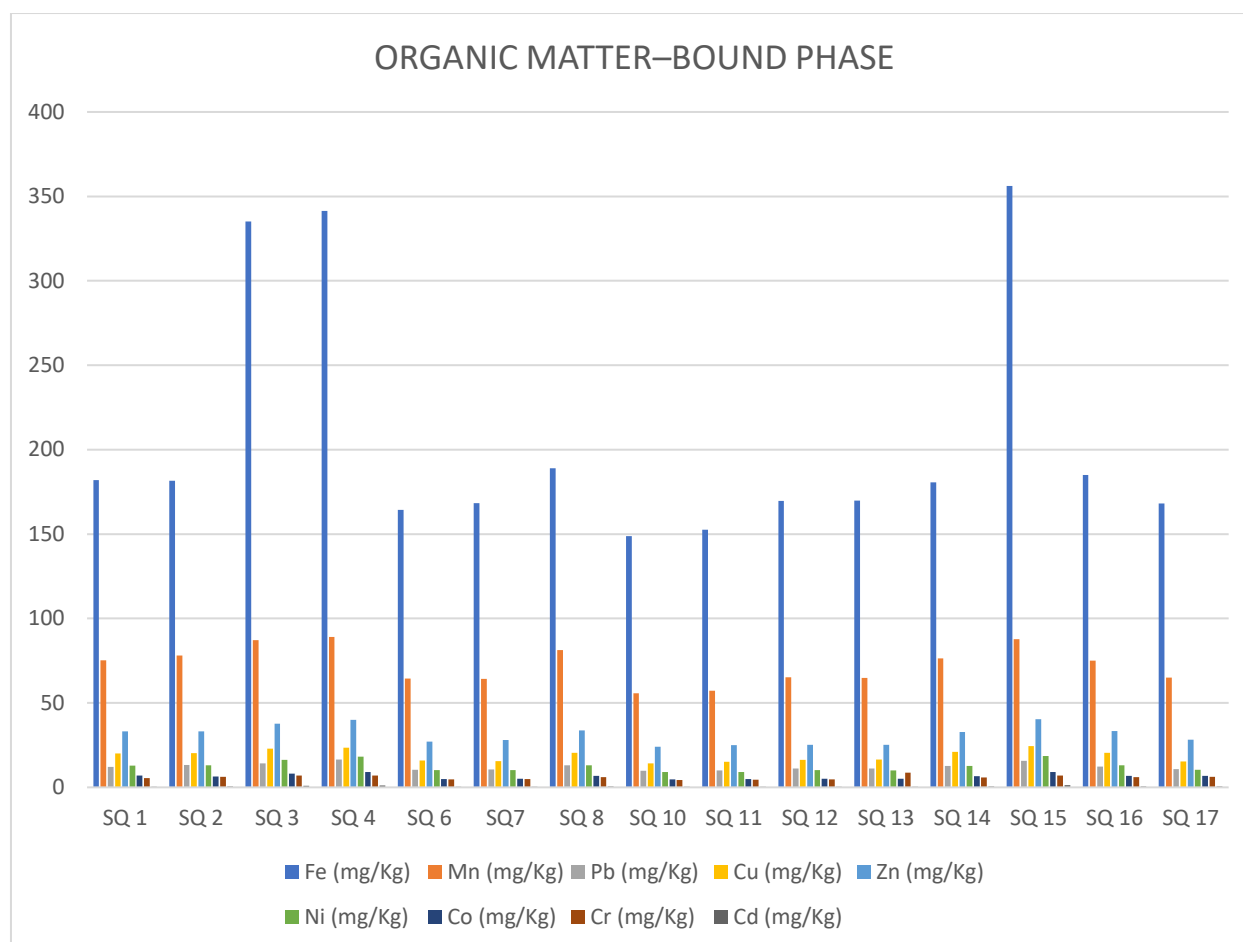


Figure 8. Cluster column chart of the heavy metal concentrations in the organic matter-bound phase (mg/kg).

Sulfide/Strongly Bound Phase

The sulfide/strongly bound fraction comprises trace elements incorporated within sulfide minerals and resistant mineral lattices and represents one of the most stable geochemical reservoirs for trace elements. Metals associated with this fraction are strongly retained and are typically released only under intense oxidative weathering or other severe environmental disturbances, making this phase an important long-term sink for potentially toxic elements (Tessier et al., 1979; Alloway, 2013). As presented in Table 6, iron (Fe) recorded the highest concentrations (184.382–353.506 mg/kg), followed by manganese (Mn) (75.148–150.084 mg/kg), whereas Zn, Cu, Pb, Ni, Co, Cr, and Cd occurred at comparatively lower concentrations.

