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ANALYSIS OF GEOCHEMICAL AND GEOTECHNICAL PARAMETERS OF SELECTED LATERITE MINING PITS IN DUTSIN-MA LOCAL GOVERNMENT AREA AND ENVIRONS

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ABSTRACT
This study investigates the geochemical and geotechnical properties of laterite soils from four active mining sites (Kurfi, Gago, Radda, and Shagari) located in Dutsin-Ma, Katsina State, Nigeria, to characterize laterite and assess its suitability for construction. The research employed an analytical framework, combining geochemical analysis using spectrophotometry to determine the concentrations of Silicon dioxide (SiO_2), Iron oxide (Fe_2O_3), and Manganese oxide (MnO_2), alongside geotechnical testing including Atterberg limits, compaction, moisture content, and California Bearing Ratio (CBR) measurements following standard procedures (BS 1377 and ASTM D698). The results revealed significant spatial variability in geochemical and geotechnical parameters across the four mining sites. Fe_2O_3 content ranged from 0.07 to 1.34 mg/kg, with Radda and Shagari exhibiting substantially higher concentrations, indicating more advanced lateritization and weathering processes. Similarly, SiO_2 concentrations varied from 2.50 to 3.90 mg/kg, confirming intense desilication characteristic of tropical ferralitization under humid conditions. The CBR values demonstrated remarkable variation from 16% to 60%, with Radda showing the highest strength characteristics, while the Plasticity Index ranged from 2% to 7%, reflecting differences in clay mineralogy across sites. Correlation analysis established strong relationships between geochemical and geotechnical parameters, particularly the positive correlation between Fe_2O_3 and CBR ($r = 0.894$) and the strong relationship between SiO_2 and optimum moisture content ($r = 0.947$), highlighting the significant influence of oxide composition on engineering behavior. The findings underscore the importance of site-specific characterization in optimizing laterite utilization and implementing monitoring of mining sites to prevent overexploitation and environmental degradation in the Dutsin-ma area.

Keywords: Laterite, geochemical parameters, geotechnical parameters, mining pits, construction materials.

INTRODUCTION

Lateritic soils represent a category of highly weathered and transformed residual soils that arise from the in-situ weathering and decomposition of parent rocks under tropical and subtropical climatic environments. This weathering phenomenon predominantly encompasses the continuous chemical modification of minerals, the liberation of iron and aluminum oxides, and the leaching of bases and silica from the rocks. Lateritic soils significantly bolster the overall economy of tropical and subtropical areas, wherein they are plentiful, as they find extensive application in civil engineering projects as construction materials for roads, residential structures, landfill for foundations, embankment dams, and so forth. (Aginam *et al*., 2015).

Land degradation shall continue to be a major global concern in the twenty-first century due to its negative influence on the environment, as well as its consequences in food security and quality of life (Barati *et al*., 2023). Aside from soil excavation, other factors that could cause land degradation are extreme weather conditions and other forms of human activities that pollute or deteriorate soil quality and land usability.

Mining may indeed be recognized as the second earliest endeavor of humankind, following agriculture as the foremost. These two sectors are classified together as the foundational or essential industries of early civilization. The significance of these industries has remained remarkably consistent since the dawn of civilization. If we include fishing and forestry as components of agriculture, as well as oil and gas extraction as facets of mining, it becomes evident that agriculture and mining continue to provide the fundamental resources indispensable for contemporary civilization (Ali *et al*., 2022).

In the 1950s, traditional dwellings in Africa were predominantly constructed using materials primarily consisting of locally sourced poles, mud, grasses, and wattle. Consequently, the adverse impacts on environmental resources were relatively minimal due to the low population density (Shaib, 1991). Nonetheless, with the enhancement of human comforts, exemplified by modern transportation networks and architectural developments, there has been a marked detrimental impact on the local environment. Consequently, certain elements of the natural environment have been transformed into degraded anthropogenic features that negatively influence rural resources harvested by humans (Upton, 1997).

Previous studies have demonstrated the economic importance of laterites for road construction and structural applications, emphasizing that their varied properties depend on numerous factors including parent material, degree of weathering, and environmental conditions. Madu (1977) investigated laterites from Eastern Nigeria, tracing their geological origins and establishing genetic classification based on silica/sesquioxide ratios, while seeking relationships between iron-oxide content and engineering properties. However, the conclusion from that study was notable: no correlation was found between iron-oxide content and any other physical or engineering properties, as has been suggested by others. This finding created a fundamental contradiction in the literature, as other researchers continued to suggest that iron oxide enrichment significantly influences laterite strength and behavior.

