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Physicochemical Characterisation of Mineral Sands from Northwestern Nigeria for Industrial Applications

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Abstract
Mineral sands contain heavy minerals, which are raw materials for the manufacturing and other valuable industries. The physicochemical characteristics of many alluvial mineral sand deposits of northwestern Nigeria are mostly undocumented, which affects the industrial development of the region. This study presents the physicochemical characteristics of four alluvial heavy-mineral sand samples from northwestern Nigeria. (KS-01 and KS-02 from Saminaka, Kaduna State; KS-03 and KS-04 from Doguwa, Kano State) collected via stratified random sampling at multiple depth horizons. Grain-size distribution, pH, electrical conductivity, loss-on-ignition, specific gravity, X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric–differential scanning calorimetry (TGA–DSC), and magnetic susceptibility were determined for each sample. The sands were dark-coloured with a near-neutral to mildly alkaline mean pH of 7.53, low electrical conductivity (2.35–4.85 dS/m), and a mean specific gravity of 2.933. XRD and FTIR revealed a quartz-dominated framework with Fe–Ti oxide accessory phases. An elevated magnetic susceptibility (150×10^{-5} to 346×10^{-5}) indicated appreciable ilmenite-group concentration. TGA–DSC profiles indicated high thermal stability across all samples, with negligible mass loss in KS-01 to KS-03 and a distinct 0.4–0.45% possible dehydroxylation step in KS-04. XRF results showed the deposits are dominated by Fe_2O_3 (39.74–45.06 wt.%) and TiO_2 (37.16–40.97 wt.%), together accounting for 79–86 wt.% of bulk composition. Appreciable ZrO_2 (2.93–6.74 wt.%) and trace Nb, Y, Th, and Sn were also detected. These findings establish the Kano–Kaduna alluvial sands as a high-grade Fe–Ti heavy-mineral placer with meaningful zircon enrichment. Thus, subject to appropriate beneficiation, the deposits hold strategic potential as feedstock for titanium pigment and metal production, ceramics, refractories, foundry, and glass industries. The results provide the first systematic physicochemical baseline for Northwestern Nigerian riverine mineral sands and offer an evidence base for resource valuation.

Keywords: *Heavy mineral sands; Ilmenite–zircon placer; Physicochemical characterisation; Alluvial resource potential; Sustainable mineral beneficiation.*

1.0 Introduction

Mineral sands are heterogeneous sands that contain varying concentrations of valuable naturally occurring minerals. Mining in Nigeria remains a sector with enormous untapped potential. The sector is driven by global demand for rare earth elements used in various high-tech applications ranging from electronics and renewable energy to medical equipment and defence technologies. [1]. Mining is a source of economic and infrastructural benefits to the mining communities and the country at large. However, uncontrolled, unlicensed mining brings threats to human and animal lives. As the need to address environmental concerns in mining and the demand for critical metals and minerals increase globally, a key area of emphasis in the mining and metallurgical industries is the full characterisation of the abundant mineral deposits.

De Meijer [2] described sand as mineral grains with diameters ranging from 0.063 to 2 mm, formed by the mechanical weathering of rocks. Mineral sands are a group of minerals commonly found and mined from concentrated deposits in water or wind. The mineral sands industry consists of two major valuable product streams, which include titanium dioxide minerals in the form of rutile (TiO_2), ilmenite ($FeTiO_3$), leucoxene ($FeTiO_3 . TiO_2$), and Zircon ($ZrSiO_4$). Based on their specific gravity, there are two main classes of mineral sands, which include light and heavy mineral sands. While light mineral sands are light and mainly contain quartz and feldspar, heavy mineral sands have a higher density and consist of minerals such as garnet, rutile, magnetite, zircon, and ilmenite [3]. Heavy minerals are derived from sedimentary rocks and, due to their opaqueness, are characteristically darkened sediments. When they attain large concentrations, they are often referred to as black sands and occur mostly as deposits in rivers and coastal environments. [4]. Heavy mineral sands are critical resources for the modern economy, serving as feedstocks for several industrial processes, including electronics, military hardware, control rods in nuclear reactors, white paint pigments, high-purity silicon, and proppants for

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hydraulic fracturing in oil and gas wells [4]. Table 1 shows some common heavy minerals and their industrial applications.

Table 1: Some common heavy minerals and some of their industrial applications

Heavy mineral	Chemical formula	Principal industrial applications	References
Ilmenite	$FeTiO_3$	TiO_2 pigments; titanium metal; aerospace alloys; welding electrodes; photocatalysts	[5]–[8]
Rutile	TiO_2	Titanium feedstock; pigments; alloys; photocatalysts	[5]–[8]
Zircon	$ZrSiO_4$	Ceramics; refractories; foundry; zirconia; nuclear zirconium	[5]–[8]
Monazite	$(Ce, La, Nd, Th)PO_4$	REE source; magnets; catalysts; electronics	[5], [9]
Xenotime	YPO_4	Yttrium/HREE source; phosphors; lasers	[5], [9]
Garnet	$(Fe, Mg, Ca, Mn)_3Al_2(SiO4)_3$	Abrasives; water-jet cutting; filtration	[5], [8]
Chromite	FeCr2O4	Ferrochrome; stainless steel; refractories	[5], [10]
Magnetite	Fe3O4	Dense media; steel; concrete; water treatment	[5], [10]
Aluminium silicate (Sillimanite/Kyanite/Andalusite	Al_2SiO_5	Refractories; ceramics, porcelain, kilns	[5], [8][6]
Cassiterite	SnO_2	Tin production; solder; electronics	[10]
Columbite–Tantalite	$(Fe, Mn)(Nb, Ta)_2O_6$	Nb/Ta extraction; capacitors; implants	[9], [10]
Wolframite	$(Fe, Mn)WO_4$	Tungsten; carbides; tools	[6]
Zirconolite	$CaZrTi_2O_7$	Advanced ceramics; nuclear waste immobilisation	[5]

The release of fine particles and dust, as well as greenhouse gases from some mineral sands, affects air quality, which poses respiratory hazards to humans and animals and contributes to global warming. Leaching of heavy metals from certain mineral sands can contaminate water bodies, rendering the water unfit for domestic use, harming aquatic life, and posing health risks to humans. In the soil, mineral sands can alter soil pH, leading to reduced nutrient availability and soil fertility. [11], [12]. Effective management, treatment, and utilisation of mineral sands are vital to curtailing their several environmental hazards. Towards addressing challenges related to mineral sands, they can be channelled to various applications, including in construction for structural filling, use as thermal insulation panels, roadbed filling materials, and new building materials related to bricks and cement, and refractory materials. [12]. The activities of unlicensed miners pose serious environmental and health challenges to the ecosystem and serve as a source of revenue loss to the government and tend to initiate civil unrest between the farmers and owners of farmland. [13]. For these reasons, the full characterisation of the mineral sands is necessary to put its economic value in perspective. An understanding of the properties and value of the material will guide the government in formulating policies that will safeguard the people and the environment while the country ensures maximum utilisation and prudent management of its resources, and boost revenue generation.