The spatial distribution illustrated in Figure 9 shows relatively elevated concentrations at sampling locations SQ3, SQ4, and SQ15, while lower concentrations were observed at SQ10. These variations are primarily attributed to lithological heterogeneity and mineralogical composition of the basement rocks rather than anthropogenic contamination (Abule & Ekpote, 2025; Delina, 2024). The predominance of Fe and Mn within this fraction further indicates that a substantial proportion of the trace elements is incorporated within stable mineral phases, thereby limiting their mobility under the prevailing environmental conditions.

Overall, the sulfide/strongly bound fraction demonstrates that most trace elements are firmly retained within resistant mineral structures and therefore exhibit low mobility and limited bioavailability. Consequently, the present concentrations suggest minimal immediate ecological and human health risks within the Ikole–Itapaji area. However, prolonged oxidative weathering, mining activities, or other environmental disturbances capable of destabilizing sulfide minerals may enhance the release of these trace elements into more mobile forms, thereby increasing their potential environmental impact (De Matteis et al., 2023; Firmino et al., 2025).

Table 6: Heavy metal concentrations in the sulfide/strongly bound phase (mg/kg). The table shows metals strongly associated with sulfide minerals and resistant phases, reflecting their low mobility and long-term geochemical stability within the soil matrix.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	251.118	105.746	18.723	14.103	31.411	11.652	6.342	5.126	0.343
SQ 2	252.049	108.224	17.916	14.321	30.782	11.761	6.226	5.472	0.345
SQ 3	345.371	147.602	24.432	20.438	35.255	15.004	7.752	6.159	0.798
SQ 4	352.217	147.916	25.543	20.825	36.126	15.243	8.116	6.458	1.128
SQ 6	184.382	83.239	12.621	13.127	26.134	9.827	4.279	4.174	0.312
SQ7	186.641	84.043	12.584	13.312	26.187	10.022	4.853	4.956	0.331
SQ 8	262.248	115.741	19.251	14.329	31.732	12.021	6.349	5.765	0.372
SQ 10	201.508	75.148	11.016	12.503	22.101	8.217	4.251	4.329	0.314
SQ 11	205.421	77.713	11.172	13.008	23.061	8.734	4.584	4.457	0.325
SQ 12	216.142	85.062	11.729	13.543	27.658	10.964	5.866	4.586	0.337
SQ 13	217.618	84.927	11.972	13.729	27.851	11.492	5.982	8.148	0.421
SQ 14	250.354	106.109	18.649	15.021	30.496	12.035	6.264	5.228	0.432
SQ 15	353.506	150.084	25.791	22.129	37.022	15.232	8.335	6.784	1.147
SQ 16	253.127	107.732	18.069	16.011	32.029	12.022	6.016	5.822	0.441
SQ 17	184.783	85.106	11.967	12.938	25.867	10.112	5.241	5.013	0.437