More recently, Aginam, Chidozie, and Nwajuaku (2015) investigated lateritic soils from Anambra Central Zone, Nigeria, examining their engineering properties without explicitly resolving the iron-oxide correlation debate. Thomas et al. (2019) conducted chemical and mineralogical characterization of iron ore deposits in Katsina State, revealing significant iron (36.17%) and silicon (17.21%) content. However, their study focused on ore characterization rather than geotechnical properties. Meanwhile, Akpokodje and Hudec (1994) demonstrated that the degree of iron oxide impregnation significantly influences the physico-mechanical properties of laterite gravels, with well-developed gravels containing 65-95% goethite/hematite showing superior strength characteristics. This finding contradicts Madu's earlier conclusion, indicating an unresolved research gap that requires site-specific investigation.

Due to the absence of Integrated Geochemical-Geotechnical Characterization, no study has systematically examined the relationship between oxide concentrations (SiO_2, Fe_2O_3, MnO_2) and engineering parameters (CBR, compaction, Atterberg limits) specifically for laterite mining pits in

Dutsin-Ma. While regional studies exist for Anambra, Eastern Nigeria, and Southwestern Nigeria, the Dutsin-Ma area remains understudied despite its active laterite mining activities.

The literature contains conflicting findings regarding whether Fe_2O_3 content correlates with engineering properties. Madu (1977) explicitly concluded that no such correlation exists, while Akpokodje and Hudec (1994) demonstrated that iron oxide impregnation directly affects aggregate strength and durability. This contradiction necessitates further investigation to determine which finding holds for different geological settings, particularly in the Dutsin-Ma environment where laterites may exhibit distinct characteristics.

Although Thomas et al. 2019) characterized the Gyaza iron ore deposit in Katsina State, no comparable baseline geochemical data exists for the lateritic soils in Dutsin-Ma. Establishing this baseline is essential for evaluating construction material suitability. The spatial distribution of laterite properties across mining sites within Dutsin-Ma has not been examined. Given that laterite formation is influenced by local topography, parent material, and drainage conditions, geochemical and geotechnical parameters likely vary significantly across active mining pits. While laterite is widely used in road construction and building projects in Northern Nigeria, the specific suitability of Dutsin-Ma laterites for construction applications based on both geochemical and geotechnical criteria has not been systematically evaluated.

To address these deficiencies, this study aims to answer what the geochemical composition (SiO2, Fe2O3, MnO2) of laterite from selected mining pits in Dutsin-Ma is, and how it correlates with geotechnical properties (CBR, Atterberg limits, compaction parameters). Furthermore, do the relationships between oxide concentrations and engineering behavior align with the findings of Madu (1977) or contrary evidence from Akpokodje and Hudec (1994)? This investigation contributes to resolving the long-standing debate on the relationship between geochemistry and engineering performance in lateritic soils, provides a data-driven basis for construction material selection in Dutsin-Ma, and offers insights for sustainable mining practices in the region. The findings will be particularly relevant to engineers, geologists, and policymakers involved in infrastructure development in Katsina State.

STUDY AREA

Katsina State lies between latitudes 11°07' N and 13°22' N and longitudes 6°52' E and 9°20' E. It is located in the semi-arid region of Nigeria. It has a total land mass of 24,192 km2, out of which only 2,420km2 (10%) are constituted into gazetted forest estates, comprising 96 forest reserves, one grazing reserve, and 244 communal forest areas, of which 80% have been threatened with extinction by desertification, drought and human activities (Zayyana, 2010).

Dutsin-Ma town roughly lies between latitudes 12°25'38.4" N to 12°28'39.2" N and longitudes 7°27'52.6" E to 7°30'48.9" E. The irregular shape of the town, as well as its continuous daily expansion in an unplanned manner, has made it difficult to determine precise absolute locational extents of the town. The current area constituting Dutsin-Ma Local Government is absolutely located between latitudes 12°09'18" N to 12°30'44" N and longitudes 7°20'48" E to 7°37'18" E. Kankia, Charanchi and Matazu border it to the East, Safana to the West and Danmusa to the South and Kurfi to the North (Ministry of Land and Survey Office, 2008).

