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Termite mounds as bioindicators of soil geochemistry in the Guinea and Sudan Savannah zones of northeastern Nigeria: A multi-parameter synthesis

Hannatu Akanang

Department of Chemistry, Abubakar Tafawa Balewa University, Bauchi, Nigeria
e-mail: akananghannatu@gmail.com

Abubakar Habib Idris

Department of Chemistry, National Open University of Nigeria, Abuja, Nigeria

Dedah John

Department of Chemistry, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Musa Runde

Department of Chemistry, National Open University of Nigeria, Abuja, Nigeria

Jamila Ibrahim Shekarau

Department of Chemistry, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Hafsat Abubakar Garba

Department of Chemistry (Material Science and Explosives), Nigerian Defence Academy Postgraduate School, Ribadu Campus, Kaduna, Nigeria

Warji Muhammad Ibrahim

Department of Science Laboratory Technology, Federal Polytechnic Kaltungo, Gombe, Nigeria

Aisha Habib Idris

Department of Biological Science, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Abstract

The capacity of termite mounds to reflect, amplify and transmit the geochemical signature of the local soil profile was evaluated through a multi-parameter synthesis integrating XRF oxide analysis, heavy metal distribution, NPK quantification and physical characterization of Nausititermes walkeri and Coptotermes acinoformis mound soils and adjacent control soils from nine communities across three ecological zones of Bauchi State, Nigeria. Across all analytical streams, results consistently reflected the geochemical signature of regional parent material: the oxide order $SiO_2 > Al_2O_3 > Fe_2O_3$ tracked the Guinea–Sudan savannah weathering gradient; Fe_2O_3 anomalies in Bauchi LGA mounds reflected Jos Plateau basement geology; heavy metal profiles showed Fe consistently highest and Cd consistently lowest across all sample types, though the relative order of Zn, Pb, Cr and Mn varied

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by LGA and sample type rather than following one fixed hierarchy (see the companion heavy-metal study for detail), with inter-metal correlations calculated from LGA-level means that are suggestive of, but cannot confirm, common geogenic sources (Zn–Cr: $r = 0.997$; Cd–Zn: $r = 0.998$, both from $n = 3$, 1 degree of freedom); and NPK patterns reflected local organic matter quality and subsoil mineral K content. ANOVA showed no significant differences between mound and control soils for most parameters ($p > 0.05$), consistent with, though not proof of, geochemical continuity between mound and parent soil. The synthesis supports a three-tier bioindicator framework: Tier 1 regional geochemistry signal (oxide order as ecological zone indicator); Tier 2 local subsurface anomaly signal (Fe, K_2O enrichment as geological anomaly indicators); Tier 3 fertility status signal (NPK enrichment ratios as soil fertility potential indicators). An operational mound geochemical sampling protocol with 5–6× cost savings versus conventional soil survey is proposed for Bauchi State.

1. Introduction

Environmental bioindicators (organisms, populations, or biological structures whose properties provide reliable information about the state of the surrounding environment) have become indispensable tools in ecological assessment, environmental monitoring and natural resource management (Markert *et al.* [8]). Their utility arises from a combination of integrative and amplifying functions: bioindicators accumulate environmental signals over time, concentrate specific components of the environmental matrix and present them in forms that are analytically accessible and often more informative than direct environmental sampling. The diversity of bioindicator systems in active use(from diatom communities for water quality assessment, to lichen diversity for air pollution mapping, to soil mesofauna assemblages for soil health assessment) reflects the breadth of environmental questions that can be addressed through biological proxies (Markert *et al.* [8]).

Termite mounds represent one of the most compelling and practically accessible natural soil geochemical bioindicators available in tropical landscapes. As ecosystem engineers whose mound-building activities systematically sample, transport and concentrate specific fractions of the sub-surface soil profile, mound-building termites create surface-accessible geochemical structures that reflect the physical, chemical and biological properties of the sub-surface environment at the colony's excavation depth (Jouquet *et al.* [5]). This bioindicator function has been demonstrated across three main application domains: mineral exploration (detecting ore-element enrichment in sub-surface geological formations; Chandra and Sekhar Reddy [4], Nwachukwu *et al*. [10]), soil fertility assessment (identifying NPK-rich subsoil zones and mapping fertility island distribution; Sileshi *et al*. [11]) and ecological zone characterization (tracking regional geochemical gradients associated with weathering intensity and parent material transitions; Abiyot *et al*. [1]).