Riverine mineral sands found along many rivers of Kano and Kaduna State, northwestern Nigeria, are being harvested by artisanal miners and sold in tons daily to some foreign firms. [14],[15]. The mineral sand is a locally recognised heavy-mineral concentrate occurring within alluvial sand deposits, characterised by a dark grey to black colouration and elevated specific gravity. An enormous amount of resources is spent by foreign firms to obtain the mineral concentrate. [16]. Farmland areas from which this mineral concentrate is extracted are generating a large extension of drastically altered areas that are difficult to farm [14].

The global demand for rare earth elements, most of which are found in mineral sands, has been rising steadily. These elements are very important in emerging technologies such as the production of electric vehicles, smartphones, and technologies for renewable energy production. Damaluk [17] reported that Nigeria is endowed with about 44 assorted mineral types in various commercial quantities, while Ahmed [18] reported that Nigeria

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has close to 34 mineral occurrences in about 450 locations, which include precious metals and stones as well as metallic and industrial minerals. Considering the enormous potential of the solid mineral sector in Nigeria, its contribution to the Gross Domestic Product (GDP) is very negligible, contributing less than 3% to the GDP [18], with a very slow growth rate, which is placed at 0.26, 0.45, and 0.63 % in 2019, 2020, and 2021, respectively. In 2021, the federal government generated only N193.59 billion from the sector. [19]. The slow phase-in in the sector can be largely attributed to a lack of developed infrastructure, appropriate policies, and legislation towards developing the production sector. Northwest states of Zamfara, Sokoto, Kano and Kaduna are among the most endowed Nigerian states with the most mineral resources [20]. The Kaduna Mining Development Company Limited [20] reported that solid minerals, which are spread across many of the local governments in the state, include columbite, garnet, granite, gold, iron, laterite, tantalite, and laterite among others.

Several studies have been conducted to characterise Nigeria's major minerals. However, data on mineral sands are very scarce or location-specific. Ige and Rehren [11] used XRF to determine the level of TiO2 in the black sands of southwestern Nigeria, while Clement et al. [12] performed a textural characterisation and heavy mineral studies of the beach sediments in Ibeno and Western Obolo LGAs of Akwa Ibom State and reported that the heavy minerals in the sediments include rutile, zircon, tourmaline, and others. A detailed description of Nigeria's mineral deposits covering potential targets for mineral exploration, non-metallic, metallic, industrial minerals, solid energy, and gemstones, with emphasis on their physical and chemical characteristics, ore reserve estimates, various locations, geological settings, modes of occurrence, and metallogeny was reported by Olade. [21]. The zircon-tourmaline-rutile (ZTR) index was mostly greater than 50%, which indicated that the sediments were mineralogically sub-mature. Okoli [22] characterised Nigerian Zircon sand and gave an overview of its suitability for various industrial applications. Their analysis showed that the zircon sand was predominantly zirconium oxide, quartz, and other heavy minerals with potential applications in the aerospace and industrial sectors.

The Nigerian mineral deposit that receives the most research attention in terms of its characterisation is the mining tailings deposit. Nigeria's mine tailings deposits that have been researched and reported so far include the iron ore tailings at the Itakpe iron ore mine. [23], the minerals of cassiterite tailings of Jos Tin Mining Community Resource Centre [24], and the tin mine tailings of Riyom LGA, also of Plateau State [25]. All industrial mineral utilisation of sand deposits to ascertain their economic index relies on the deposits' reliable textural and chemical classification. According to Uddin et al. [26] state-of-the-art techniques for evaluating and quantifying the characteristics and amount of mineral contents of mineral sands include wavelength dispersive X-ray fluorescence(WDXRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX), among others. While significant work has been done on many mineral sand deposits in southern and north-central Nigeria, there is a critical lack of data on the physicochemical properties and industrial potentials of mineral sands, specifically from the northwestern region. Nig

Characterisation of Nigerian zircon sands from multiple localities has demonstrated pH values in the near-neutral range (7.3–7.8), with specific gravity, hardness, and refractive-index measurements used to distinguish samples requiring beneficiation from those meeting industrial specification directly. [22]. Similarly, characterisation of selected southwestern Nigerian silica sand deposits for foundry moulding applications has emphasised the importance of grain-size distribution, clay content, and chemical purity in determining suitability for sand-casting operations. [27]. These studies collectively establish a transferable analytical framework that combines sieve analysis, specific-gravity determination, XRD, SEM, and XRF for the characterisation of Nigerian industrial sand deposits, which this study adapts and applies to the previously uncharacterised alluvial sands of the Kaduna and Kano River basins.

This study aims to conduct a physicochemical characterisation of riverine mineral sands mined along the Kano River and River Karami and their tributaries as they spread across northwest Nigeria's Kano and Kaduna States, respectively. The objectives are to determine the physicochemical properties (grain size distribution, mineralogy via sieve analysis, XRD, and chemical composition via XRF) of the mineral sands from selected sites. The concentrations of heavy minerals in the sands will be identified and quantified. The mineralogical and physicochemical properties of the mineral sands will be compared.

