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Mineralogy and Trace Element Composition of Termite Mound Soil from Selected Communities in Delta State, Nigeria

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***Abstract**: Termite mounds are biogenic structures that modify soil properties through the selective excavation, transportation and redistribution of soil materials, making them useful indicators of mineralogical and geochemical characteristics of their environments. This study investigated the mineralogical composition, major-element geochemistry, trace-element distribution and weathering characteristics of termite mound soils from seven communities in Delta State, Nigeria. Termite mound soil samples were collected from Warri, Agbor, Ogbehasi, Abraka and Oleh, prepared and analyzed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) techniques. The major-element composition was dominated by SiO_2, Fe_2O_3 and TiO_2, with concentrations ranging from 32.20–58.34%, 13.52–37.44% and 1.23–3.56%, respectively, whereas Al_2O_3, CaO, K_2O, Na_2O, MnO and P_2O_5 generally occurred at concentrations below 1%. XRD analysis identified quartz, montmorillonite, kaolinite, orthoclase and albite as the principal mineral phases. Provenance discrimination indicated predominantly igneous source contributions with evidence of both mafic and felsic components, while the weathering relationships suggested variable chemical alteration characterized by clay-mineral formation, silica retention and relative iron enrichment. Trace-element distributions also varied spatially among the sampling locations, reflecting differences in geological background, mineralogical composition, weathering intensity and termite-mediated redistribution of soil materials. The findings demonstrate that termite mound soils preserve useful mineralogical and geochemical signatures of their surrounding environments and can serve as complementary materials for geological and geochemical assessment in Delta State, Nigeria.*

Keywords: *Termite mound soil, Mineralogy, Geochemistry, Trace elements, Chemical weathering*

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1.0 Introduction

Termites are important ecosystem engineers whose activities can substantially modify the physical, chemical, mineralogical and biological properties of soils. Through excavation, transportation, selection and redistribution of soil particles, termites construct mounds (termitaria) that differ in composition and structure from the surrounding undisturbed soils. The construction and maintenance of termite mounds involve the selective collection and mixing of soil materials, clay enrichment, particle aggregation and biochemical binding, processes that can alter the distribution of minerals and chemical elements within the soil profile. Termite-modified soils may therefore provide useful information on soil formation, weathering processes, elemental redistribution and the geological materials from which the soils were derived. In addition, biological processes associated with microorganisms and plants can contribute to mineral weathering and clay-mineral transformation through the production of organic acids, proton exchange, complexation and the mobilization or uptake of interlayer and structural elements (Augusto *et al*., 2001; Hinsinger, 1990; Landeweert *et al*., 2001; Robert & Berthelin, 1986).

The mineralogical characteristics of termite mound soils are particularly important because the minerals incorporated into mound structures can reflect both the parent materials available to termite colonies and the processes operating during soil modification. Weathering of silicate minerals can result in the formation and transformation of clay minerals, while iron-bearing minerals may become concentrated through selective particle transport and geochemical processes. Consequently, mineralogical investigation of termite mound soils can provide information about the nature of the source materials, degree of weathering and processes responsible for soil development. X-ray diffraction (XRD) is particularly useful for identifying crystalline mineral phases, whereas X-ray fluorescence (XRF) provides quantitative information on major-element oxides and selected trace elements. The combined application of these techniques therefore provides a useful approach for relating mineral assemblages to the geochemical characteristics and weathering history of termite mound soils.

Previous studies have demonstrated the potential of termite mounds as sources of mineralogical and geochemical information. Termite mound construction has been associated with substantial modification of the physical and chemical properties of soil relative to adjacent soils (Lee, 1983; Lobry & Conacher, 1990). Because termites selectively transport and concentrate soil materials during mound construction, termite mounds have also been investigated as potential indicators of subsurface mineralization and geochemical anomalies. Earlier studies reported the usefulness of termite structures in mineral exploration, including applications involving uranium mineralization and other mineral deposits (D'Orey, 1975; Le Roux & Humbleton-Jones, 1991; Nagaraju *et al*., 2013; Petts *et al*., 2009; Prasad & Vijayasaradhi, 1984; Sankaran & Prasad, 2000; Watson, 1972). The ability of termite mounds to accumulate or redistribute elements has consequently generated interest in their application as biological or geochemical indicators of underlying geological conditions (Bode *et al*., 2013; Kedebe, 2004).

Studies in Nigeria have further demonstrated considerable variation in the mineralogical and geochemical characteristics of termite mound soils. Idoko and Okieimen (2020), in their investigation of termite mound soils from the Idoma area of Benue State, reported that the samples were dominated by SiO_2 (49.64%), Fe_2O_3 (22.88%) and Al_2O_3 (19.42%), while other major oxides occurred at concentrations below 1%. XRD analysis identified hematite, phlogopite and chrysotile as important mineral phases, with additional minerals occurring in particular sampling locations. The authors also reported high Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Plagioclase Index of Alteration (PIA) and Mineralogical Index of Alteration (MIA) values, indicating a high degree of chemical weathering of the source materials. These findings demonstrate that mineralogical and geochemical characteristics of termitaria can provide useful information about the lithology and weathering conditions of their source environments.

The significance of termite mound soils has also been demonstrated in Delta State. Momah and Okieimen (2020) investigated the mineralogy, geochemical composition and geotechnical properties of termite mound soils from nine locations in the Ika area of Delta State, Nigeria. Their XRF results showed that the soils were dominated by SiO_2 (40.25%), Fe_2O_3 (29.27%), Al_2O_3 (24.25%) and TiO_2 (4.27%), while CaO, MnO, MgO, Na_2O and P_2O_5 occurred at concentrations below 1%. The trace elements included Cr (8.20–23.10 mg kg^{-1}), Pb (3.95–13.85 mg kg^{-1}), Cu (2.75–12.00 mg kg^{-1}), Zn (3.60–9.60 mg kg^{-1}) and Cd (1.90–3.15 mg kg^{-1}). Their XRD results further indicated substantial hematite contents of 60.17–83.78%, antigorite contents of 5.24–24.17% and quartz contents of 7.14–14.67%, with anthophyllite occurring in one sample. These results confirm that termite mound soils in Delta State can exhibit distinctive mineralogical and geochemical signatures.

More recent investigations have broadened understanding of the properties of termite-modified soils in the Niger Delta region. Momah *et al*. (2026) examined nutrient enrichment patterns in termite mounds from selected locations in Delta and Edo States and found that mound soils generally contained higher concentrations of several soil fertility-related parameters than adjacent uncolonized soils. The reported mound-soil pH ranged from 5.86 to 6.61, while total phosphorus, total nitrogen, total organic carbon and total organic matter ranged from 0.50–1.54, 1.07–4.20, 13.30–19.90 and 21.50–33.96 mg kg^{-1}, respectively. These findings indicate that termite activity can produce chemically enriched soil matrices and reinforce the importance of termite mounds as modified geochemical environments. Similarly, Momah *et al*. (2026) reported significant spatial variation in the geotechnical properties of termite mound soils from selected communities in Edo and Delta States. Liquid limit values ranged from 32–52%, plasticity index from 16.9–26.7%, maximum dry density from 1.61–1.82 Mg m^{-3} and specific gravity from 2.43–2.86. Such variations indicate that the properties of termite mound soils are strongly influenced by their local environmental and geological settings. The potential engineering significance of termite mound soils has also received attention. Suleiman *et al*. (2024) reported that termite mound soil could improve the maximum dry density and compressive strength of lateritic soil when used as an additive, with the improvement being more pronounced in lateritic than clayey soil. These findings, together with the studies of Momah and Okieimen (2020) and Momah *et al*. (2026), demonstrate that termite mound soils have properties that may be relevant to geotechnical applications. However, the engineering characteristics of termite mound soils are influenced by their mineralogical and geochemical composition, making mineralogical and elemental characterization important for understanding their broader properties and potential applications.

Despite these investigations, important gaps remain in the mineralogical and trace-element characterization of termite mound soils across different communities of Delta State. The study by Momah and Okieimen (2020) provided valuable mineralogical and geochemical information for termite mound soils in the Ika area, but the spatial variability of mineral phases, major-element composition, trace elements and weathering characteristics across other selected communities in Delta State remains inadequately documented. Furthermore, variations in geological background, degree of weathering, soil-forming processes and termite-mediated material selection may produce significant differences between termite mounds from geographically distinct locations. A broader characterization is therefore necessary to establish whether the observed mineralogical and geochemical signatures are locally consistent or vary according to the geological and environmental conditions of individual communities.

The assessment of trace elements is particularly important because these elements can provide additional evidence of parent-material composition, weathering intensity and elemental enrichment or depletion associated with termite activity. Trace-element distributions may also provide useful information for distinguishing between different geological settings and identifying anomalous elemental concentrations. When combined with mineralogical data and weathering indices such as the Chemical Index of Alteration (CIA) and Chemical Index of Weathering (CIW), trace-element information can provide a more comprehensive understanding of the processes controlling the composition of termite mound soils.

Therefore, this study investigates the mineralogy and trace-element composition of termite mound soils from selected communities in Delta State, Nigeria. The study specifically characterizes the mineral phases present using XRD, determines the major-element oxide and trace-element compositions using XRF, evaluates spatial variations in the elemental composition of the mound soils, and uses appropriate geochemical indices to assess weathering characteristics and infer relationships with the geological background of the study locations.

The significance of this study lies in providing additional mineralogical and geochemical information on termite mound soils from Delta State and extending existing knowledge beyond previously investigated locations. The findings will contribute to understanding the influence of termite activity on soil mineralogy and elemental redistribution, provide information on the weathering characteristics and geological provenance of the mound materials, and establish baseline data for subsequent environmental, geological and mineral-exploration studies. The results may also complement existing geotechnical and soil-fertility investigations of termite mound soils in the Niger Delta and provide a basis for comparing termite-modified soils across different communities and geological environments.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in Delta State, Nigeria. Termite mound soil samples were collected from seven selected locations within the State, namely Warri, Agbor (Alihagu), Agbor (Oki), Ogbehasi, Abraka, Oleh and Agbor (Alihami). The selected locations represent different geographical and environmental settings within Delta State. The distribution of the sampling locations within the State is shown in Fig. 1.