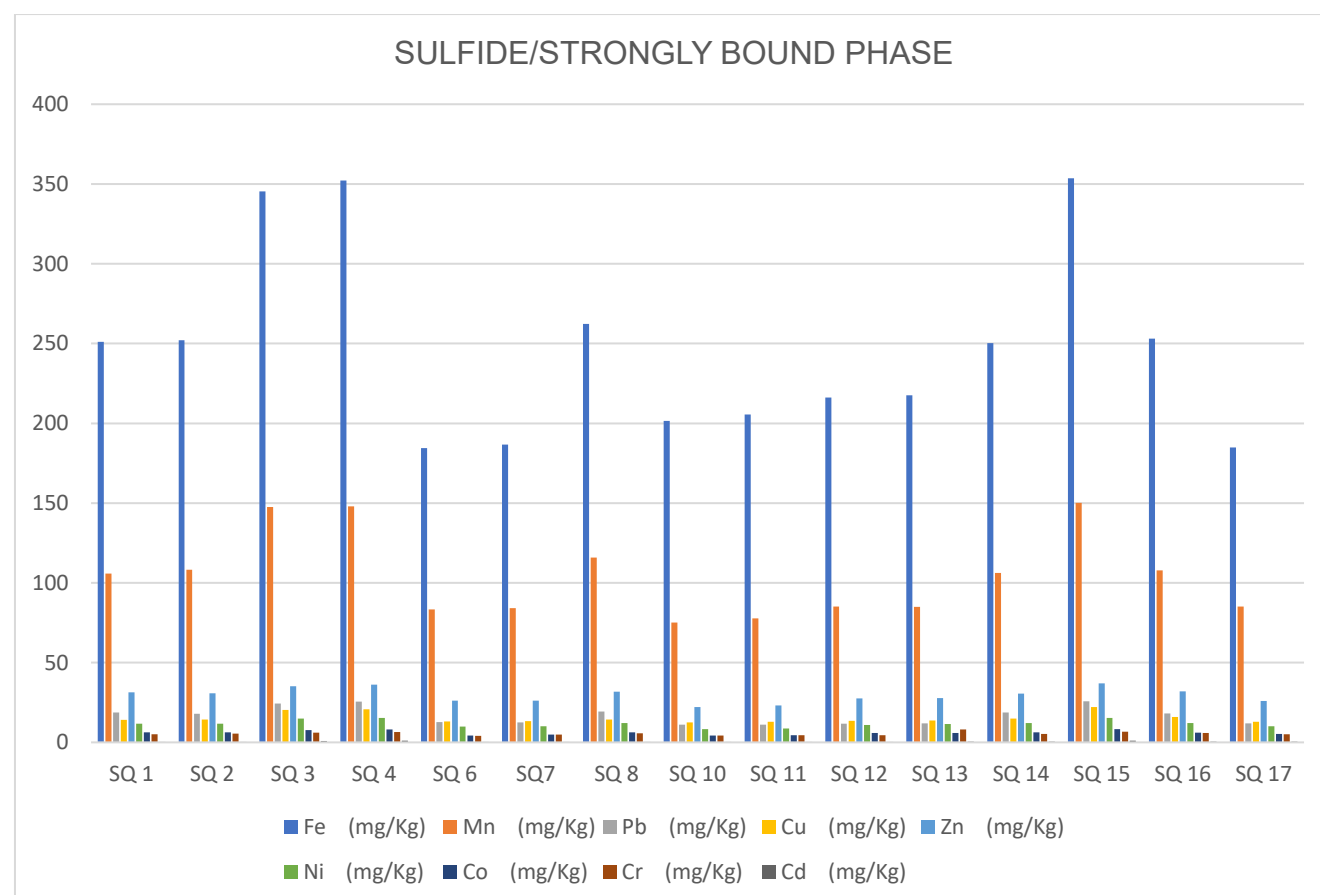


Figure 9. Cluster column chart of the heavy metal concentrations in the sulfide/strongly bound phase (mg/kg).

Residual Phase

The residual fraction comprises trace elements structurally incorporated within primary and secondary mineral lattices and represents the most stable and least mobile geochemical phase. Trace elements in this fraction are strongly bound within silicate and oxide minerals and are generally released only through prolonged weathering or complete mineral dissolution (Tessier et al., 1979; Kabata-Pendias, 2011). As presented in Table 7, iron (Fe) overwhelmingly dominates the residual fraction, with concentrations ranging from 12,532.459 to 16,416.143 mg/kg, followed by manganese (Mn) (769.814–946.516 mg/kg). The remaining trace elements, including Zn, Cu, Pb, Ni, Co, Cr, and Cd, occur at comparatively lower concentrations, indicating that they are largely incorporated within resistant mineral structures rather than enriched through secondary geochemical processes.

The spatial distribution shown in Figure 10 further confirms relatively higher Fe concentrations at sampling locations SQ3, SQ4, SQ14, and SQ15, reflecting variations in lithology and mineralogical composition across the Ikole–Itapaji Basement Complex (Abule & Ekpote, 2025; Delina, 2024). The predominance of Fe and Mn within the residual fraction indicates that these elements are principally controlled by the parent rock mineralogy and remain largely unaffected by contemporary weathering or anthropogenic influences.

Overall, the residual fraction demonstrates that the majority of trace elements are retained within stable mineral lattices, resulting in very low mobility and negligible bioavailability under the prevailing environmental conditions. Consequently, the current trace element distribution poses minimal immediate ecological and human health risks within the study area. Nevertheless, prolonged chemical weathering, intensive mining activities, or extensive rock alteration may gradually release these elements into more labile geochemical fractions, thereby increasing their environmental significance over time (Alloway, 2013; De Matteis et al., 2023).