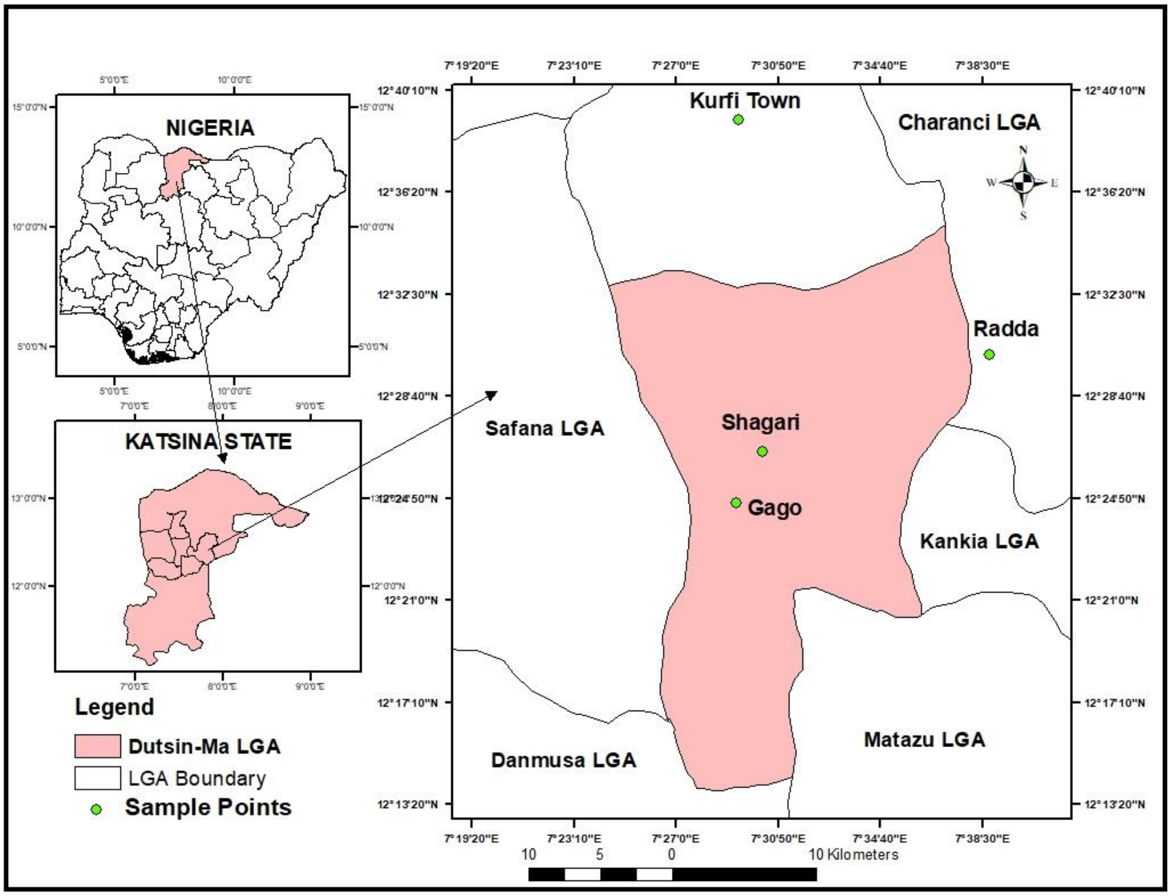

Figure 1: Map Showing Sample Location
Source: Fieldwork, 2025.

MATERIALS AND METHODS

Because of the vastness of the study area, some mining sites are active while others are dormant; coupled with the insecurity bedeviling some parts of the study area, four laterite mining sites in Shagari, Gago, Kurfi, and Radda were selected as the sample locations. The research utilizes purposive sampling techniques. The research methodology includes both field and laboratory (experimental) methods. The fieldwork primarily focused on observing the study area and collecting samples for laboratory analysis; field tools included a Global Positioning System (GPS) device to acquire precise coordinates of the study site.

Sample Collection

Laterite samples at a depth of 0- 2 m were taken from each selected mining site that has been used for construction purposes. Four major laterite mining sites in Shagari, Gago, Kurfi and Radda are the sample locations. Spade, sample bags, and a moisture-proof container were used to collect the samples and the samples were stored and labeled properly using a marker.

Sample preparation and procedure

Geochemical

To identify silicon oxides, iron oxide and manganese oxide.