2.0 Materials and Methods/Methodology

The study area is the banks of Rivers Kano (latitude 10o10'N to 11o50'N; longitude 8o17'E to 8o40'E) and River Karami (latitude 10o19'56 " N, longitude 8o40'16"E) and their major tributaries across Doguwa and Lere LGAs of Kano and Kaduna State, respectively. Riverine mineral sand samples were collected from 3 mining sites for each of the 2 riverbanks along the selected areas to minimise spatial heterogeneity. To ensure spatial representativeness, a stratified random sampling scheme across each zone was adopted. 10 composite samples per geological zone were collected at multiple vertical depths, including the surface, 50 cm, and 100 cm horizons. Clean stainless-steel augers, scoops, and spatulas were used for the collection to prevent cross-contamination. At each location, bulk samples of approximately 10–20 kg were collected. Complete chain-of-custody documentation of every sampling point and collected sample was ensured. Each collected sample was packed in airtight polyethene

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bags. Unique identifiers, which include GPS sampling site coordinates, field description, and horizon depth of the samples, were used to label the polyethene bags. The samples were transported from the sampling points under ambient conditions. The samples were air-dried under ambient conditions and subsequently oven-dried at 40–60°C to constant weight to prevent mineral alteration. Dried samples were gently disaggregated using a rubber pestle to avoid contamination from metallic tools. The disaggregated material was sieved using a standard sieve stack to separate gravel (>2 mm), sand (2 mm–63 μm), and fines (<63 μm). Four representative subsamples labelled serially from KS-01 to KS-04 were finally obtained using coning and quartering to ensure homogeneity. Gravity separation technique via panning, followed by heavy liquid separation using bromoform of specific gravity ≈2.8, was used to obtain heavy mineral concentrates. Magnetic separation was further conducted using a Frantz isodynamic separator to isolate magnetic fractions. The bulk density of the samples was determined using a pycnometer. Measurements were taken for the empty bottle, the bottle with water, and the bottle containing the sample and water, and density was computed using the standard relationship. The pH of the samples was determined in a 1:2.5 solid-to-liquid suspension using 10 g of sample in 25 mL of distilled water. The sample was stirred and allowed to equilibrate for 30 minutes before measurement using a calibrated pH meter. To estimate the organic matter and carbonate content, the loss on ignition was determined. Oven-dried samples were first weighed (W_1), then heated in a muffle furnace at 550°C to remove organic matter and subsequently at 950–1000°C to decompose carbonates. After cooling in a desiccator, samples were reweighed (W_2), and loss of ignition (LOI) was calculated as:

$$LOI\ (\%) = \frac{w_1 - w_2}{w_1} \times 100 \quad (1)$$

The samples were dispersed using sodium hexametaphosphate to prevent flocculation. A combination of dry sieving for coarse fractions and hydrometer analysis for fine fractions was used to analyse the particle sizes.

Selected grains were mounted on carbon tape and coated with gold/palladium to ensure conductivity. Imaging was conducted under high vacuum conditions, and elemental composition was determined using an attached Energy Dispersive Spectroscopy (EDS) system.

The samples were further pulverised to <75 μm and back-loaded into sample holders. XRD analyses were conducted over a scanning range of 5–70° 2θ in a Rigaku MiniFlex 300/600 XRD machine. Mineral phases were identified using standard diffraction databases.

Quantitative phase analysis was performed on XRD data using Rietveld refinement techniques. Structural and phase parameters were refined using appropriate crystallographic software to determine relative mineral abundances. Major and trace element compositions were determined using XRF. The samples were prepared as fused beads using lithium tetraborate flux. FTIR analysis was conducted using KBr pellet techniques. Spectra were recorded over the range of 4000–400 cm^{-1} to identify functional groups and mineral-specific vibrational features. Approximately 10–20 mg of finely powdered sample was heated at a controlled rate (≈10°C/min), and mass loss was recorded as a function of temperature to evaluate thermal stability and compositional changes via thermogravimetric (TGA) analysis. Magnetic susceptibility measurements were carried out using a susceptibility meter to assess the concentration of ferromagnetic minerals such as magnetite and ilmenite. All analyses were conducted in duplicate to ensure reproducibility.

3.0 Results and Discussion

The adopted preparation protocol ensured minimal contamination and preservation of primary grain characteristics. After final preparations for analyses, the samples were grouped into two groups, with each group comprising two samples each. The two samples from Kaduna River were labelled as KS-01 and KS-02, while the samples from Kano River were labelled as KS-03 and KS-04. The physicochemical analysis results are shown in Table 2.

Table 2: Physical characteristics of the samples

Sample ID	Colour	Grain size distribution (>2 mm/2 mm–63 μm/<63 μm	pH	EC (dS/m)	LOI (%)	Specific Gravity
KS-01	Deep black	35/40/25	8.1	4.85	6.5	2.89
KS-02	Deep black	37/38/25	7.5	2.95	10.5	2.94
KS-03	black	39/41/20	7.3	2.45	11.2	3.02
KS-04	black	40/35/25	7.2	2.35	11.8	2.85
Mean	-	**38/39/24**	7.525	3.15	10.0	2.933

The trends shown in Table 2 are consistent with heavy mineral-enriched alluvial mineral sands. The dark colours of the samples are high-probability visual indicators of ilmenite, magnetite, or related opaque heavy mineral enrichments. The near-neutral to mildly alkaline average pH of 7.53 reflects values reported for Nigerian zircon-bearing sands, where pH ranged between 7.3 and 7.8. The relatively low and narrow EC range (2.35–4.85 dS/m) likely indicates limited soluble salt content typical of fluvial sediments rather than saline-contaminated deposits, and is markedly lower than EC values reported for contaminated or organically enriched soils elsewhere in Nigeria. The LOI values (6.5–11.8%, mean 10.0%) likely reflect combined loss of structural water, adsorbed moisture, and minor organic or clay fractions associated with the finer, darker-coloured fractions (KS-03, KS-04). The specific gravity range (2.85–3.02, mean 2.933) exceeds the conventional quartz baseline of 2.65 and falls within the recognised threshold (>2.85–2.9) used to define heavy mineral-bearing sands, given that heavy mineral grains typically have a specific gravity greater than 2.9. Compared with about 2.65 for common quartz sand grains, the result corroborates the deep black to black colouration observed in KS-01 and KS-02. Heavy minerals in fluvial and coastal environments are generally defined as those with specific gravity greater than approximately 2900 kg/m^3. These parameters support the possibility of the samples as heavy mineral-bearing alluvial deposits, which warrant further mineralogical (XRD/XRF) confirmation.