The principal scientific gap in the termite mound bioindicator literature is the absence of multi-parameter validation studies that integrate oxide geochemistry, heavy metal distribution, NPK content and physical properties within a single ecological framework. Most existing studies examine one analytical dimension in isolation (XRF geochemistry, or NPK, or heavy metals) and cannot therefore assess the coherence of the bioindicator signal across multiple chemical and physical parameters. Such coherence is essential for establishing the reliability of mound material as a multi-purpose bioindicator: if different analytical streams generate conflicting signals about the mound's relationship to its soil environment, the bioindicator concept is weakened; if they generate convergent signals, it is substantially strengthened.

This synthesis paper integrates findings from four companion studies of N. walkeri and C. acinoformis mound soils in Bauchi State covering XRF oxide analysis (81 analyses), heavy metal distribution (AAS), NPK quantification and physical property characterization to provide the first multi-parameter bioindicator validation for northern Nigerian termite mound soils. The objectives are to: (i) assess geochemical continuity between mound and control soils across all analytical dimensions; (ii) document and quantify the bioindicator signals generated at regional, local and fertility assessment scales; (iii) compute mound enrichment factors for key parameters; (iv) propose a three-tier bioindicator framework with specific applications for soil survey and agricultural planning; and (v) outline an operational sampling protocol for systematic mound geochemical surveys in the Bauchi State context.

This is a synthesis paper: none of the four analytical streams integrated here are newly generated in this manuscript. Each stream derives from a distinct companion study conducted on the same nine communities, three LGAs and two termite species by the same research group; two are currently under peer review, one has been accepted subject to minor revision and one draws on unpublished institutional data.

2. Theoretical and Conceptual Framework

2.1. Bioindicator properties and criteria

Markert *et al*. [8] established four criteria for qualifying an organism or biological structure as a reliable environmental bioindicator: (i) Accumulation; the bioindicator must concentrate specific environmental components beyond ambient background levels, providing signal amplification; (ii) Accessibility; the bioindicator must be more easily sampled than the environment it monitors, providing practical cost or logistical advantages; (iii) Reproducibility; the bioindicator signal must be consistent within zones of similar environmental conditions, enabling interpolation and mapping; and (iv) Interpretability; the signal must be translatable into actionable environmental information through established mechanistic models.

Termite mounds satisfy all four criteria as soil geochemical bioindicators. Accumulation is demonstrated by elevated NPK concentrations in mound soils relative to adjacent control soils (up to 35× enrichment for P; up to 10× for K; up to 3.5× for N), by higher moisture content and organic matter in mound soils (approximately 2.3× and 1.9× control values respectively) and by the concentration of Fe-Mn-associated trace metals in mound material through selective excavation of deep laterite sub-horizons. Accessibility is evident from the large, surface-accessible nature of mound structures easily sampled by digging to 30 cm depth at the mound periphery compared to the deep pit or auger profiles needed for equivalent sub-surface soil characterization. Reproducibility is confirmed by the non-significant within-zone ANOVA results for most parameters in this study and by the consistent oxide order across all 81 XRF analyses. Interpretability is supported by the extensive mechanistic literature on termite ecology, soil geochemistry and savannah pedology (Jouquet *et al.* [5], Sileshi *et al*. [11]).

2.2. Historical development of the termite mound bioindicator concept

The formal use of termite mounds as geochemical bioindicators originated in mineral exploration. Goldschmidt (1937) first proposed the use of plant geochemistry for mineral prospecting and the extension of this principle to termite mounds was made by Rattigan (1966) in Australia, who noted that mound soils in Ni-Cu mineralized zones showed elevated metal concentrations compared to surrounding bulk soils. Systematic application of termite mound geochemistry for prospecting was developed in the 1970s–1990s across Africa and Australia (Boyer [3], Agarwal [2], Chandra and Sekhar Reddy [4]), culminating in the formalization of mound-based geochemical sampling as a standard reconnaissance prospecting method in several geological survey programmes.