2.2 Materials and Equipment

The materials and equipment used for sample collection, preparation and analysis included a core scoop, hammer, spade, sieve, pestle and mortar, crucibles, analytical balance, X-ray diffraction (XRD) diffractometer and X-ray fluorescence (XRF) spectrometer.

2.3 Sampling and Sample Preparation

Sampling was carried out using a modified procedure based on the method described by Bode *et al*. (2013). Termite mounds within the selected sampling locations were identified through field surveys conducted with the assistance of local farmers. Representative termite mound soil samples were randomly collected from selected mounds at each sampling location using clean sampling tools.

The sampling approach was based on procedures commonly employed in soil mineral prospecting, with emphasis on the collection of termite mound materials for mineralogical and geochemical characterization. The collected samples were

placed in clean, properly labelled containers and transported to the laboratory for preparation and analysis.
In the laboratory, the samples were air-dried at room temperature and subsequently crushed and gently disaggregated to break down soil aggregates. The dried samples were passed through a 2-mm mesh sieve to remove coarse particles and other unwanted materials. The sieved samples were thoroughly homogenized and stored in clean, labelled containers until required for mineralogical and geochemical analyses. Representative portions intended for XRD analysis were further pulverized to obtain a fine and homogeneous powder.

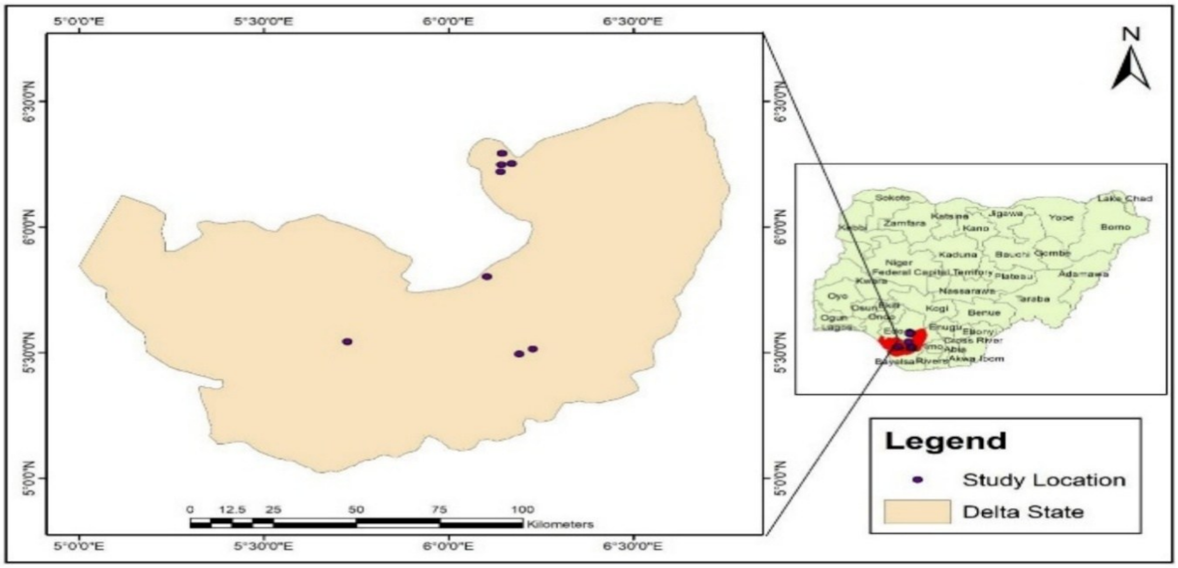

Fig. 1; Map of Delta State showing sampling locations

2.4 Analytical Procedures
2.4.1 X-ray Diffraction Analysis

The mineralogical composition of the termite mound soil samples was determined using X-ray diffraction (XRD) following a modified procedure described by Adesakin and Olunlade (2011). Approximately 0.35 g of each finely pulverized sample was used for the analysis. The powdered sample was uniformly spread and mounted on a sample holder to produce a smooth and relatively flat surface and to ensure uniform exposure of the sample to the incident X-ray beam.
The samples were analyzed using Cu Kα radiation with a wavelength of 1.5418 Å. The diffraction patterns were recorded over a 2θ range of 10–45° at an increment of 0.04°, with a counting time of 4 s per step. The resulting diffraction patterns were used to identify the crystalline mineral phases present in the samples by comparison with standard reference patterns. The relative abundance of the identified mineral phases was subsequently determined using the applicable analytical procedure/software.

2.4.2 X-ray Fluorescence Analysis

The major-element oxide and trace-element compositions of the termite mound soil samples were determined using X-ray fluorescence (XRF) spectrometry following a modified procedure described by Baranowska *et al*. (2002). Approximately 25 g of each sieved and homogenized termite mound soil sample was mixed thoroughly with 0.40 g of stearic acid, which served as a binding agent. The mixture was prepared for XRF analysis using a hydraulic press to obtain a compact analytical specimen.

The prepared samples were subsequently subjected to XRF analysis. The characteristic X-rays emitted by the constituent elements following excitation were measured by the instrument, and the resulting intensities were used to determine the concentrations of the elements present. The major elements were expressed as their corresponding oxides, including SiO_2, Fe_2O_3, Al_2O_3, TiO_2, CaO, MgO, Na_2O, K_2O, MnO and P_2O_5, while the trace elements were reported in mg kg^{-1}.

The XRF measurements were used to characterize the geochemical composition of the termite mound soils and to evaluate variations in major and trace-element concentrations among the sampling locations.

3.0 Result and Discussions

3.1 Mineralogical Composition and Provenance of the Termite Mound Soils

The mineralogical characteristics of the termite mound soils provide useful information on the nature of the source materials and the processes responsible for their formation and modification. The identified mineral phases in the samples include montmorillonite, kaolinite, quartz, orthoclase and albite. The occurrence and relative abundance of these minerals indicate that the termite mound materials were derived from weathered parent materials containing both silicate and aluminosilicate minerals. The mineralogical assemblage also provides evidence of weathering and selective transportation of soil particles during termite mound construction.

Quartz is generally resistant to chemical weathering and can therefore persist during prolonged weathering and soil redistribution. Its occurrence in the termite mound soils is consistent with the relatively high SiO_2 concentrations recorded in the samples. . The abundance of SiO_2, particularly in the Warri, Abraka and Oleh samples, is therefore compatible with the presence of quartz and other silica-bearing phases. In contrast, the occurrence of clay minerals such as montmorillonite and kaolinite indicates that part of the source material has undergone chemical alteration of primary silicate minerals.

Montmorillonite is commonly associated with the alteration of volcanic and mafic to intermediate parent materials under conditions in which leaching is not sufficiently intense to remove all of the mobile base cations. Its occurrence in the samples may therefore indicate contribution from weathered ferromagnesian and feldspathic minerals in the parent materials. Kaolinite, on the other hand, is commonly associated with more advanced chemical weathering and leaching. The coexistence of montmorillonite and kaolinite suggests that the termite mound materials may represent mixtures of materials subjected to different degrees of weathering rather than a single uniform weathering environment.

The occurrence of orthoclase and albite further indicates that feldspathic components persist in the source materials. Albite is a sodic plagioclase feldspar, whereas orthoclase is a potassium feldspar. Their presence suggests that some primary feldspar minerals have survived weathering or have been incorporated into the mound from relatively less-weathered materials. Therefore, the mineral assemblage should be interpreted collectively rather than assigning the entire soil composition to a single parent-rock type (Murray, 2006).

The provenance discrimination diagram presented in Fig. 2 provides additional information on the possible source of the mound materials. The samples plot predominantly within the field associated with basic igneous provenance, suggesting that mafic to basic igneous materials may have contributed to the source sediments. This interpretation is consistent with the relatively high Fe_2O_3 contents recorded in several samples, particularly Agbor 2, Ogbehasi and Agbor 3. However, the presence of quartz and feldspar minerals indicates that the source material may have experienced mixing and sedimentary redistribution before incorporation into the termite mounds. Consequently, the provenance interpretation should be regarded as an indication of the dominant geochemical source rather than definitive evidence of a single parent rock.

The TiO_2/Al_2O_3 binary discrimination diagram in Fig. 3 provides complementary evidence concerning the source characteristics of the clay-bearing materials. The distribution of the samples on the diagram suggests a predominantly igneous contribution to the source materials. The relatively low Al_2O_3 concentrations measured in the samples should, however, be considered when interpreting the diagram because Al_2O_3 is an important component in many clay minerals. The combined evidence from the mineral assemblage, major-element composition and provenance diagrams therefore suggests that the termite mound soils represent weathered and redistributed materials derived from predominantly igneous source components.

The observed mineralogical assemblage is consistent with previous studies of termite mound soils in Nigeria. Idoko and Okieimen (2020) reported hematite, phlogopite, chrysotile and quartz among the mineral phases identified in termite mound soils from the Idoma area of Benue State, while Momah and Okieimen (2020) identified hematite, antigorite, quartz and anthophyllite in termite mound soils from the Ika area of Delta State. The differences in mineral assemblages between the present study and these earlier investigations demonstrate that the mineralogy of termite mound soils can vary considerably according to local geological conditions, weathering processes and the materials selectively transported by termites.