Table 7: Heavy metal concentrations in the residual phase (mg/kg). The table shows metals strongly locked within primary and secondary mineral lattices, representing the most stable and least mobile geochemical fraction in the soil system.

Samples	Fe	Mn	Pb	Cu	Zn	Ni	Co	Cr	Cd
	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
SQ 1	13124.2	851.125	37.231	51.609	86.332	31.861	18.715	66.322	0.597
SQ 2	13231.6	862.197	35.793	52.096	84.809	32.168	19.207	66.188	0.553
SQ 3	16265.6	946.516	40.714	62.631	95.119	42.732	23.061	78.751	1.177
SQ 4	16416.1	941.849	42.028	61.979	97.151	43.833	23.146	80.015	1.185
SQ 6	15693.2	874.034	38.624	56.235	93.009	40.635	21.081	72.231	0.682
SQ7	12758.9	780.623	32.627	53.018	66.745	30.561	13.196	57.592	0.414
SQ 8	14753.7	865.106	36.942	54.723	88.126	34.642	20.731	68.685	1.127
SQ 10	12593.7	789.702	30.574	51.052	65.905	29.364	14.211	55.885	0.534
SQ 11	12682.4	776.937	31.077	51.031	68.016	29.902	13.723	55.759	0.511
SQ 12	14723.8	867.369	38.362	56.387	86.972	34.558	20.148	69.101	0.746
SQ 13	12532.5	769.814	30.984	52.125	68.132	32.092	13.741	55.704	0.642
SQ 14	15562.5	876.614	39.072	58.521	90.165	38.965	22.094	73.672	0.779
SQ 15	15469.5	872.607	40.729	57.985	92.007	39.018	21.628	71.961	1.302
SQ 16	13063.5	856.735	35.071	53.081	84.717	35.109	18.591	67.412	0.698

SQ 17	13274.2	842.699	34.866	52.983	85.458	35.238	18.793	66.923	0.602
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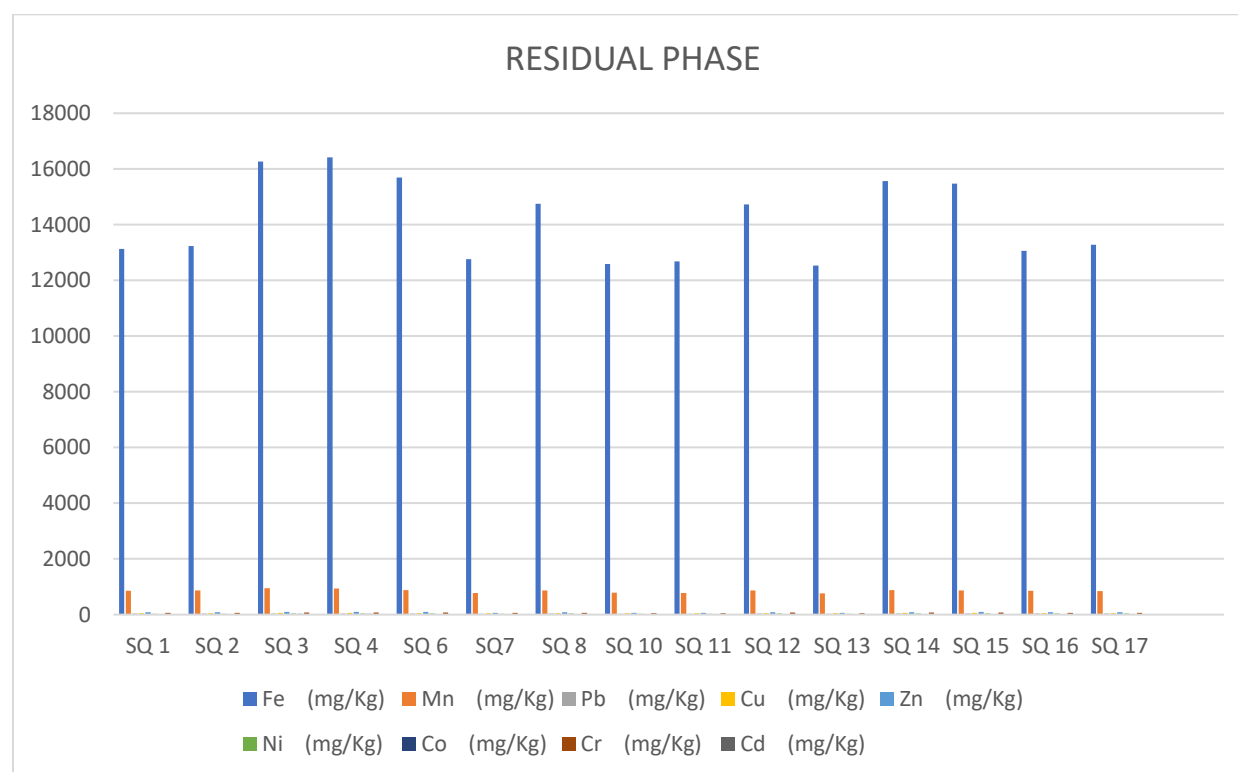