XRD analysis of the samples of the samples repsented using the results for sample KS-01 is shown in Figure 1. The XRD result yielded a diffractogram comprising fifteen resolvable reflections spanning 19.41°–86.04° 2θ. The result indicates the likely predominance of a crystalline, multi-phase mineral assemblage typical of fluvial sediments. The most intense and best-resolved reflection, centred at 2θ = 26.32° (d = 3.386 Å), closely approximates the characteristic (101) reflection of quartz (SiO_2; ideal d ≈ 3.34 Å).

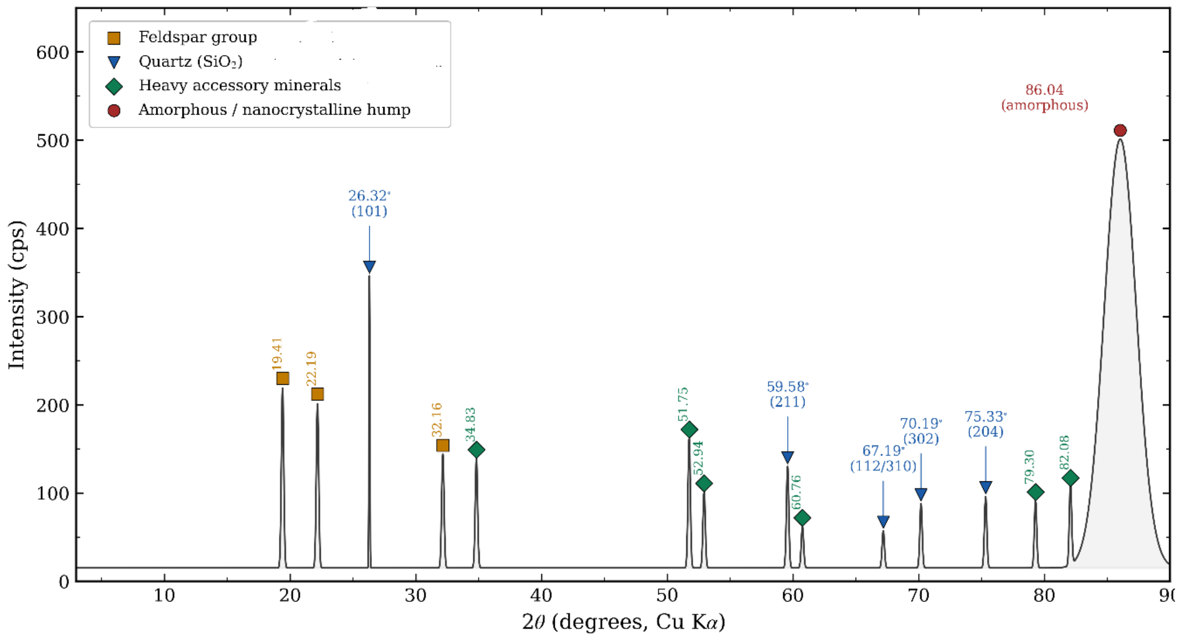

Figure 1: XRD pattern of the component of sample KS-01 of River Kaduna mineral sand

This is consistent with the near-abundant dominance of quartz in siliciclastic alluvial deposits. Additional moderate-intensity reflections at d ≈ 4.57, 4.01, 2.78, 2.58 and 1.73 Å are tentatively attributable to accessory feldspar/mica-group silicates. The results indicate a high possibility of Fe–Ti oxide phases such as ilmenite-group minerals, which are frequently reported as heavy-mineral constituents of similar alluvial placers in north-central Nigeria. Overall, the diffraction data support a quartz-dominated mineralogy with subordinate feldspathic and heavy-mineral accessory phases.

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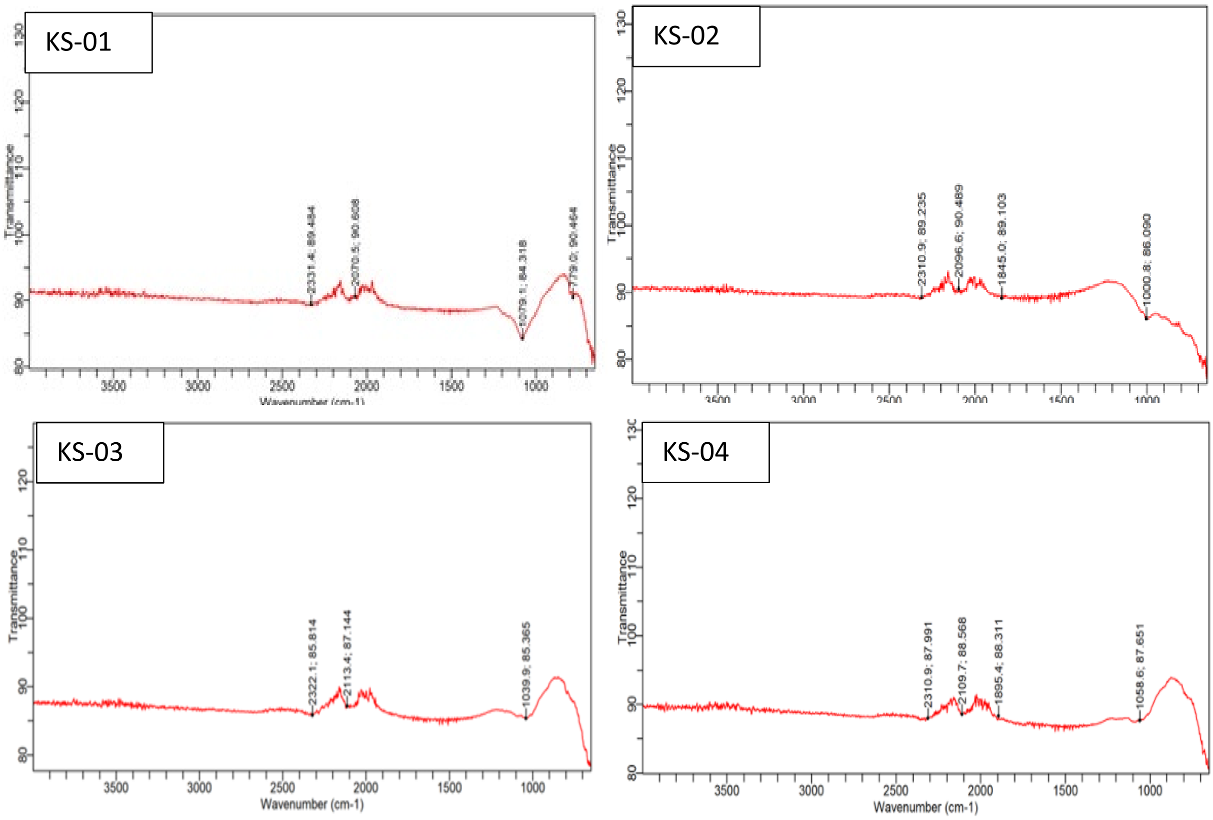