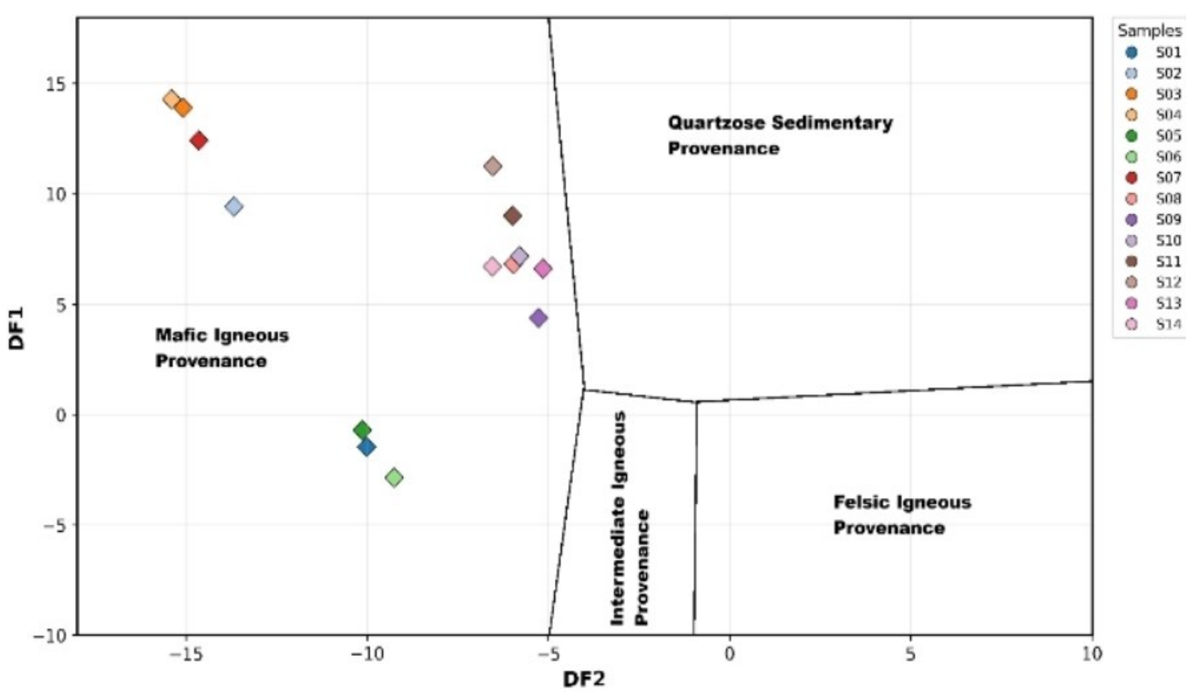

Fig 2: Discriminant Diagram for Sedimentary provenance of study area (after Roser and Korsch, 1988)

3.2 Major-Element Geochemistry

The major-element oxide composition of the termite mound soils is presented in Table 1. The samples are dominated by SiO_2 and Fe_2O_3, while Al_2O_3 and the other major oxides occur at substantially lower concentrations. SiO_2 ranges from 32.20 to 58.34%, with the highest concentration recorded at Warri (58.34%) and the lowest at Agbor 3 (32.20%). Fe_2O_3 ranges from 13.52 to 37.44%, with the highest value occurring at Ogbehasi and the lowest at Oleh. Al_2O_3 ranges from 0.07 to 0.58%, whereas TiO_2 ranges from 1.23 to 3.56%.

The dominance of SiO_2 indicates a substantial contribution from quartz and other silica-bearing minerals, which is consistent with the mineralogical results. The relatively high Fe_2O_3 concentrations, particularly in the Agbor 1, Agbor 2, Ogbehasi and Agbor 3 samples, suggest enrichment in iron-bearing minerals. Such enrichment may be associated with the weathering of ferromagnesian minerals and the accumulation of relatively resistant iron-bearing phases during tropical weathering. The combination of relatively high SiO_2 and Fe_2O_3 is therefore an important characteristic of the investigated termite mound soils.

The very low Al_2O_3 concentrations recorded in the present samples require careful interpretation. Although kaolinite and montmorillonite were identified mineralogically, the low bulk Al_2O_3 concentrations suggest that these minerals may not constitute the dominant mass fraction of the analyzed samples or that the mineralogical and geochemical measurements represent different aspects of the sample composition. Consequently, the occurrence of clay minerals should not be inferred solely from the major-element concentrations.

The concentrations of K_2O, CaO, MgO, Na_2O, MnO and P_2O_5 are generally below 0.5%, indicating relatively low abundance of these oxides compared with SiO_2 and Fe_2O_3. The low concentrations of Na_2O and K_2O may reflect the weathering and partial depletion of feldspar minerals, although orthoclase and albite were identified by XRD. Similarly, the relatively low CaO and MgO concentrations may indicate the removal of readily weathered minerals containing these elements during chemical weathering.

Spatial variation in the major-element composition is evident among the seven sampling locations. The Warri, Abraka and Oleh samples are characterized by relatively high SiO_2 and comparatively low Fe_2O_3, whereas Agbor 1, Agbor 2, Ogbehasi and Agbor 3 exhibit lower SiO_2 and considerably higher Fe_2O_3. This spatial variation suggests differences in parent-material composition, degree of weathering and/or selective incorporation of soil materials during termite mound construction. The differences may also reflect local variations in drainage and redox conditions that influence the mobility and accumulation of iron.

The results are broadly comparable with those reported by Momah and Okieimen (2020) for termite mound soils in the Ika area of Delta State, where SiO_2, Fe_2O_3, Al_2O_3 and TiO_2 were also the dominant major oxides. However, the relative proportions differ between the two studies, emphasizing the spatial heterogeneity of termite mound materials within Delta State. Idoko and Okieimen (2020) similarly reported dominance by SiO_2, Fe_2O_3 and Al_2O_3 in termite mound soils from Benue State. These similarities indicate that termite mound soils commonly preserve strong signatures of their geological and weathering environments.

3.2 Major-Element Geochemistry

The major-element oxide composition of the termite mound soils is presented in Table 1. The samples are dominated by SiO_2 and Fe_2O_3, while Al_2O_3 and the other major oxides occur at substantially lower concentrations. SiO_2 ranges from 32.20 to 58.34%, with the highest concentration recorded at Warri (58.34%) and

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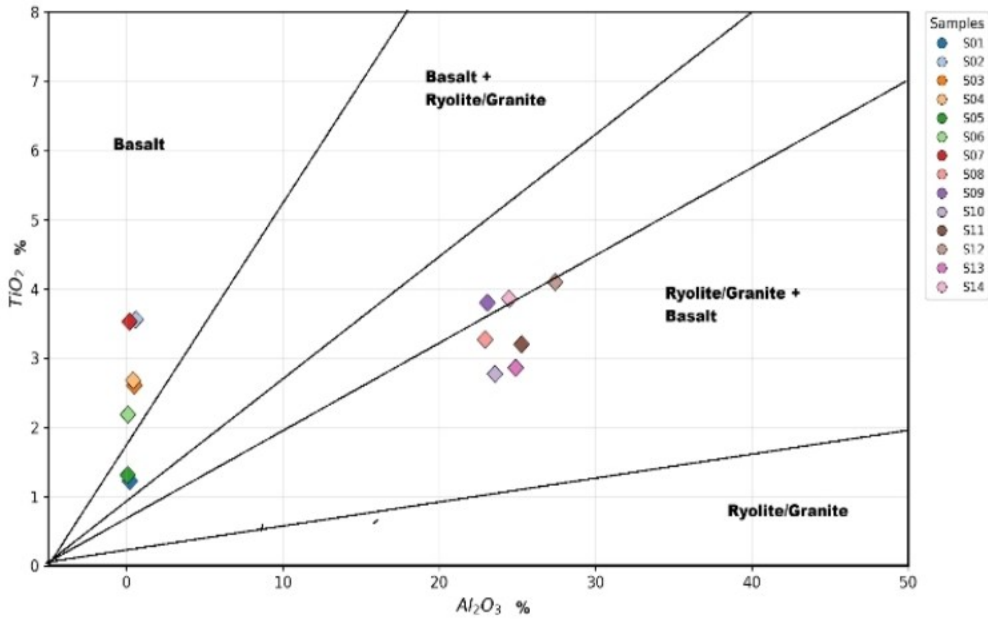


Fig. 3: Shows point of Clay deposit samples from the study location on TiO_2/Al_2O_3 binary diagram suggested by Ekosse, 2001.

Table 1: Composition of Major elements for the termite sample.

Sample Location	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	K_2O	CaO	MgO	Na_2O	MnO	P_2O_5
Warri	58.34	13.57	0.20	1.23	0.07	0.10	0.40	ND	0.01	0.30
Agbor 1	39.27	32.78	0.58	3.56	0.04	0.10	0.30	ND	0.03	0.10
Agbor 2	35.97	36.53	0.49	2.61	0.02	0.08	0.30	ND	0.03	0.10
Ogbehasi	35.56	37.44	0.43	2.68	0.02	0.07	0.40	ND	0.04	0.08
Abraka	53.67	14.75	0.07	1.31	0.10	0.05	0.30	ND	0.01	0.20
Oleh	54.19	13.52	0.10	2.19	0.07	0.03	0.10	ND	0.01	0.09
Agbor 3	32.20	36.78	0.19	3.53	0.02	0.05	0.20	ND	0.03	0.04

The dominance of SiO_2 indicates a substantial contribution from quartz and other silica-bearing minerals, which is consistent with the mineralogical results. The relatively high Fe_2O_3 concentrations, particularly in the Agbor 1, Agbor 2, Ogbehasi and Agbor 3 samples, suggest enrichment in iron-bearing minerals. Such enrichment may be associated with the weathering of ferromagnesian minerals and the accumulation of relatively resistant iron-bearing phases during tropical weathering. The combination of relatively high SiO_2 and Fe_2O_3 is therefore an important characteristic of the investigated termite mound soils.

The very low Al_2O_3 concentrations recorded in the present samples require careful interpretation. Although kaolinite and montmorillonite were identified mineralogically, the low bulk Al_2O_3 concentrations suggest that these minerals may not constitute the dominant mass fraction of the analyzed samples or that the mineralogical and geochemical measurements represent different aspects of the sample composition. Consequently, the occurrence of clay minerals should not be inferred solely from the major-element concentrations.