Figure 10. Cluster column chart of the heavy metal concentrations in the residual phase (mg/kg).

Trace elements geochemistry

The factor analysis results presented in Table 8 and Figure 11 extracted two significant components with eigenvalues greater than one, collectively explaining 92.04% of the total geochemical variance. Component 1 has an eigenvalue of 8.034 and accounts for 80.34% of the variance, while Component 2 has an eigenvalue of 1.171 and explains an additional 11.71%. The high cumulative variance indicates that the two components adequately represent the geochemical relationships among the analysed trace elements (Rollinson, 1993; Rollinson & Pease, 2021).

Component 1 is characterized by strong positive loadings of Cu (0.966), Ni (0.983), Co (0.951), Fe (0.939), Zn (0.863), and Mn (0.849), indicating a common lithogenic origin controlled by the composition of the basement rocks. This component is therefore interpreted as the lithological factor, reflecting the primary geochemical signature of the host rocks (Rollinson, 1993; Olade, 2020).

Component 2 is dominated by As (0.728), Th (0.356), Ag (0.224), and Pb (0.008). This association represents a pathfinder factor, suggesting localized hydrothermal alteration and trace element enrichment associated with mineralization (Rose et al., 1979; Olade, 2020).

The high communality values (0.773–0.998) indicate that the extracted components explain most of the variability of the analysed elements, confirming the robustness of the factor model. Figure 11 further illustrates the dominance of Component 1 over Component 2, emphasizing that lithology is the principal control on trace element distribution, whereas hydrothermal processes exert a secondary influence.

Overall, the factor analysis indicates that trace element distribution in the Ikole–Itapaji Basement Complex is primarily controlled by lithology, with localized hydrothermal alteration contributing to the enrichment of pathfinder elements and highlighting areas of mineralization potential.

Table 8. Results of factor analysis showing the extracted principal components, corresponding factor loadings, and the percentage of variance explained by each component. The analysis identifies the major geochemical associations and underlying processes controlling elemental distribution and mineralization patterns within the study area.

Variables	Comp1	Comp2	Communality
Cu	0.966		0.998
Pb		0.008	0.956
Zn	0.863		0.958
Ag		0.224	0.963
Ni	0.983		0.967
Co	0.951		0.997
Mn	0.849		0.773
Fe	0.939		0.921
As		0.728	0.809
Th		0.356	0.863
EV	8.034	1.171	
VAR%	80.34%	11.71%	
CVAR%	80.34%	92.04%	