Figure 2: Comparative FTIR spectra of the samples showing the characteristic infrared absorption bands associated with the principal mineral constituents and functional groups

The FTIR spectrum in Figure 2 shows a comparatively featureless, high-transmittance baseline (85–92%) punctuated by a dominant absorption feature in the 1000–1080 cm^{-1} region attributable to Si–O–Si asymmetric stretching of the silicate framework. Sample KS-01 displayed the most diagnostic signature, with a well-resolved doublet at 1079.1 cm^{-1} and 779.0 cm^{-1}. The doublet respectively corresponds to the asymmetric and symmetric Si–O stretching modes. The two constitute the classic infrared indicators of crystalline α-quartz. By contrast, samples KS-02, KS-03, and KS-04 exhibited their principal Si–O absorption shifted progressively toward lower wavenumbers (1000.8, 1039.9, and 1058.6 cm^{-1}, respectively). The samples lacked a clearly resolved quartz companion band near 780 cm^{-1}, instead showing a broader, less-defined shoulder in the 1845–1895 cm^{-1} region. This band-position shift and loss of doublet resolution suggest a comparatively lower proportion of well-crystallised quartz and a greater contribution from amorphous silica, aluminosilicates, or minor clay-mineral phases. The weak, low-intensity features observed near 2070–2331 cm^{-1} across all four samples are attributed to residual atmospheric CO_2 absorption and minor combination bands rather than functional groups.

The FTIR results shown in Figure 2 indicate a possible broad silicate-dominated mineralogy and reveal possible inter-sample variability in crystallinity and quartz purity that has direct implications for industrial suitability. KS-01's sharper quartz signature points to possible higher-purity silica sand favourable for glass or foundry applications. KS-02, KS-03, and KS-04 may be better suited to applications tolerant of a more heterogeneous silicate/aluminosilicate assemblage, such as construction aggregate or ceramic feedstock.

The magnetic susceptibility measurements of the samples indicated moderate to high values of 150 × 10^{-5} to 346 × 10^{-5} in concentrated fractions. These values strongly indicate a high possibility of concentration of moderately magnetic minerals such as ilmenite (FeTiO3), garnet, or tourmaline.

The simultaneous thermogravimetric–differential scanning calorimetric (TG–DSC) analysis of the four samples conducted from ambient temperature to 950 °C at a heating rate of 20 °C min^{-1} is shown in Figure 3. The result shows an overall pattern of thermal stability consistent with a quartz-dominated mineral assemblage.

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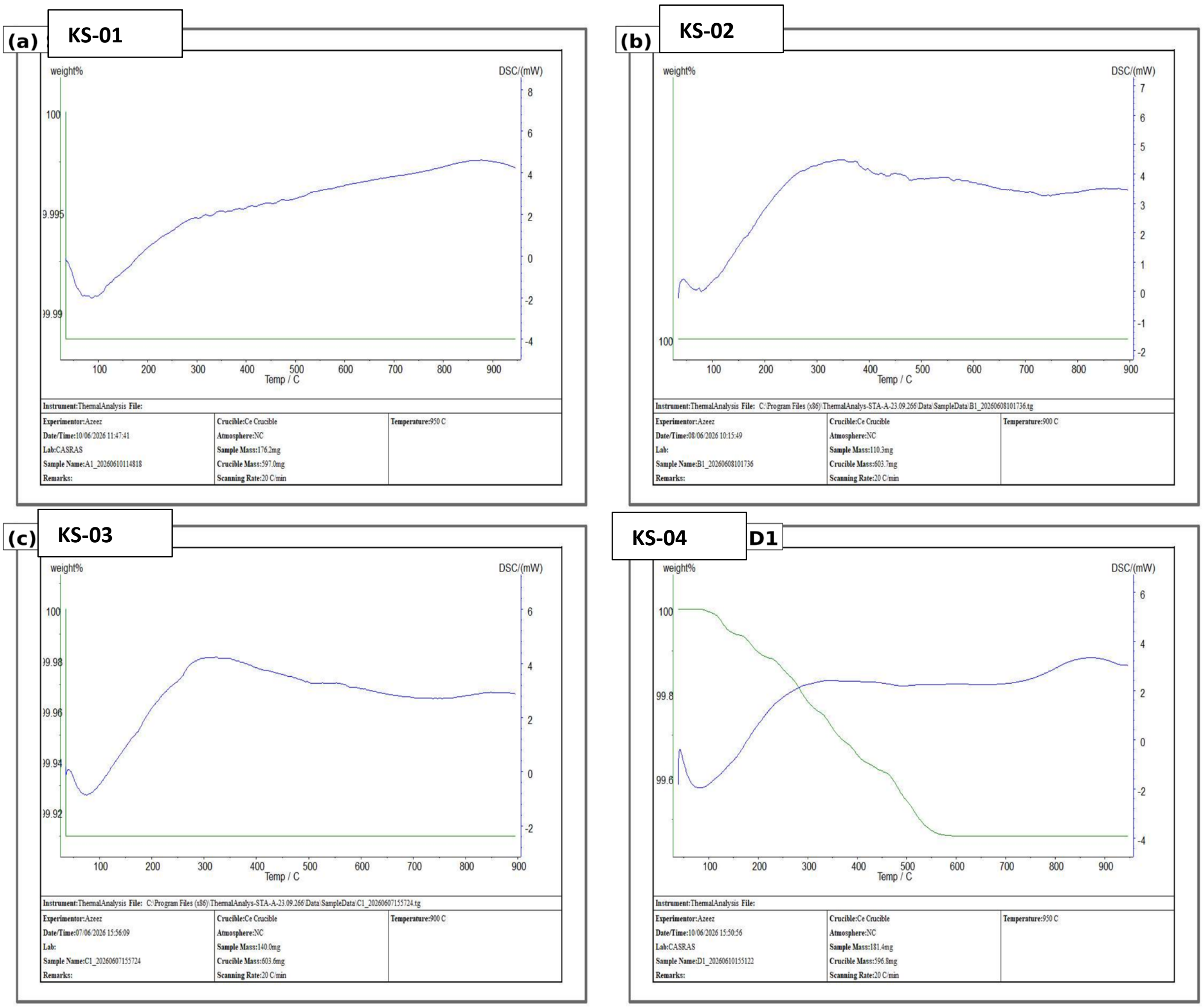