The concentrations of K_2O, CaO, MgO, Na_2O, MnO and P_2O_5 are generally below 0.5%, indicating relatively low abundance of these oxides compared with SiO_2 and Fe_2O_3. The low concentrations of Na_2O and K_2O may reflect the weathering and partial depletion of feldspar minerals, although orthoclase and albite were identified by XRD. Similarly, the relatively low CaO and MgO concentrations may indicate the removal of readily weathered minerals containing these elements during chemical weathering.

Spatial variation in the major-element composition is evident among the seven sampling locations. The Warri, Abraka and Oleh samples are characterized by relatively high SiO_2 and comparatively low Fe_2O_3, whereas Agbor 1, Agbor 2, Ogbehasi and Agbor 3 exhibit lower SiO_2 and considerably higher Fe_2O_3. This spatial variation suggests differences in parent-material composition, degree of weathering and/or selective incorporation of soil materials during termite mound construction. The differences may also reflect local variations in drainage and redox conditions that influence the mobility and accumulation of iron.

The results are broadly comparable with those reported by Momah and Okieimen (2020) for termite mound soils in the Ika area of Delta State, where SiO_2, Fe_2O_3, Al_2O_3 and TiO_2 were also the dominant major oxides. However, the relative proportions differ between the two studies, emphasizing the spatial heterogeneity of termite mound materials within Delta State. Idoko and Okieimen (2020) similarly reported dominance by SiO_2, Fe_2O_3 and Al_2O_3 in termite mound soils from Benue State. These similarities indicate that termite mound soils commonly preserve strong signatures of their geological and weathering environments.

3.3 Chemical Weathering Characteristics

The chemical weathering characteristics of the termite mound soils were evaluated using the Chemical Index of Alteration (CIA) and Chemical Index of Weathering (CIW). These indices are useful for assessing the degree to which feldspar and other primary minerals have been altered during chemical weathering. The CIA is calculated as:

$$CIA = \frac{Al_2O_3}{Al_2O_3+CaO+Na_2O+K_2O} \times \frac{100}{1} \quad (1)$$

while the CIW is expressed as:

$$CIW = \frac{Al_2O_3}{Al_2O_3+CaO+Na_2O} \times \frac{100}{1} \quad (1)$$

where CaO* represents the calcium associated with silicate minerals. The indices should be calculated using molar proportions rather than direct weight percentages, and the treatment of CaO* should be clearly defined.

The weathering relationships are presented in **Fig. 4**. The coexistence of montmorillonite, kaolinite and residual feldspar minerals suggests that the termite mound materials have experienced chemical alteration of varying intensity. The occurrence of montmorillonite indicates that weathering was not sufficiently intense to completely remove mobile base cations from all parts of the source material, whereas the presence of kaolinite indicates that portions of the material experienced stronger chemical alteration.

The weathering characteristics are also supported by the SiO_2–Al_2O_3–Fe_2O_3 ternary diagram shown in **Fig. 5**. The samples predominantly occupy the fields interpreted as representing kaolinization and weak laterization. This distribution suggests that the soils have undergone tropical chemical weathering involving the alteration of primary minerals, partial removal of mobile components and relative enrichment of silica and iron. The coexistence of relatively high SiO_2 and Fe_2O_3 with low concentrations of several mobile base oxides is consistent with progressive weathering and material redistribution.

The observed weathering pattern is compatible with the humid tropical environment of the Niger Delta, where high rainfall, elevated temperature and seasonal water movement can promote chemical alteration of primary minerals. Nevertheless, local drainage, groundwater conditions and parent-material composition can modify the intensity and direction of weathering. The mineralogical evidence therefore suggests a heterogeneous weathering history rather than a uniform weathering regime throughout the study area.

The weathering results are consistent with the findings of Idoko and Okieimen (2020), who reported high CIA, CIW, PIA and MIA values for termite mound soils from Benue State and interpreted the results as evidence of intense chemical weathering. The differences between their results and the present samples may reflect differences in parent material, drainage conditions, degree of leaching and geographical setting. The previously reported occurrence of both montmorillonite and kaolinite in termite mound soils from Delta State (Momah & Okieimen, 2020) also supports the interpretation that termite mound materials can incorporate materials from different stages of weathering.

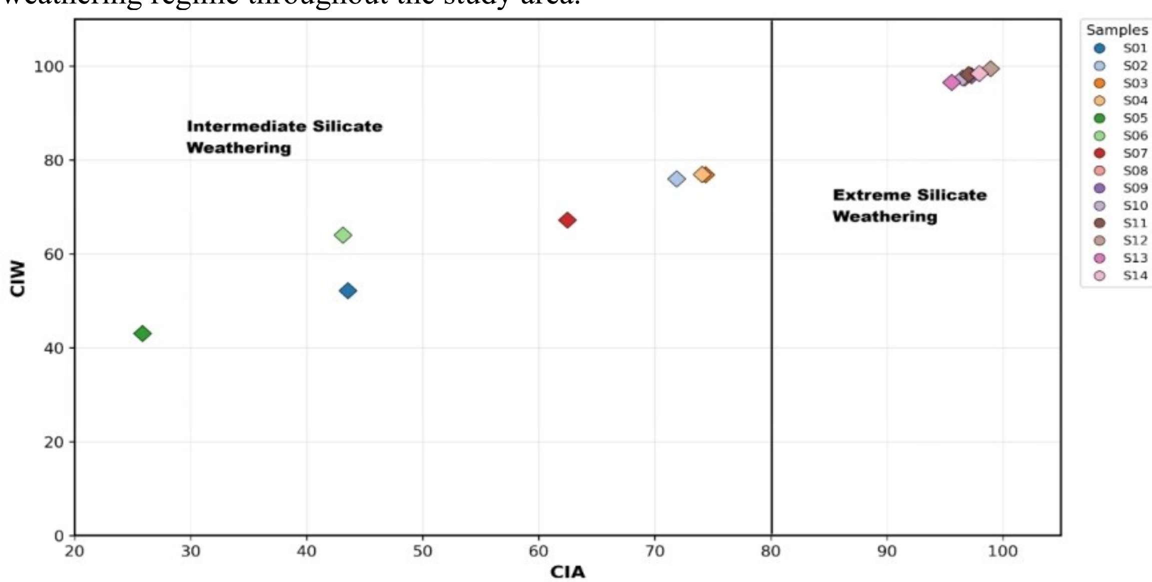


Fig. 4 X-ray diffraction patterns and modal composition of samples After Nesbitt and Young 1982. CIW = [$Al_20_3/(Al_2O_3+CaO^*+Na_2O)$] while CIA = [$Al203/(Al2O3+CaO^*+Na2O+K2O)$]

The Chemical Index of Alteration (CIA) assumes that the dominant process during chemical weathering is the degradation of feldspar and the formation of clay minerals. Values of CIA (20-10000.00) and CIW (Chemical Index of Weathering) of 50-100. The termite mound samples of the southern area show intermediate weathering. This diagram indicates that termite mound samples having the presence of montmorillonite were formed due to an intermediate weathering stage where there was no intense leaching and kaolinite from extreme weathering, as shown in Fig. 4. This reflects the humid tropical climate moderated by poor drainage and high water table typical of the Niger Delta coastal plain.

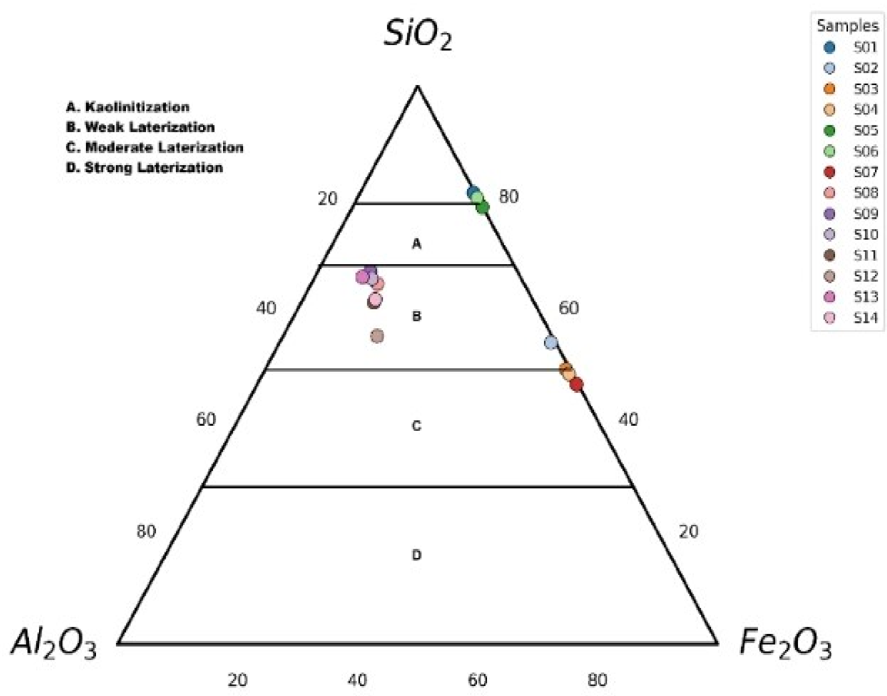


Fig. 5; Ternary diagram for laterization using the SiO_2-Al_2O_3-Fe_2O_3 (After Schellmann, 1986)

3.4 Laterization and Kaolinization

The SiO_2–Al_2O_3–Fe_2O_3 ternary diagram in **Fig. 5** was used to further assess the degree of laterization and kaolinization of the termite mound soils. The plotted samples predominantly fall within the zones associated with kaolinization and weak laterization. Kaolinization involves the transformation of primary aluminosilicate minerals into kaolinite under chemical weathering conditions, whereas laterization is generally associated with intense tropical weathering and the relative accumulation of iron and aluminium oxides.