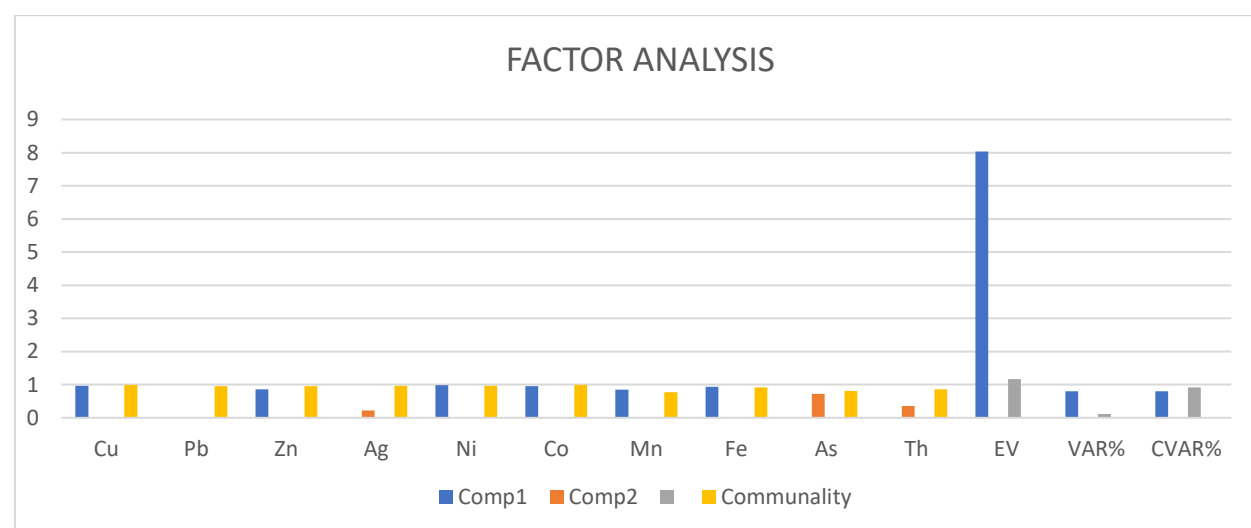


Figure 11. Factor analysis chart showing the loadings of Components 1 and 2, communalities, eigenvalues (EV), percentage variance explained (VAR%), and cumulative variance (CVAR%) for the analysed geochemical elements.

The correlation coefficient matrix Table 9 and the corresponding chart Fig. 12 reveal significant relationships among the analysed trace elements, reflecting their geochemical behaviour and possible mineralization processes. Strong positive correlations were observed among Cu–Ni ($r = 0.845$), Cu–Co ($r = 0.824$), Cu–Fe ($r = 0.804$), Ni–Co ($r = 0.935$), Ni–Fe ($r = 0.917$), and Co–Fe ($r = 0.876$), indicating a common lithological source and similar geochemical affinity. Zinc also shows moderate to strong positive correlations with Cu, Ni, Co, and Fe, suggesting its association with the same mineralizing system (Olade, 2020; Rollinson & Pease, 2021).

In contrast, Ag exhibits strong negative correlations with Cu, Ni, Co, and Fe but strong positive correlations with Pb ($r = 0.913$) and Th ($r = 0.829$), indicating that these elements are controlled by a different geochemical process or mineral phase. Similarly, the strong positive correlation between Pb and Th ($r = 0.891$), together

with the moderate correlation between Pb and As ($r = 0.500$), suggests localized hydrothermal enrichment and association with felsic lithologies (Odewumi & Olarewaju, 2013).

Mn and As generally display weak correlations with most of the analysed elements, indicating relatively independent geochemical behaviour. Figure 20 further illustrates the close association among Cu, Ni, Co, Fe, and Zn, while Ag, Pb, and Th form a separate elemental group. Overall, the correlation analysis identifies two principal geochemical associations: a Cu–Ni–Co–Fe–Zn suite reflecting lithological control and a Pb–Ag–Th suite indicative of hydrothermal processes and potential mineralization within the study area.

Table 9. Correlation coefficient matrix showing the degree and direction of relationships among the analyzed geochemical elements. Positive and negative correlation values indicate possible common sources, mineral associations, and geochemical processes influencing elemental distribution. The matrix provides a basis for interpreting elemental affinities and assessing mineralization potential within the study area.

	Cu	Pb	Zn	Ag	Ni	Co	Mn	Fe	As	Th
Cu	1									
Pb	-.543**	1								
Zn	.606**	-.424*	1							
Ag	-.858*	.913*	-0.7598	1						
Ni	.845**	-.496*	.596**	-.914*	1					
Co	.824**	-.557**	.683**	-.849*	.935**	1				
Mn	-0.294	-0.1273	0.20883	-.820*	-0.3365	-0.281	1			
Fe	.804**	-.710**	.529**	-.890*	.917**	.876**	-0.2066	1		
As	-0.176	.500*	-0.0909	0.75	-0.1921	-0.0929	0.00011	-.401*	1	
Th	-.506*	.891**	-.407*	.829*	-.493*	-.460*	-0.1191	-.700**	.636**	1