Figure 3: Simultaneous TGA–DSC thermograms of samples showing thermal stability, mass-loss characteristics, and phase-transition behaviour over the temperature range 30–950 ^{o}C

Across all the samples, total mass loss over the full temperature range for the analyses was minor, ranging from a negligible ~0.01–0.02% in KS-01 and an essentially undetectable change in KS-02, to ~0.07–0.08% in KS-03. Thus, the results reflect only minor loss of adsorbed surface moisture at low temperature (<100 °C) with no evidence of significant organic combustion, carbonate decomposition, or clay dehydroxylation reactions. Corresponding DSC traces for these four samples were largely small following a possible initial small low-temperature endothermic change. KS-02 showed a broad, low-intensity exothermic feature centred near 300–350 °C that, in the absence of a coincident mass-loss step, is possibly due to solid-state oxidation of accessory ferrous-bearing heavy minerals such as ilmenite/magnetite-group of Fe–Ti oxides. Sample KS-04 diverged from this pattern, showing a well-defined, increasing mass-loss step of approximately 0.4–0.45% between ~100 °C and 550 °C before stabilising to 950 °C. The pattern may be due to the dehydroxylation of a hydrous phase such as a clay mineral or iron oxyhydroxide. It may also be due to a minor combustible organic fraction which may not be present to the same percentage in the other three samples. This distinction is consistent with the comparatively broader, lower-wavenumber Si–O absorption feature observed for KS-04 by FTIR (see Figure 1), relative to the sharp, well-resolved quartz doublet recorded for KS-01.

The oxide and elemental compositions as obtained from XRD and XRF analyses are presented in Tables 3 and 4, respectively. The oxide and elemental compositions of samples KS-01 to KS-04 indicate that the investigated heavy mineral-bearing sands are dominated by iron- and titanium-bearing phases. There is also the presence of minor silicate, zirconium, and trace-element constituents. Among the major oxides, Fe_2O_3 (39.74–45.06 wt.%) and TiO_2 (37.16–40.97 wt.%) collectively account for approximately 79–86 wt.% of the total composition. This confirms that the deposits are composed of Fe–Ti oxide minerals, most likely mixtures of ilmenite and iron oxides such as hematite or magnetite.

Table 3 shows the relatively high Fe_2O_3 content in KS-01 (45.06 wt.%) compared with the other samples, suggesting greater enrichment of iron-bearing minerals. KS-02 exhibits the highest TiO_2 concentration (40.97

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wt.%), indicating spatial variability in Fe–Ti mineral distribution across the sampling locations. Silica (SiO_2) constitutes the third most abundant oxide, increasing from 7.98 wt.% in KS-02 to 12.34 wt.% in KS-04, implying varying degrees of quartz dilution within the deposits. Similarly, ZrO_2 ranges from 2.93 to 6.74 wt.%, with KS-02 recording the highest concentration, reflecting localised enrichment of zircon, a mineral of considerable industrial importance because of its applications in ceramics, refractory materials, and nuclear technology. Minor oxides including Al_2O_3, MnO, MgO, CaO, Nb_2O_5, K_2O, Na_2O and SO_3 occur at concentrations generally below 3 wt.%. Also, numerous trace constituents (ThO_2, Y_2O_3, ZnO, BaO, SnO_2, CuO, Bi_2O_3, Tl_2O_3, SeO_2 and Cr_2O_3) are present only in trace quantities. The trace elements highlight the geochemical complexity of the deposit without significantly affecting its bulk composition.

Table 3: Composition of oxides in the samples

Oxide/ Sample ID	KS-01	KS-02	KS-03	KS-04
	Oxide composition (%)			
Fe_2O_3	45.06	41.74	39.74	41.05
TiO_2	37.60	40.97	38.73	37.16
SiO_2	8.73	7.98	10.46	12.34
ZrO_2	2.93	6.74	4.96	3.26
Al_2O_3	2.21	-	2.84	3.07
MnO	1.36	1.39	1.64	1.46
MgO	0.666	0.303	0.612	0.69
CaO	0.57	0.208	0.211	0.221
Nb_2O_5	0.211	0.189	0.242	0.166
K_2O	0.205	0.186	0.119	0.287
Na_2O	0.16	-	-	-
SO_3	0.109	0.067	-	0.063
Cl	0.0647	0.0727	0.0689	0.0592
As_2O_3	0.0292	0.0445	0.0417	0.0277
ZnO	0.0226	0.0258	0.0224	0.0206
ThO_2	0.0215	-	0.103	0.0187
Y_2O_3	0.0209	0.0309	0.123	0.0469
BaO	0.0121	0.0127	0.0135	-
SnO_2	-	0.0112	0.0433	-
CuO	-	0.0086	0.0069	-
Bi_2O_3	-	0.0066	0.008	-
Tl_2O_3	-	0.0059	-	-
SeO_2	-	-	0.0062	-
Cr_2O_3	-	-	-	0.0391

The elemental composition shown in Table 4 reflects the oxide chemistry from Table 3, with Fe (45.49–51.15 wt.%) and Ti (34.27–37.16 wt.%) dominating all samples, followed by Si (4.92–7.87 wt.%) and Zr (3.72–8.35 wt.%), which were the second and third most abundant elements, respectively. The consistency between oxide and elemental analyses demonstrates the reliability of the compositional measurements and confirms that iron and titanium are the principal economically significant elements within the deposit. Sample KS-02 is particularly noteworthy because it combines the highest Ti (37.16 wt.%) and Zr (8.35 wt.%) concentrations, suggesting superior potential for the recovery of both titanium and zirconium-bearing minerals. KS-01 contains the highest Fe concentration (51.15 wt.%), indicating relatively greater iron mineralisation. Trace elements such as Nb, Y, Th, Sn and Cr occur at low but detectable concentrations, which may provide additional economic value to the mineral sands as by-products depending on beneficiation efficiency and market demand. The compositional data indicate high-grade Fe–Ti heavy minerals with appreciable zircon enrichment and limited gangue mineral content. These are characteristics that are consistent with economically promising heavy mineral placer deposits and favourable for subsequent mineral processing and resource evaluation. The compositions tally with findings of Ahmed [18] for common solid mineral deposits of Nigeria.