The distribution of the samples indicates that chemical alteration has occurred, but the available data do not support describing the entire study area as undergoing extreme laterization. The relatively high SiO_2 concentrations in several samples suggest that silica has not been completely removed, while the elevated Fe_2O_3 contents in the Agbor and Ogbehasi samples indicate relative enrichment of iron. The combined pattern is consistent with partial laterization accompanied by clay-mineral formation.

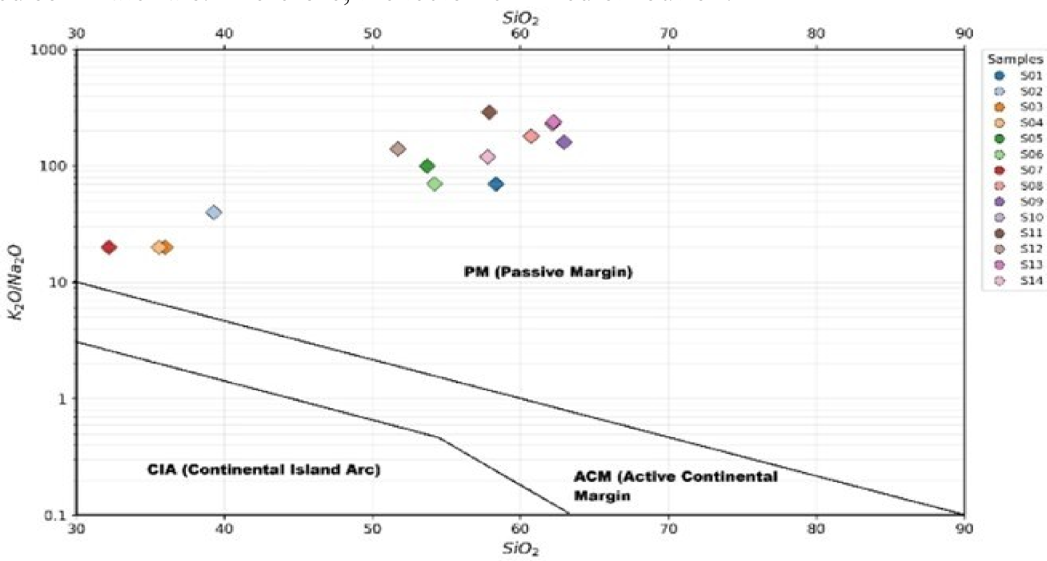
The differences among the samples may reflect variations in drainage and parent-material composition. Locations with greater retention of silica may have experienced less intense leaching, whereas samples with relatively high Fe_2O_3 may have undergone stronger iron enrichment. Thus, the ternary diagram in Fig. 5 complements the CIA and CIW assessment in Fig. 4 by demonstrating that weathering processes have not operated uniformly across all sampling locations.

3.5 Geochemical Evidence of Provenance and Tectonic Setting

The K_2O/Na_2O versus SiO_2 discrimination plot presented in Fig. 6 was used to assess the possible tectonic setting and provenance of the source materials. Geochemical discrimination diagrams of this type are based on the premise that sediment composition can retain information about the geological setting and source rocks from which the materials were derived (Roser & Korsch, 1986).

The distribution of the samples in Fig. 6 suggests an affinity with materials associated with a passive-margin setting. This interpretation should be regarded as a geochemical indication rather than definitive evidence of the depositional history of the termite mound soils. Termite mound materials are not necessarily primary sedimentary deposits; they are biologically transported and reworked soil materials. Therefore, the tectonic interpretation reflects the inferred geological characteristics of the source materials rather than the environment in which the termite mounds themselves were constructed.

The provenance and tectonic interpretations from Fig. s 2 and 6 should consequently be considered together with the mineralogical assemblage and major-element composition. The presence of quartz, feldspars and clay minerals, together with the dominance of SiO_2 and Fe_2O_3, indicates that the mound materials have experienced both geological inheritance and subsequent weathering and biological redistribution.



Fiure 6 K_2O/Na2O versus SiO_2 plot of clay samples in the study area. Modified after Roser and Korsch (1986).

3.6 Trace-Element Composition

The elemental composition of the termite mound soils is presented in Table 2, while the spatial distributions of the individual elements are shown in Fig. s 7–19. The elements reported include Co, Cu, Zn, Cd, Pb, Cr, Mn, Si, Al, Fe, Ti, S and V. The results demonstrate considerable variation in elemental concentrations among the sampling locations, indicating spatial differences in the geochemical composition of the mound materials.

Cobalt concentrations are presented in Fig. 7, while copper and zinc distributions are shown in Fig. s 8 and 9, respectively. Cadmium, lead and chromium concentrations are presented in Fig. s 10–12, while manganese concentrations are shown in Fig. 13. These variations may reflect differences in parent-material composition, mineral weathering, adsorption processes and selective transportation of soil particles during termite mound construction.

The relatively low concentrations of Cu, Zn, Cd, Pb and Cr compared with the dominant Si- and Fe-bearing components indicate that the elemental composition of the termite mound soils is strongly controlled by the major mineral constituents. However, the distribution of individual trace elements among locations demonstrates that their concentrations are not uniform. Differences in soil mineralogy, organic matter, pH, redox conditions and the abundance of reactive mineral surfaces can influence trace-element retention and mobility (Laveuf & Cornu, 2009; Mihajlovic *et al*., 2019; Temga *et al*., 2021).

The distributions of Si, Al and Fe are shown in Fig. s 14–16, respectively. These elements are more appropriately considered major or major-associated elements at the concentrations reported in Table 2 rather than trace elements. Their distributions generally correspond with the major-element oxide data in Table 1. In particular, the Fe distribution reflects the strong spatial variation in Fe_2O_3, while the Si distribution corresponds with the high SiO_2 concentrations. This agreement provides additional evidence that the dominant geochemical differences among the samples are related to variations in silica- and iron-bearing mineral phases.

Titanium concentrations are presented in Fig. 17, sulfur concentrations in Fig. 18, and vanadium concentrations in Fig. 19. The relatively low concentrations of these elements indicate that they constitute minor components of the mound materials. Nevertheless, their spatial variation can provide useful information on differences in source material and weathering processes. Titanium is generally associated with relatively resistant mineral phases, whereas sulfur may be influenced by redox conditions and organic or sulphide-related processes. Vanadium can occur in association with iron-bearing minerals and may therefore show relationships with Fe-rich materials.

The distribution of trace elements in soils is controlled by several interacting processes, including weathering of parent materials, adsorption and desorption, complexation, precipitation, mineral transformation and changes in redox conditions (Laveuf & Cornu, 2009; Mihajlovic *et al*., 2019; Temga *et al*., 2021). Soil pH is also important because it influences the surface charge and sorption capacity of clay minerals and iron and aluminium oxides. Consequently, differences in the chemical environment of individual termite mounds can contribute to the observed spatial variation in elemental concentrations.

Termite activity may further modify these processes by transporting soil particles from different depths to the mound surface and selectively incorporating materials according to particle size, mineral composition and availability. The resulting mound therefore represents a biologically reworked soil environment in which materials from different parts of the soil profile may become mixed. The observed elemental variation is consequently likely to reflect both natural geological controls and termite-mediated redistribution.

The results are broadly consistent with the observation that termite mound soils can act as chemically modified and enriched soil matrices. Momah *et al*. (2026) reported higher concentrations of several soil-fertility-related parameters in termite mound soils than in adjacent uncolonized soils in selected communities of Delta and Edo States. Similarly, Momah and Okieimen (2020) documented measurable concentrations of Cr, Pb, Cu, Zn and Cd in termite mound soils from the Ika area of Delta State. These studies support the interpretation that termite activity can alter the chemical composition and elemental distribution of soil.

3.7 Relationship Between Mineralogy, Weathering and Elemental Distribution

The combined mineralogical and geochemical results indicate that the composition of the termite mound soils is controlled by the interaction of geological provenance, chemical weathering and termite-mediated soil redistribution. The dominance of SiO_2 and Fe_2O_3, together with the occurrence of quartz, clay minerals and feldspar phases, indicates that the mound materials retain a strong geological signature while simultaneously showing evidence of weathering and biological modification.

Table 2, Trace Element (mg/g) Composition

Sample Location	Co	Cu	Zn	Cd	Pb	Cr	Mn	Si	Al	Fe	Ti	S	V
WARRI	0.40	0.03	0.06	0.00	0.59	0.02	0.08	58.34	2.00	13.57	1.23	0.05	0.76
Agbor 1	1.00	0.03	0.10	0.00	0.32	0.15	0.34	39.27	5.82	32.78	3.57	0.05	0.20
Agbor 2	2.00	0.02	0.10	0.02	0.99	0.16	0.25	35.97	4.90	36.53	2.61	0.03	0.22
Ogbehasi	2.00	0.02	0.04	0.00	0.31	0.16	0.36	35.60	4.29	37.44	2.67	0.01	0.24
Abraka	0.50	0.01	0.05	0.01	0.16	0.06	0.13	53.67	0.70	14.57	1.31	0.01	0.65
Oleh	0.50	0.02	0.04	0.01	0.37	0.04	0.13	54.18	1.00	13.52	2.19	0.001	0.65
Agbor 3	3.00	0.01	0.05	0.00	0.24	0.14	0.27	32.20	0.19	36.78	3.53	0.04	0.20

The relatively high SiO_2 concentrations in the Warri, Abraka and Oleh samples are consistent with the presence of silica-rich mineral phases, particularly quartz. Conversely, the higher Fe_2O_3 concentrations in Agbor 1, Agbor 2, Ogbehasi and Agbor 3 suggest greater relative enrichment in iron-bearing phases. These differences are reflected in the elemental distributions shown in Fig. s 14 and 16. Such spatial variability may arise from differences in source-rock composition, weathering intensity and the selective collection of soil materials by termites.