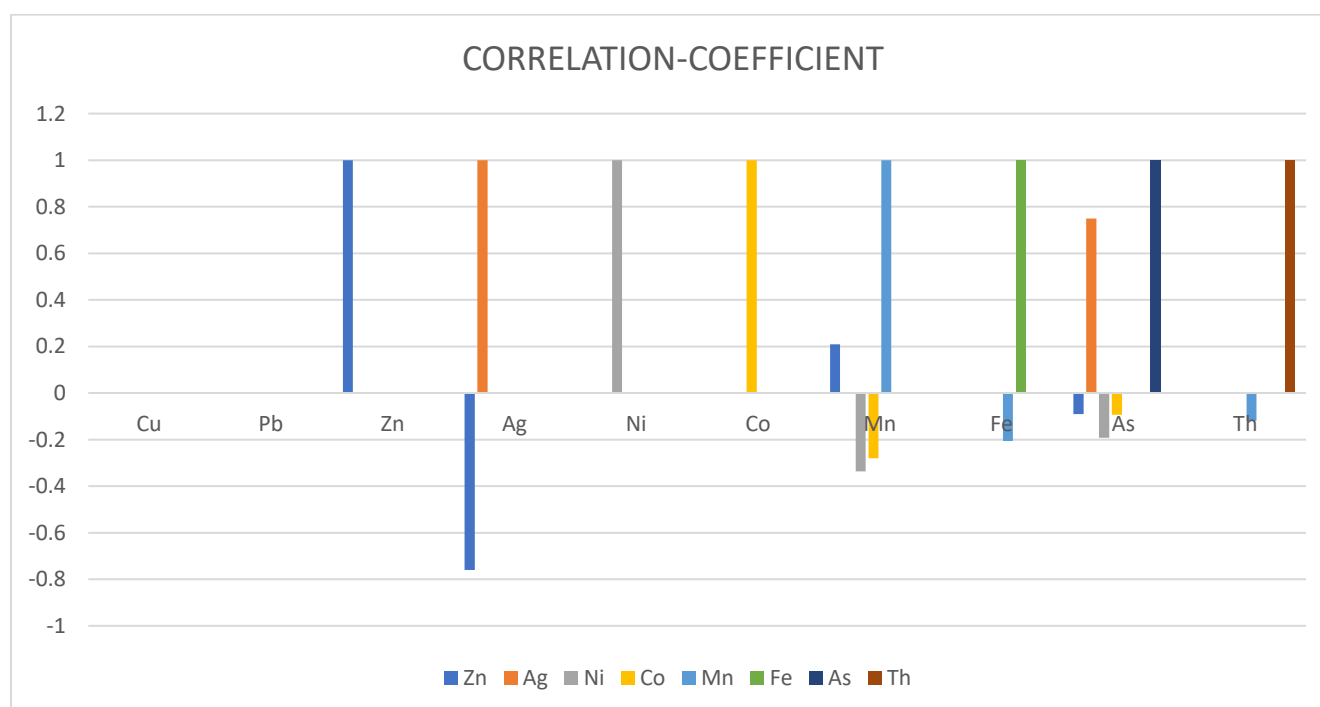


Figure 12. Correlation coefficient chart illustrating the strength and direction of relationships among the analyzed trace elements.

Integration of Sequential Extraction and Trace Element Geochemistry

The integration of sequential extraction and trace element geochemistry provides a comprehensive assessment of the distribution, fractionation, and mobility of trace elements within the Ikole–Itapaji Basement Complex. While trace element geochemistry establishes the overall abundance and geochemical associations of the analysed elements, sequential extraction distinguishes their distribution among different geochemical fractions, thereby providing insight into their mobility, stability, and potential environmental behaviour (Tessier et al., 1979; Rollinson & Pease, 2021).

The trace element geochemistry indicates that Fe, Mn, Cu, Ni, Co, and Zn constitute the dominant elemental association, reflecting the lithological characteristics of the basement rocks. This interpretation agrees with the sequential extraction results, where Fe and Mn occur predominantly within the Fe–Mn oxide, sulfide/strongly bound, and residual fractions, indicating strong lithological control and limited mobility. Similarly, Cu, Ni, Co, and Zn are largely concentrated in the less mobile fractions, suggesting that these elements are mainly retained within stable mineral phases rather than readily available for environmental transport (Alloway, 2013; Abule & Ekpete, 2025).