Table 4: Elemental composition of the samples

Element/Sample ID	KS-01	KS-02	KS-03	KS-04
	Elemental Composition (%)			
Fe	51.15	46.65	45.49	47.65
Ti	34.27	37.16	35.77	34.53

Received: 23/07/2026; Revised: 30/07/2026; Accepted: 03/08/2026; Published: 14/08/2026

Element/Sample ID	KS-01	KS-02	KS-03	KS-04
	Elemental Composition (%)			
Si	5.5	4.92	6.57	7.87
Zr	3.72	8.35	6.33	4.23
Mn	1.7	1.71	2.07	1.86
Al	1.57	-	2.0	2.2
Ca	0.599	0.219	0.224	0.236
Mg	0.53	0.23	0.48	0.554
Nb	0.252	0.22	0.29	0.202
K	0.247	0.224	0.145	0.353
Na	0.153	-	-	-
Cl	0.0914	0.103	0.0989	0.0852
S	0.047	-	-	--
As	0.0378	0.056	0.054	0.0368
Th	0.0323	-	0.155	0.0288
Zn	0.031	0.0345	0.0309	0.029
Y	0.0282	0.0407	0.167	0.0647
Ba	0.0175	0.0182	0.0195	-
Bi	0.007	0.0095	0.012	-
Se	0.0057	0.0057	0.0072	0.0058
Cu	0.0051	0.0114	0.0094	0.006
Sn	-	0.0148	0.0586	-
Tl	-	0.0088	-	-
I	-	-	0.0066	-
Cr	-	-	-	0.0429

From an applications point of view, the high thermal stability and minimal volatile content demonstrated across all four samples, and particularly KS-01, KS-02, and KS-03, is favourable for high-temperature industrial processes such as glass melting, ceramic firing, and foundry sand use. In these applications, excessive mass loss or gas evolution during heating is undesirable. However, KS-04's greater thermal reactivity suggests it may require additional beneficiation such as attrition scrubbing or clay-fraction removal before use in such high-purity applications.

The oxide and elemental compositions of samples KS-01–KS-04 also indicate that the alluvial heavy mineral sands possess significant industrial and strategic resource potential. The high concentrations of Fe_2O_3 (39.74–45.06 wt.%) and TiO_2 (37.16–40.97 wt.%), corresponding to elemental Fe (45.49–51.15 wt.%) and Ti (34.27–37.16 wt.%), suggest that the deposits are a promising source of Fe–Ti oxide minerals. The result is consistent with the pattern for mineral sands resources of Hatiya Island, Bangladesh, as reported by Island [26]. In particular, ilmenite, which is the principal feedstock for the production of titanium dioxide pigments and titanium metal, is used extensively in aerospace, biomedical implants, marine engineering, and corrosion-resistant alloys. The appreciable ZrO_2 (2.93–6.74 wt.%) and elemental Zr (3.72–8.35 wt.%) contents indicate the presence of economically valuable zircon, which is widely used in ceramic glazes, refractory materials, precision casting, and nuclear reactor components. Zircon is used in these applications because of its excellent thermal stability and low neutron absorption. In addition, the detectable concentrations of Nb, Y, Th and Sn suggest potential for the recovery of critical and strategic minerals as secondary products, with applications in high-strength superalloys, advanced electronics, renewable energy technologies, and specialised optical materials. However, the relatively low abundances of these elements would require economic evaluation before commercial extraction. Generally, the dominance of Fe–Ti minerals, coupled with substantial zircon enrichment and relatively low gangue mineral content, indicates that the heavy mineral sand deposit of northwest Nigeria represents a potentially valuable resource for titanium pigment production, metallurgical feedstocks, and ceramic and refractory industries. The deposits also represent sites for the possible recovery of critical mineral by-products following appropriate beneficiation and mineral separation processes.

4.0 Conclusion

This study provides physicochemical data on the riverine heavy-mineral deposits of northwest Nigeria. An integrated grain-size, mineralogical, thermal, and geochemical baseline for the Kano River and River Karami alluvial sands was provided. Four convergent lines of evidence (specific gravity, XRD, FTIR, and magnetic susceptibility were used. The results showed a consistent quartz-hosted, Fe–Ti oxide-enriched heavy-mineral placer of industrial importance. The dominance of Fe_2O_3 and TiO_2, together comprising up to 86.00 wt.% of bulk

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composition, with appreciable zircon co-enrichment and low gangue content, places the deposits within the compositional envelope of economically exploitable ilmenite–zircon placers reported elsewhere in the world. This study elevates the heavy mineral sands to high economic importance. A near-neutral mean pH of 7.53, low electrical conductivity (2.35–4.85 dS/m), mean specific gravity of 2.9, and high thermal stability recorded across the samples indicate that the sands are geochemically processable without the need for extraordinary pre-treatment. This is an advantage for prospective beneficiation and downstream titanium, zirconium, and refractory-grade applications. Beyond its mineralogical contribution, this work carries direct policy relevance. By quantifying, for the first time, the resource value locked within sediments currently extracted informally and exported with minimal domestic benefit, the study provides the northwestern states Kano and Kaduna with an evidence base for regulating artisanal mining. A limitation of the study is that the four-sample dataset, while internally consistent, cannot yet capture the full spatial variability of the two river systems, and estimates of recoverable reserves and beneficiation economics await dedicated volumetric and pilot-scale processing studies. Future work should extend sampling density and depth coverage across both riverbanks. The findings of this study reposition northwestern Nigeria's riverine mineral sands from an environmental liability into a characterised, quantifiable, and strategically significant mineral resource.