The occurrence of montmorillonite alongside kaolinite provides further evidence for variable weathering conditions. Montmorillonite formation is generally favoured where chemical alteration occurs under conditions that permit some retention of base cations, whereas kaolinite is commonly associated with stronger leaching. The coexistence of these phases suggests that the mound materials may incorporate soil particles originating from different microenvironments and depths.

The trace-element patterns also reflect the combined influence of mineralogy and weathering. Elements can become associated with clay minerals, iron and aluminium oxides or organic matter through adsorption and complexation, while changes in pH and redox conditions can promote their release or immobilization. Weathering of the parent material provides the initial elemental inventory, while termite activity can redistribute these elements by transporting soil particles and mixing materials from different depths (Laveuf & Cornu, 2009; Temga *et al.*, 2021).

The results therefore demonstrate that termite mound soils provide useful geochemical information about their surrounding geological environment. However, the mound material should not be interpreted as a direct and undisturbed representation of the underlying parent rock because termites modify, mix and redistribute soil materials during mound construction. The mineralogical and geochemical signatures are consequently best understood as integrated products of geological inheritance, weathering and biological soil modification.

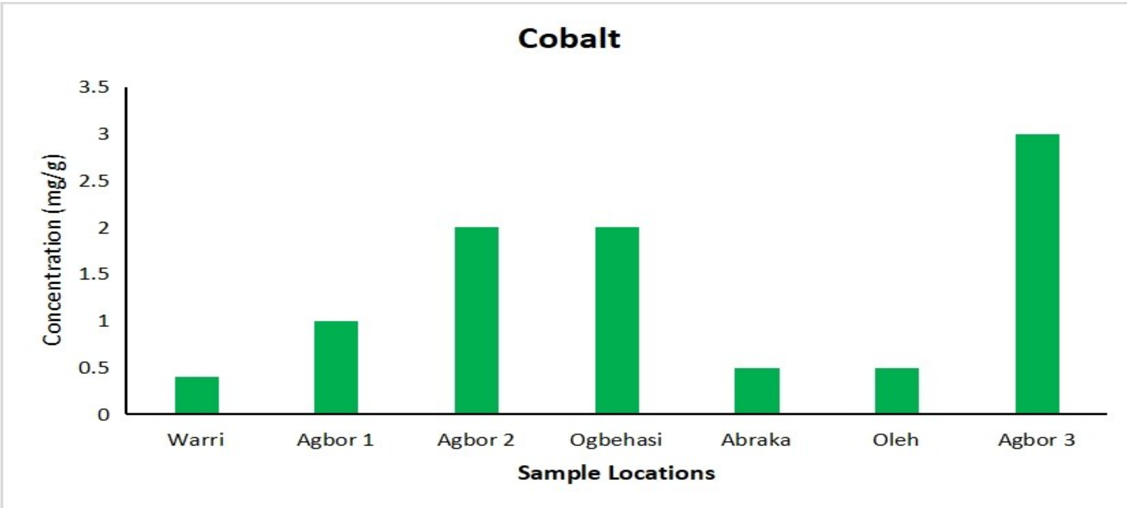


Fig. 7: Cobalt concentrations in termite mound soil

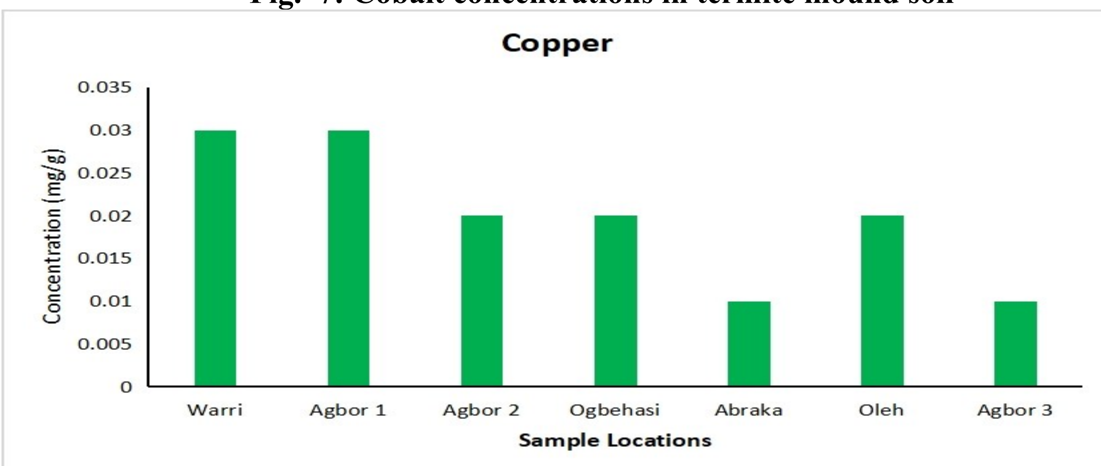


Fig. 8: Copper concentrations in termite mound soil

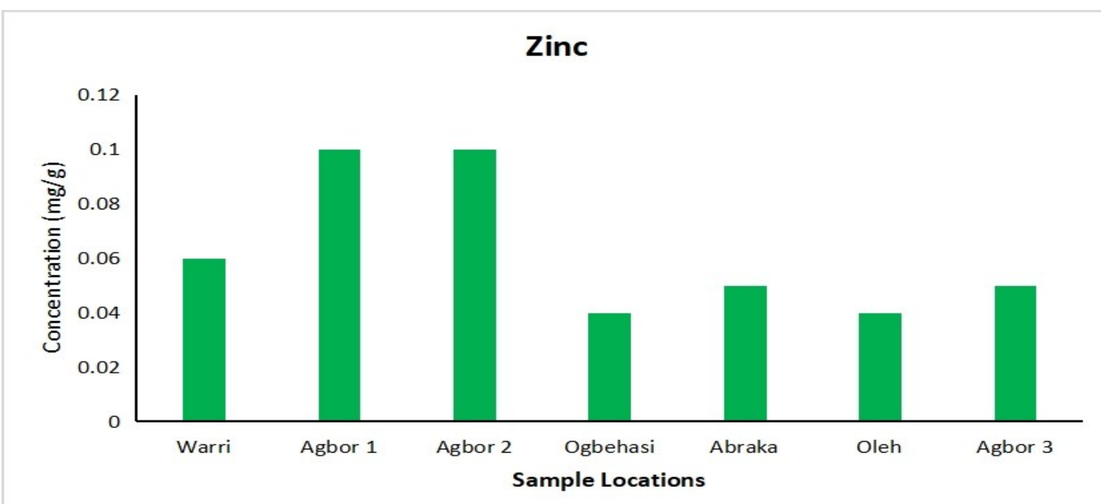


Fig. 9: Zinc concentrations in termite mound soil

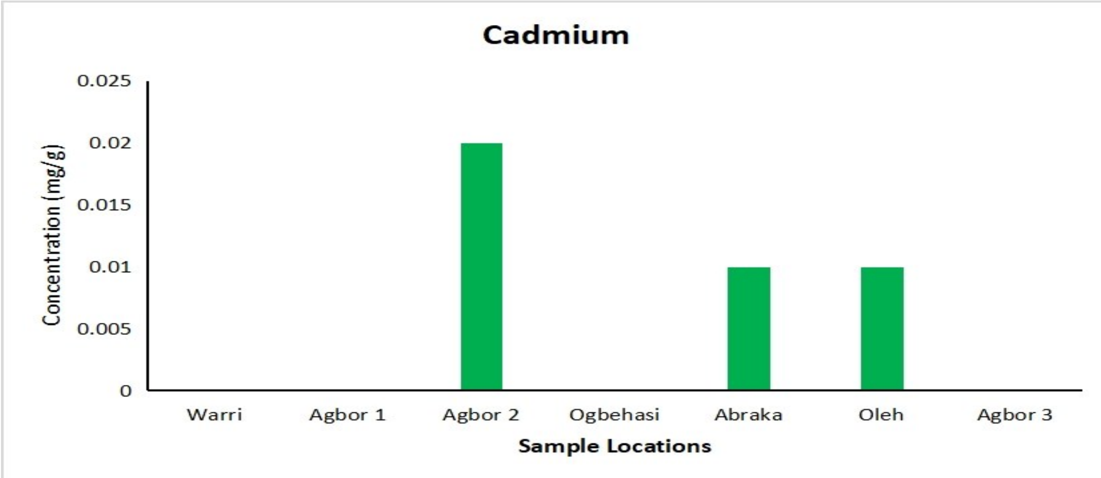


Fig. 10: Cadmium concentrations in termite mound soil

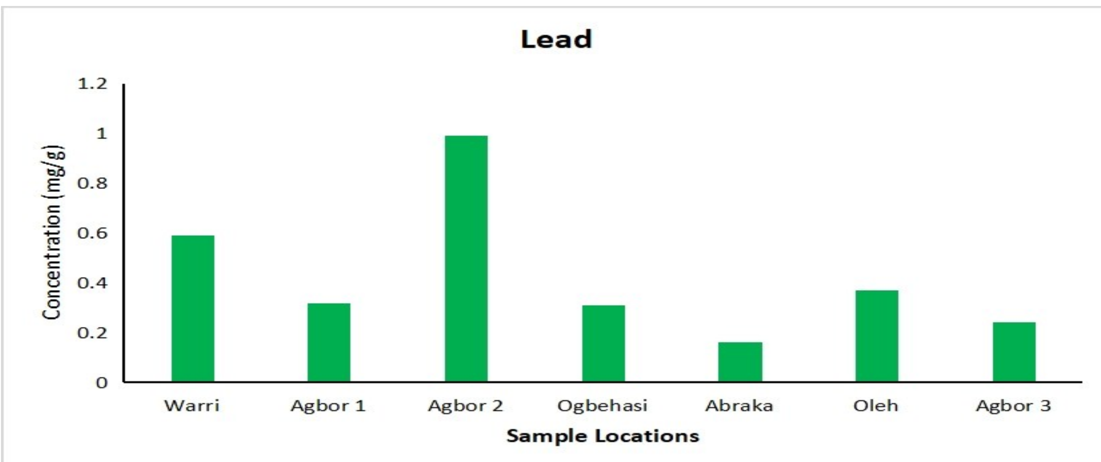


Fig. 11: Lead concentrations in termite mound soil

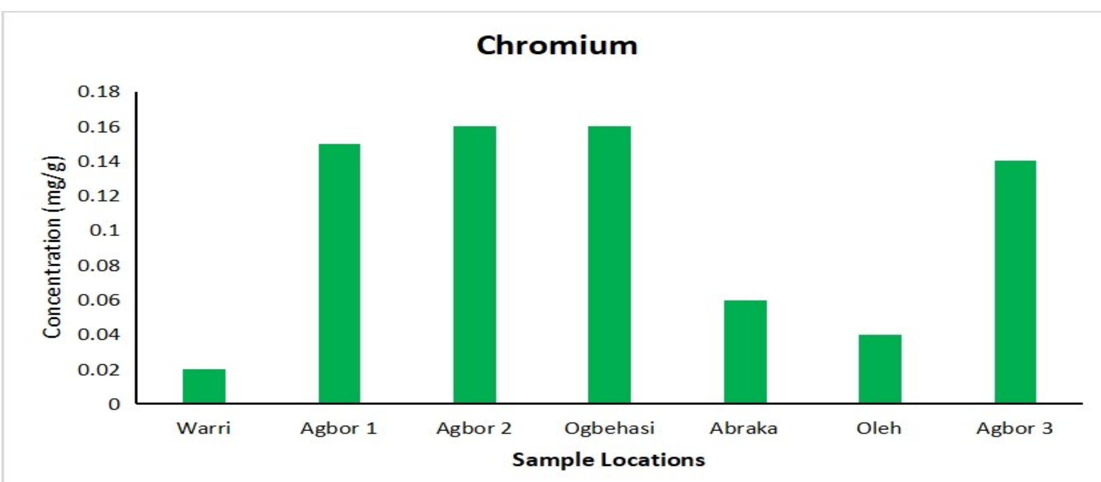


Fig. 12: Chromium concentrations in termite mound soil

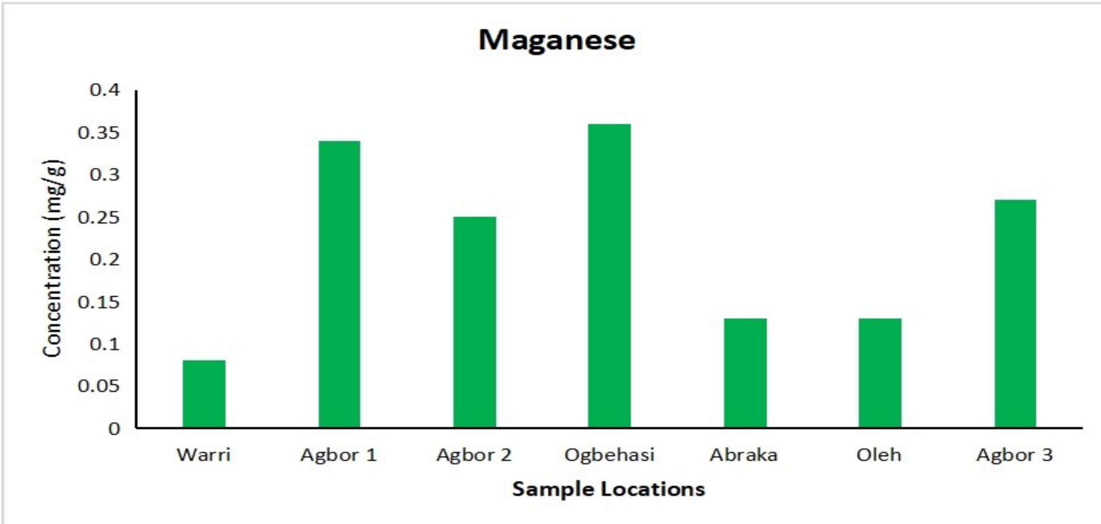


Fig. 13: Manganese concentrations in termite mound soil

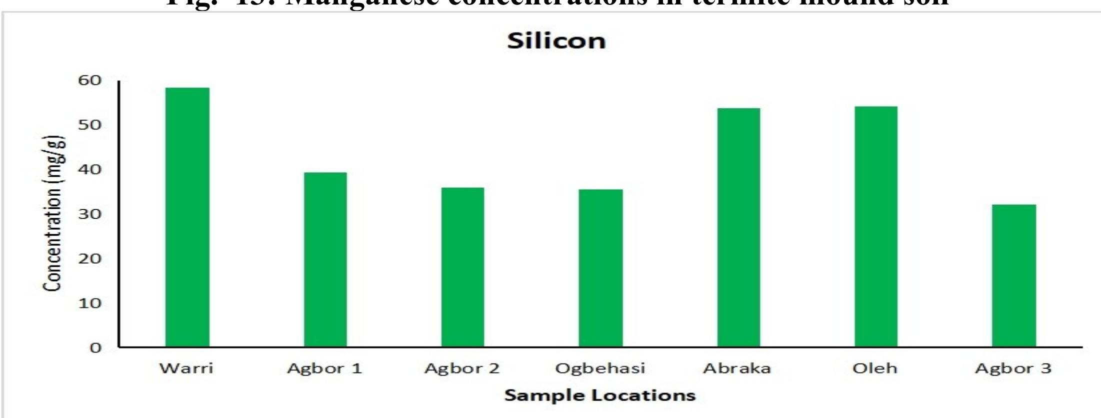


Fig. 14: Silicon concentrations in termite mound soil

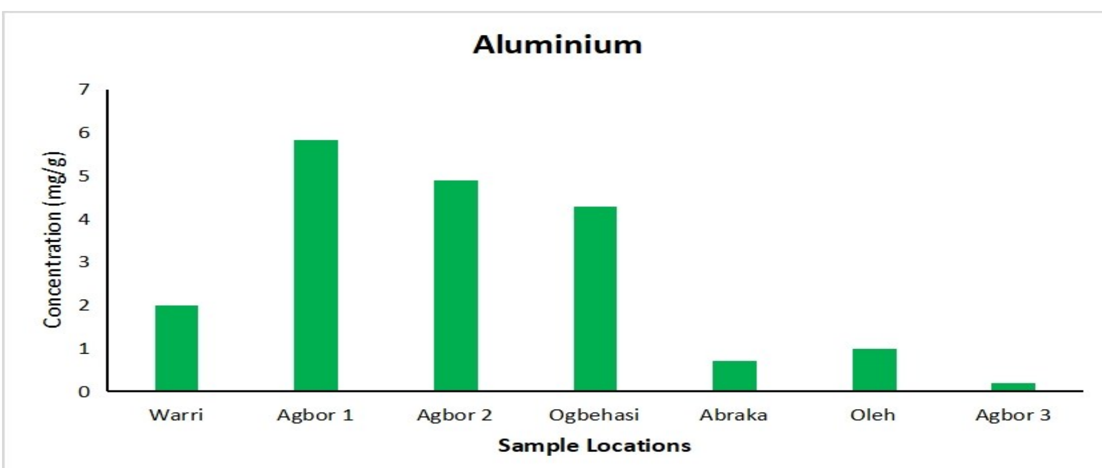


Fig. 15: Aluminum concentrations in termite mound soil

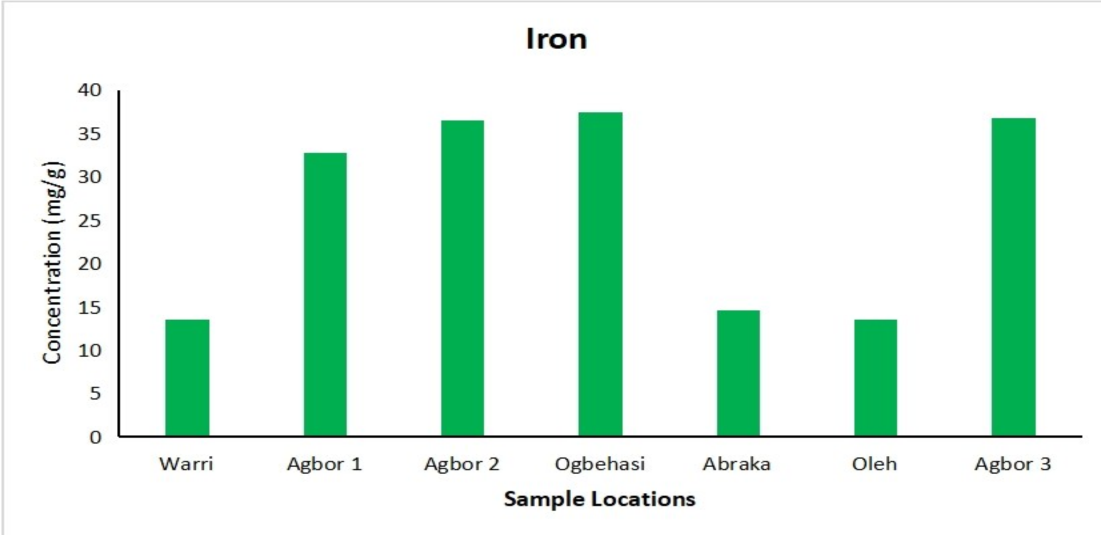


Fig. 16: Iron concentrations in termite mound soil

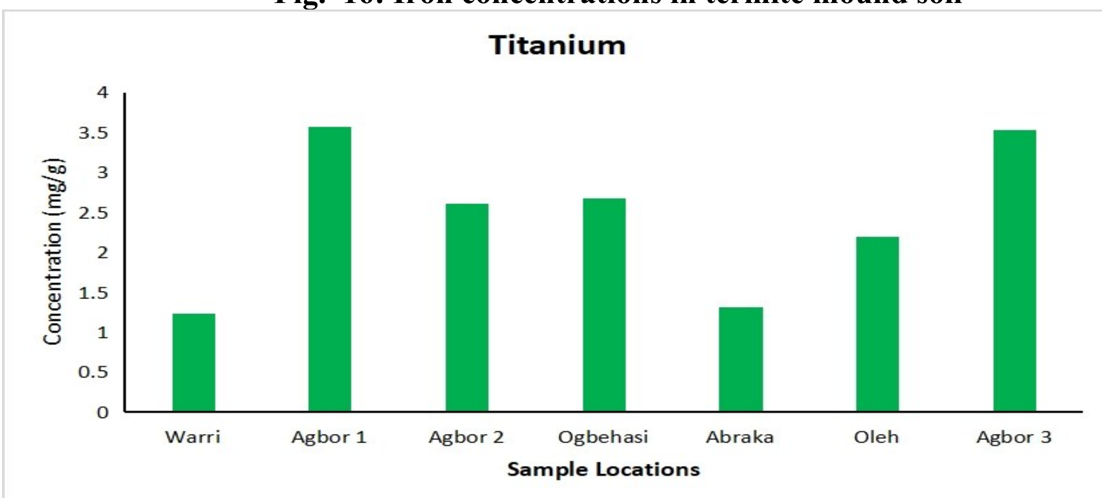


Fig. 17: Titanium concentrations in termite mound soil

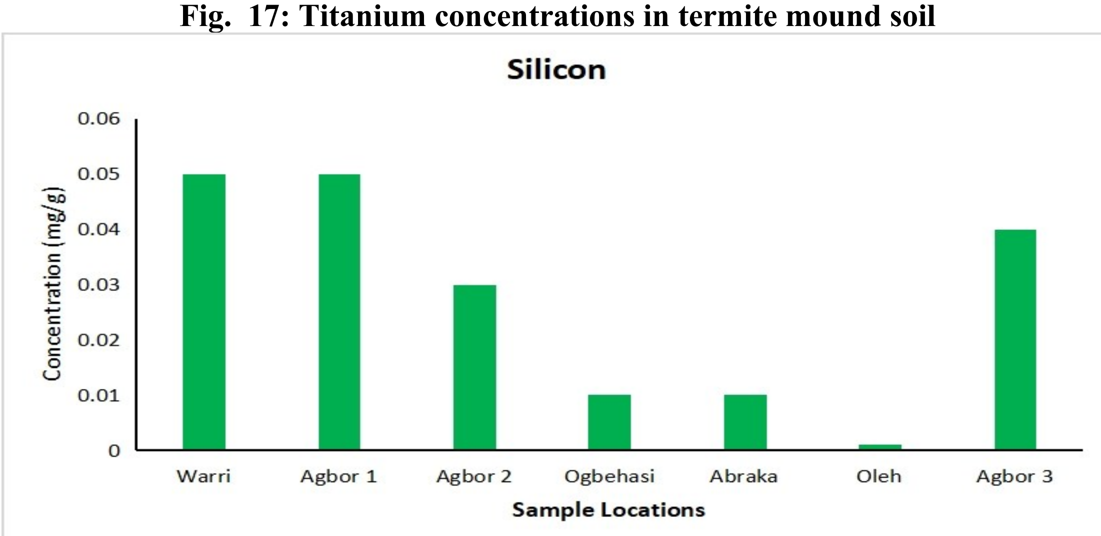


Fig. 18: Silicon concentrations in termite mound soil

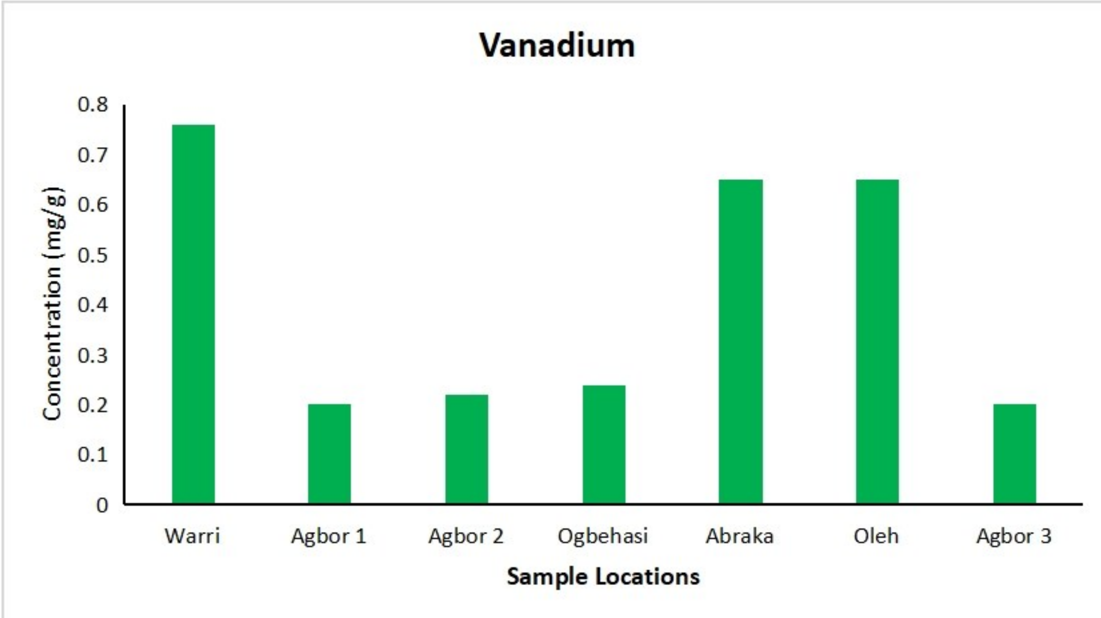