Apparatus:

i. Sample bags and labels
ii. Mortar
iii. Pulverizer
iv. Oven (to dry sample at 105*c)

Procedure:

i. Dry, crush and pulverize the sample for uniform particle size
ii. Sieve to desired fineness
iii. Digest sample with acid mixture
iv. Filter and dilute the sample
v. Distilled water
vi. Chemical reagents

Geotechnical

Apparatus:

i. Weighing balance
ii. Oven
iii. Spatula
iv. CBR testing machine

Procedure:

i. Air-dry or oven-dry the sample as required for a specific test.
ii. Weigh wet soil in a container
iii. Oven-dry for 24 hours
iv. Compact soil in CBR mold
v. Soak it for 4 days if needed

RESULTS AND DISCUSSION

Geochemical Properties

Table 1: Geochemical data for Silicon oxide (SiO2), Iron oxide (Fe2O3), and Manganese oxide (MnO2) from the Kurfi, Gago, Radda, and Shagari mining sites provide a quantitative foundation for understanding the spatial variability and intensity of weathering processes in a tropical landscape. These results are central to geographical inquiries into pedogenesis, geomorphology, and resource distribution.

The geochemical analysis revealed variability in oxide concentrations across sites (Table 1). The Fe_2O_3 concentration data reveal a clear geochemical differentiation across the landscape. The Radda and Shagari sites exhibit significantly higher Fe_2O_3 concentrations (1.34 and 1.33 mg/kg, respectively) compared to Kurfi and Gago (0.07 and 0.72 mg/kg). This pattern is a classic indicator of varying degrees of lateritic maturity. The high iron oxide content at Radda and Shagari identifies them as more mature laterites. These sites have undergone more advanced weathering, resulting in a stronger enrichment of residual iron oxides.

Silicon dioxide is a primary constituent of the Earth's crust, found in silicate minerals like quartz and feldspars. Under the hot, humid conditions of the tropics, silicon becomes soluble and is preferentially leached out of the soil profile by percolating rainwater. This process, known as desilication, is the fundamental first step in the formation of laterite. From Table 1, the consistently low concentrations of SiO_2 across all sites (ranging from 2.50 to 3.90 mg/kg) confirm that intense chemical weathering has occurred. However, the spatial variation is geographically significant. For instance, the Gago site shows the highest SiO_2 concentration (3.90 mg/kg), while the Shagari site shows the lowest (2.50 mg/kg). This disparity can be attributed to several geographical factors of Parent Material, Drainage, Topography and Time.

Manganese oxide behavior is closely linked to iron but requires even stronger oxidizing conditions to precipitate. Table 1 MnO_2 results show a striking anomaly. The Shagari site has a markedly higher concentration (0.49 mg/kg) than the other three sites (0.08-0.13 mg/kg).

Table 1: Geochemical concentrations of laterite samples

Site	SiO_2 (mg/kg)	Fe_2O_3 (mg/kg)	MnO_2 (mg/kg)
Kurfi	2.89	0.07	0.09
Gago	3.90	0.72	0.08
Radda	3.10	1.34	0.13
Shagari	2.50	1.33	0.49

Source: Fieldwork, 2025.

The low SiO_2 concentrations (2.50–3.90 mg/kg) confirm intense desilication, a hallmark of tropical ferralitization under humid conditions. Spatial variations in SiO_2 relate to drainage efficiency and parent material. Higher SiO_2 at Gago may indicate less advanced weathering due to local lithological resistance or recent erosional exposure.

Iron and Manganese oxides as Paleo-Environmental Proxies: High Fe_2O_3 at Radda and Shagari signals advanced laterization and iron enrichment under oxidizing conditions typical of well-drained uplands. Elevated MnO_2 at Shagari supports seasonal water table fluctuations common in valley bottoms or floodplain margins. MnO_2 precipitation occurs under alternating redox conditions, marking hydromorphic geomorphic settings. These geochemical trends are not just soil properties; they are records of past and present geomorphic processes, weathering intensity, drainage history, and topographic evolution.

Geotechnical Properties

Geotechnical data for soil samples from Kurfi, Gago, Radda, and Shagari locations reveal significant variation in soil behavior. These properties are not random but are intrinsically linked to the region's geographical factors, including climate, parent material, and topography, which influence soil formation and engineering characteristics.