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References

[1] M. Mallum, "$400m Rare Earth Project Launches in Nasarawa State," Voice of Nigeria (VON), 2025. [Online]. Available: https://von.gov.ng/400m-rare-earth-project-launches-in-nasarawa-state/
[2] R. J. De Meijer, "Heavy minerals: from Edelstein to Einstein," *Journal of Geochemical Exploration*, vol. 62, no. 1, pp. 81–103, 1998.
[3] R. J. De Meijer, H. M. E. Lesscher, and R. D. Schuiling, "Estimate of heavy mineral content in the sand and its provenance by radiometric means," *Nuclear geophysics*, vol. 4, pp. 455–460, 1990.
[4] H. Elsner, "Heavy Minerals of Economic Importance: Assessment Manual," *Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)*, 2010. [Online]. Available: https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/heavy-minerals-economic-importance.pdf
[5] Subasinghe, C.S., Ratnayake, A.S., Roser, B. "Global distribution, genesis, exploitation, applications, production, and demand of industrial heavy minerals". *Arab Journal of Geosciences,* 15, 1616 (2022). https://doi.org/10.1007/s12517-022-10874-0.
[6] G. M. Mudd and A. Perks, 'Titanium, zirconium resources and production: A state-of-the-art literature review,' *Ore Geology Reviews, Ore Geology Reviews*, Volume 107, pp 629-646, https://doi.org/10.1016/j.oregeorev.2019.02.025 ,2019.
[7] D. O. Okanigbe, 'Ilmenite, rutile, and zircon recovery from Namakwa heavy mineral sand deposits,' Canadian Metallurgical Quarterly, 1–19. https://doi.org/10.1080/00084433.2026.2650958, 2026.
[8] I. Pradhan, S. S. Rath, S. Senapati and S. Angadi, 'A comprehensive review of beneficiation strategies for beach sand minerals', *Minerals Engineering*, Vol 241, 110150, https://doi.org/10.1016/j.mineng.2026.110150, 2026,
[9] I. Demir, A. M., Ayten, S. Top, M. Altiner and S. Kursunoglu. " Rare Earth Elements in the Global Economy: Usage, Recovery, and the Quest for Supply Security – A Review. *Mining, Metallurgy & Exploration* 43, 2061–2092. 2026.
[10] A. P. Jones, F. Wall, and C. T. Williams, Eds., Industrial Minerals and Their Uses: A Handbook and Formulary, 2nd ed. Amsterdam, Netherlands: *Elsevier,* 2015.
[11] T. Ige and T. Rehren, "Black sand and ironstone: iron smelting in Modakeke, Ife, and southwestern Nigeria", *Institute of Archaeo-Metallurgical Studies.,* vol. 23, pp. 15–20, 2003.
[12] C. E. Bassey, A. E. Ite, E. Asuaiko and E. E. Aidoko. "Textural and heavy minerals characterization of coastal sediments in Ibeno and Eastern Obolo Local Government Areas of Akwa Ibom State – Nigeria," *Journal of Geosciences and Geomatics,*, vol. 7, no. 4, pp. 191–200, 2019.
[13] O. S. I. Olusola Joshua Olujobi, "Strategies and regulatory measures for combating illicit mining operations in Nigeria: A comprehensive legal perspective," *Resources Policy*, vol. 88, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301420723011704
[14] C. M. Sennott, "How unregulated sand mining is depleting farmland in Nigeria," The GroundTruth Project, 2023. [Online]. Available: https://thegroundtruthproject.org/how-unregulated-sand-mining-is-depleting-farmland-in-nigeria/

[15] Q. Suleiman, "Investigation: Kano farmers helpless as sand mining destroys farmlands," *Premium Times*, 2020.

[16] O. Ojewale and F. Oluwole, "Illegal mining by Chinese actors complicates Nigeria's criminal landscape", ENACT Africa, 2023. [Online]. Available: https://enactafrica.org/enact-observer/illegal-mining-by-chinese-actors-complicates-nigeria-s-criminal-landscape.

[17] D. Damulak, "Nigeria solid mineral resource potentials: An overview," ResearchGate, pp. 2000–2014, 2017 [Online]. Available: https://www.researchgate.net/publication/318987503

[18] H. A. Ahmed, "Overview of Nigeria's solid mineral potentials, challenges and prospects," FUTY Journal of the Environment, vol. 16, no. 1, pp. 76–91, 2022.

[19] O. Osho, "Is the golden era of Nigeria's solid minerals here?," The Cable, Sep. 9, 2023. [Online]. Available: https://www.thecable.ng/is-the-golden-era-of-nigerias-solid-minerals-here/

[20] Kaduna Mining Development Company Limited (KMDC). [Online]. Available: https://kmdc.kdsg.gov.ng/.

[21] A. M. A, Olade, Mineral Deposits and Exploration Potential of Nigeria. 2020, pp. 1–401.

[22] B.I. Okoli, O.A.Agboola, A.P. Onwualu, A. Bello, O.S. Sholiyi, V.C. Anye and O.T. Yusuf, "Characterization of Nigerian zircon sand and its suitability for different industrial applications," *Minerals*, vol. 13, no. 6, 2023. https://doi.org/10.3390/min13060711

[23] R. A. Adebimpe and A. O. Fatoye, "Characterisation of tailings from Itakpe iron ore mine, Itakpe, Nigeria," *Sustainable Geoscience and Geotourism,* vol. 4, pp. 1–8, 2021, https://doi.10.18052/www.scipress.com/SGG.4.1

[24] A. A. Paul, A. Obams, and A. Ifeanyi, "Determination of minerals of cassiterite tailings and its recycling potential using empirical method at Plateau State, Nigeria," *International Journal of Advances in Scientific Research and Engineering (IJASRE).*, vol. 8, no. 3, pp. 18–42, 2022, https://.doi.10.31695/IJASRE.2022.8.3.3 .

[25] D. Bwede, R. A. Wuana, M. E. Khan, G. O. Egah, A. U. Itodo, and E. B. Duwong, "Physicochemical characterization and assessment of ecological risk of heavy metals in tin mine tailings in Riyom Local Government Area of Plateau State, Nigeria," *Journal of Environmental Analytical Chemistry.*, vol. 6, no. 3, pp. 1–8, 2019.

[26] H. Island, "Identification and economic potentiality of mineral sands," *Minerals*, vol. 12, 2022.

[27] O. A. Adeyemi, O, T. Emmanuel, O. J. Olawale, I. A. Dayo, A.R. Adetunji A. R., O, Adekoya and O. Adeyemo O., "Characterization of some selected silica sand deposits in South West Nigeria for sand moulding in foundry industry," *Nigerian. Journal of Material Science and Engineering, vol.* 11, no. 2, pp. 58–69, 2021.

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