The fertility island concept was articulated by Lavelle [6] and has been progressively quantified and formalized as a bioindicator framework by Sileshi *et al.* [11], who demonstrated through meta-analysis of 47

African field trials that mound NPK enrichment ratios predict crop yield responses with statistical reliability. Most recently, the global meta-analysis of Jouquet *et al.* [5] provided the first quantitative assessment of the relative contributions of lithological and species-specific factors to mound geochemical variability, establishing the mechanistic basis for interpreting mound signals in terms of sub-surface geology and pedology.

2.3. The three-tier bioindicator framework

Based on the functional properties of termite mound geochemistry demonstrated in this and previous studies, we propose a three-tier bioindicator framework that organizes mound geochemical signals by scale, resolution and application domain. Tier 1 (regional scale) exploits the systematic variation of major oxide compositions across ecological zones as a bioindicator of regional soil parent material and weathering intensity. Tier 2 (local scale) exploits site-specific enrichments of specific elements relative to regional baselines as bioindicators of local geological anomalies, subsurface ore deposits, or unusual parent rock compositions. Tier 3 (agricultural scale) exploits NPK enrichment ratios as bioindicators of local soil fertility potential and mound-to-soil nutrient flux status. Each tier targets a distinct application domain: Tier 1 supports regional soil survey and ecological zone mapping; Tier 2 supports mineral exploration and engineering site investigation; Tier 3 supports precision agriculture planning, extension advisory services and soil amendment decision-making.

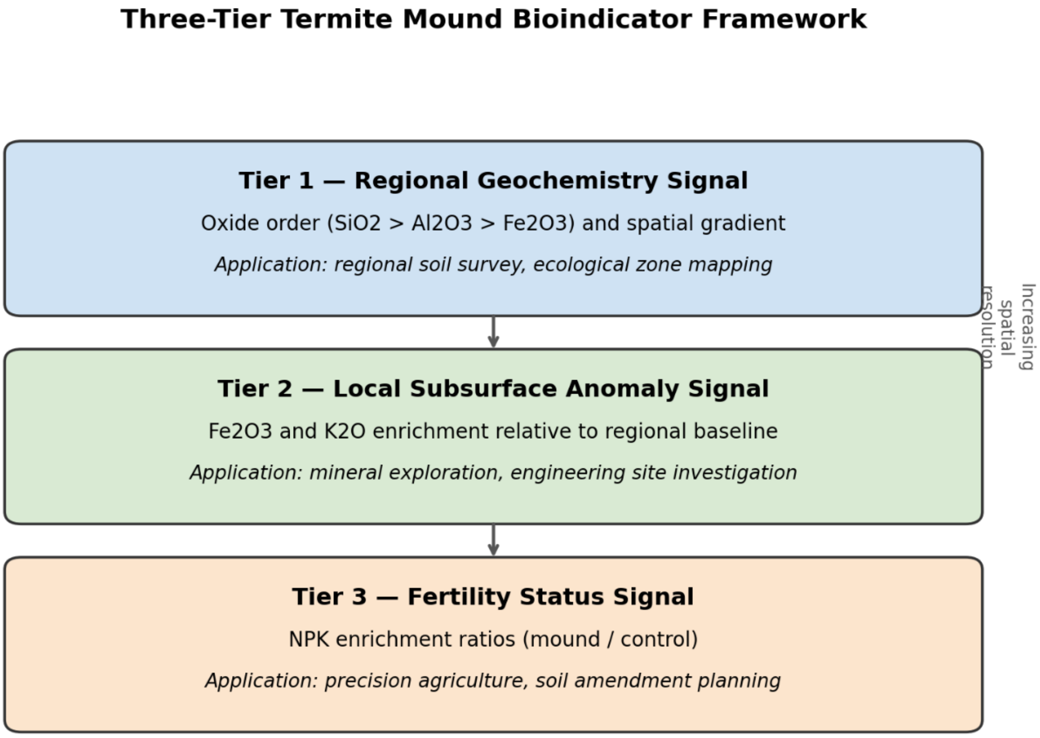

Figure 1. Schematic of the proposed three-tier termite mound bioindicator framework, showing the signal and primary application domain for each tier.