Fig. 19: Vanadium concentrations in termite mound soil

3.8 Implications for Geological and Geochemical Assessment

The mineralogical and elemental characteristics identified in this study have implications for the use of termite mound soils in geological and geochemical investigations. The occurrence of distinctive mineral phases and systematic differences in elemental composition among locations suggests that termite mounds can preserve information about the materials available within the surrounding soil and geological environment. This supports earlier observations that termite structures may be useful in geochemical exploration and geological investigations (Bode *et al*., 2013; D'Orey, 1975; Le Roux & Humbleton-Jones, 1991; Petts *et al*., 2009).

The present results also complement previous studies from Delta State. Momah and Okieimen (2020) established that termite mound soils from the Ika area contained substantial amounts of SiO_2 and Fe_2O_3 and measurable concentrations of several trace elements. The present investigation extends the available information by examining termite mound soils from seven selected communities and relating their major-element, mineralogical and weathering characteristics to spatial variation in elemental composition.

Nevertheless, the use of termite mound soils as geochemical indicators requires appropriate consideration of local environmental conditions. Termite species, mound age, mound activity, depth of material collection, parent-material composition, soil drainage and weathering history can all influence mound composition. Therefore, termite mound data are most reliable when interpreted together with regional geological information and, where possible, with analyses of adjacent undisturbed soils and underlying geological materials.

Overall, the results indicate that the termite mound soils investigated in Delta State are characterized by strong SiO_2 and Fe_2O_3 signatures, variable mineralogical assemblages and spatially heterogeneous elemental distributions. The combined XRD and XRF results suggest that the mound materials have been derived from weathered geological materials and subsequently modified through termite-mediated transportation and redistribution. The provenance and weathering diagrams provide additional evidence of predominantly igneous source contributions and variable chemical weathering, while the trace-element distributions demonstrate the influence of geological and soil-forming processes on elemental occurrence.

The findings therefore reinforce the potential of termite mound soils as complementary materials for geological, mineralogical and geochemical investigations in Delta State. However, further work involving systematic sampling of mound and surrounding soils, mineral-specific quantitative XRD analysis, additional trace-element measurements and comparison with known geological units would improve the interpretation of provenance, weathering and elemental enrichment processes.