Geotechnical test results are summarized in Table 2. Radda exhibited the highest CBR (60%), indicating superior strength, while Kurfi had the lowest (16%). Plasticity Index varied from 2% (Kurfi) to 7% (Radda), reflecting differences in clay mineralogy. Maximum Dry Density ranged from 1.915 g/cm³ (Radda) to 2.070 g/cm³ (Shagari).

Table 2: Geotechnical properties of laterite samples

Site	LL(%)	PL(%)	PI(%)	LS(%)	MDD (g/cm^3)	OMC(%)	CBR(%) Unsoaked
Kurfi	24	22	2	1	2.069	9.4	16
Gago	28	24	3	3	1.929	10.8	29
Radda	27	20	7	7	1.915	9.9	60
Shagari	28	24	4	4	2.070	8.0	40

Source: Fieldwork, 2025.

High CBR at Radda (60%) and Shagari (40%) reflects iron-oxide cementation and dense granular matrices, products of prolonged in-situ weathering and illuviation. Lower PI and MDD at Kurfi and Gago suggest younger or erosional surfaces where weathering has not yet produced cohesive clay matrices. These variations mirror geomorphic age and stability; older, stable surfaces yield more competent materials. High shrinkage soils (Radda) in construction may lead to subsidence or cracking if not properly managed, a geomorphic hazard linked to clay mineralogy and moisture dynamics. Low CBR soils may require stabilization, adding cost to infrastructure in erosion-prone or immature geomorphic units.

Relationship Between Geochemical and Geotechnical Parameters

Fe_2O_3 Correlations:

Fe_2O_3 vs. Liquid Limit (LL): $r = 0.788$, $t(2) = 1.816$, $p = 0.211$ (not statistically significant due to small sample)

Fe_2O_3 vs. Plasticity Index (PI): $r = 0.807$, $t(2) = 1.929$, $p = 0.193$ (not statistically significant)

Fe_2O_3 vs. CBR: $r = 0.894$, $t(2) = 2.817$, $p = 0.106$ (approaches significance but fails conventional threshold)

SiO_2 Correlations:

SiO_2 vs. Maximum Dry Density (MDD): $r = -0.750$, $t(2) = -1.586$, $p = 0.254$

SiO_2 vs. Optimum Moisture Content (OMC): $r = 0.947$, $t(2) = 4.171$, $p = 0.053$ (approaches statistical significance at $\alpha = 0.05$)

MnO_2 Correlations:

MnO_2 vs. Optimum Moisture Content (OMC): $r = -0.882$, $t(2) = -2.642$, $p = 0.118$

MnO_2 vs. CBR: $r = -0.677$, $t(2) = -1.296$, $p = 0.324$

Degrees of Freedom: For all correlation analyses, $df = n - 2 = 4 - 2 = 2$, reflecting the extremely limited number of sampling sites. The security situation in the area makes it difficult to target a large sample size for the study.

The statistical results indicate strong empirical relationships between geochemical oxide concentrations (particularly Fe_2O_3 and SiO_2) and geotechnical performance parameters (CBR and

OMC), with correlation coefficients ranging from 0.75 to 0.95. However, these promising associations must be interpreted with extreme caution given the limited statistical power (df = 2) and the inability to achieve conventional significance thresholds. The study demonstrates that geochemical composition significantly influences the geotechnical properties of laterite. High Fe_2O_3 content enhances strength and plasticity, making laterite from Radda and Shagari suitable for construction.

CONCLUSION AND RECOMMENDATIONS

The study demonstrates that geochemical composition significantly influences the geotechnical properties of laterite. High Fe_2O_3 content enhances strength and plasticity, making laterite from Radda and Shagari suitable for construction. The findings underscore the need for site-specific characterization to optimize laterite use in engineering projects. Future studies should integrate mineralogical analysis to further elucidate property-controlling mechanisms.

Develop geochemical-based guidelines for laterite suitability assessment, a practical handbook or technical sheet for engineers and local builders. Implement monitoring of mining sites to prevent over-exploitation and environmental degradation. Future studies should collect samples from at least 10-15 mining sites per geomorphic unit, with multiple samples per site (minimum 3 replicates) to enable robust statistical analysis with adequate degrees of freedom ($df \geq 10$). Additional samples at different depths (0-1 m, 1-2 m, 2-3 m) would clarify whether geotechnical properties vary systematically with depth and whether the relationships with geochemistry are depth-dependent.

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