The correlation and factor analyses further demonstrate that the Cu–Ni–Co–Fe–Zn association is controlled principally by lithology, whereas the Pb–Ag–Th association reflects localized hydrothermal processes. The relatively low concentrations of trace elements in the water-soluble and exchangeable fractions indicate limited bioavailability under the prevailing geochemical conditions. However, changes in environmental conditions, including weathering, acidification, or mining activities, could promote the release of metals from the carbonate-bound, Fe–Mn oxide, and organic matter-bound fractions, thereby increasing their mobility and environmental significance (Kabata-Pendias, 2011; De Matteis et al., 2023).

Overall, the integrated results demonstrate that trace element distribution in the Ikole–Itapaji Basement Complex is controlled predominantly by lithology, with localized hydrothermal alteration contributing to elemental enrichment. The predominance of trace elements within the stable geochemical fractions indicates low present-day mobility and minimal immediate environmental risk, while highlighting favourable geological conditions for metallic mineralization (Rollinson, 1993; Rollinson & Pease, 2021).

CONCLUSION

The integration of sequential extraction and trace element geochemistry has provided a comprehensive understanding of the distribution, fractionation, and mobility of trace elements within the Ikole–Itapaji Basement Complex, Southwestern Nigeria. The trace element geochemistry indicates that Fe, Mn, Cu, Ni, Co, and Zn are principally controlled by the lithological composition of the crystalline basement rocks, while the Pb–Ag–Th association reflects localized hydrothermal enrichment associated with mineralization. Correlation and factor analyses further confirm that lithology is the dominant control on elemental distribution, with hydrothermal processes exerting a secondary influence.

The sequential extraction results reveal that the majority of the analysed trace elements are concentrated within the Fe–Mn oxide, sulfide/strongly bound, and residual fractions, indicating low mobility and limited bioavailability under the prevailing environmental conditions. In contrast, only small proportions occur within the water-soluble and exchangeable fractions, suggesting minimal immediate release into the surrounding environment.

Overall, the study indicates that the Ikole–Itapaji area is characterized by a low environmental hazard, with low ecological risk, low groundwater contamination risk, and low human health risk arising from trace element mobility under the current geochemical conditions. Nevertheless, trace elements retained in the carbonate-bound, Fe–Mn oxide, and organic matter-bound fractions may become mobilized if environmental conditions are altered by prolonged weathering, soil acidification, intensive mining, or other anthropogenic disturbances. Such changes could increase trace element bioavailability and elevate the potential ecological and human health risks.



The integrated approach adopted in this study demonstrates that combining sequential extraction with trace element geochemistry is an effective framework for evaluating element fractionation, mobility, environmental risk, and mineralization potential in crystalline basement terrains. The findings provide valuable baseline information for future mineral exploration, environmental monitoring, and sustainable resource management within the Ikole–Itapaji Basement Complex.

RECOMMENDATIONS

Based on the findings of this study, periodic environmental monitoring of trace element mobility should be conducted to detect any changes associated with weathering, land-use activities, or future mining operations. Where mineral exploration is undertaken, environmentally sustainable mining practices should be implemented to minimize the release of trace elements from stable geochemical fractions into more mobile forms. In addition, further studies integrating sequential extraction with groundwater, soil, and vegetation analyses are recommended to provide a more comprehensive assessment of trace element transfer and long-term environmental risk within the Ikole–Itapaji Basement Complex.

Declaration of competing interests

Ethical Approval

This study did not involve human participants, animals, or any form of clinical or ethical experimentation. Therefore, formal ethical approval was **not required**.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (GPT-5-mini) to assist with language editing and content organization. After using this tool, the authors reviewed, revised, and verified all content to ensure accuracy, originality, and authenticity, and take full responsibility for the content of the published article.

Consent to Participate

As no human participants were involved in this research, obtaining consent for participation was **not applicable**. All research activities adhered to standard field and laboratory protocols without the involvement of people.

Consent to Publish

This study does not include any personal, sensitive, or identifiable information. Consequently, consent to publish was **not applicable**. All data presented are **scientific observations and analyses**, fully anonymized, and pose no ethical concerns.

Availability of Data and Materials:

The datasets used and analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Adeleke Ojo solely conceived and designed the study, carried out the field sampling, prepared the samples for laboratory analyses, performed the sequential extraction and trace element geochemical analyses, interpreted the results, prepared the figures and tables, drafted the manuscript, critically revised the manuscript for intellectual content, and approved the final version for publication.

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