4.0 Conclusion

The mineralogical and geochemical characteristics of termite mound soils from selected communities in Delta State, Nigeria, demonstrate substantial spatial variation controlled by parent-material composition, weathering processes and termite-mediated redistribution of soil particles. The soils are dominated by SiO_2 and Fe_2O_3, with quartz, montmorillonite, kaolinite, orthoclase and albite constituting the principal identified mineral phases. Provenance discrimination indicates a predominantly igneous contribution, with evidence of both felsic and mafic source components, although the materials have subsequently undergone weathering and sedimentary redistribution. The CIA, CIW and ternary weathering relationships indicate variable chemical weathering, ranging from moderate to relatively advanced alteration, characterized by clay-mineral formation, silica retention and relative iron enrichment rather than complete lateritic development. The spatial variation in Co, Cu, Zn, Cd, Pb, Cr, Mn, Si, Al, Fe, Ti, S and V further demonstrates that elemental distribution is influenced by geological background, weathering intensity, mineralogical composition and soil geochemical processes. Overall, the findings confirm that termite mound soils preserve useful mineralogical and geochemical signatures of their surrounding environment and can serve as complementary materials for geological and geochemical assessment in Delta State, although their interpretation should account for termite-mediated mixing and redistribution of soil materials.

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Declarations

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Conflict of interest

The author declares no known financial or non-financial conflicts of interest relevant to this manuscript.

Ethical approval

Ethical approval was obtained from the University of Calabar ethics committee before data collection. All participants provided informed consent, and confidentiality, anonymity, voluntary participation, and the right to withdraw were maintained throughout the study.

Author Contributions

Momaha, M. conceived the study, designed the methodology, coordinated sample collection and laboratory analyses, interpreted the XRD and XRF results, and prepared the manuscript. Umudia, E. Q. contributed to sample preparation, data analysis, interpretation of mineralogical and geochemical results, and critical revision of the manuscript. Andre-Obayanju, B. O. contributed geological interpretation, provenance and weathering assessment, reviewed the manuscript critically, and approved the final version for publication.