3. Multi-Parameter Evidence for the Bioindicator Framework

3.1. Tier 1 Evidence: Regional geochemistry signal

The Tier 1 bioindicator signal is embodied in the universally consistent oxide order $SiO_2 > Al_2O_3 > Fe_2O_3 > K_2O > CaO > MgO > SO_3 > Na_2O$ and its systematic spatial gradient across LGAs. SiO_2 increases consistently from Bogoro (Guinea savannah, mean 68–69%) to Katagum (Sudan savannah, mean 74–79%), inversely correlated with Al_2O_3 ($r = -0.78$, $p < 0.01$, $n = 9$ communities). K_2O decreases significantly from Bogoro/Bauchi to Katagum (ANOVA, $p < 0.05$; exact F-value, degrees of freedom and Tukey HSD pairwise p-values are reported in the companion oxide-characterization study and will be reproduced in a supplementary table here). These patterns faithfully mirror the known geological and pedological transition from ferrallitic, kaolinite-rich Guinea savannah profiles to quartz-dominated Sudan savannah profiles documented in the regional geological literature.

The Tier 1 signal is reproduced consistently by both N. walkeri and C. acinoformis mounds, confirming its species-independent reliability as a bioindicator of regional parent material. The non-significant species-level differences for most oxides (ANOVA, $p > 0.05$) indicate that community-level geological and pedological context dominates over species-specific construction preferences in determining mound oxide composition; a finding broadly consistent with the substantial lithological contribution to mound geochemical variability reported by Jouquet *et al.* [5]. For practical soil survey applications, this means that either species can serve as a Tier 1 bioindicator wherever it is the locally dominant mound-builder, without requiring species-specific calibration.

3.2. Tier 2 Evidence: Local subsurface anomaly signal

The Tier 2 bioindicator signal is most clearly demonstrated by the Fe_2O_3 anomaly in Bauchi LGA mounds (N. walkeri: up to 11.68% at Yelwa; C. acinoformis: up to 9.86% at Yelwa), which substantially exceeds the regional Bogoro baseline value (4.08%) and the Katagum value (2.75–4.58%). This anomaly is attributable to the proximity of Yelwa and Federal Lowcost communities to the Fe-enriched ring complex geology of the Jos Plateau boundary zone. The Jos Plateau is underlain by the Mesozoic "Younger Granite" ring complexes, anorogenic granitic intrusions into the Precambrian basement complex whose margins and associated country rock are commonly enriched in Fe-Ti oxide phases (magnetite, ilmenite, haematite) through igneous differentiation and subsequent lateritic weathering (Macleod *et al.* [7]). Haematite-rich weathering products derived from this boundary-zone geology have plausibly been incorporated into Bauchi LGA soil profiles and selectively excavated by termites during mound construction, though direct mineralogical confirmation (e.g., XRD phase identification) was not performed in this study and would strengthen this interpretation.

The practical significance of this Tier 2 signal is that it reveals subsurface geological information that would not be detectable from surface soil sampling alone. The control soil Fe_2O_3 at Yelwa (5.02%) is notably lower than the mound Fe_2O_3 (11.68%), demonstrating that termite excavation amplifies the sub-surface Fe signal by a factor of 2.3× relative to surface soil. In a mineral exploration context, this amplification factor means that mound-based sampling would detect the Jos Plateau Fe anomaly with greater sensitivity than surface soil sampling, enabling geological boundary delineation without resort to the more expensive and time-consuming deep auger or percussion drilling methods typically used in Nigerian geological surveys.

The elevated K_2O in Bogoro and Bauchi LGA mounds (3.54–4.16%) relative to Katagum mounds (0.79–1.20%) provides a further Tier 2 signal: the enrichment of K in Guinea savannah and transition zone mounds signals the presence of K-bearing minerals (illite, K-feldspar) in the deep subsoil horizons preferentially excavated by termites in these zones. While the K concentrations recorded here do not indicate exploitable K deposits, the principle of K enrichment amplification by termite excavation could be applied in geological surveys aimed at identifying potassic intrusive bodies or K-enriched hydrothermal zones in the Nigerian basement complex.

3.3. Tier 3 Evidence: Fertility status signal

The Tier 3 bioindicator signal is provided by the NPK enrichment ratios computed from the companion NPK study. Table 1 presents the calculated ratios for N. walkeri mounds relative to adjacent control soils at sites where both mound and control values were measured.

Table 1. NPK Enrichment Ratios (N. walkeri Mound / Control Soil) by Study Site

Study Site	N Ratio	P Ratio	K Ratio	Tier 3 Signal Interpretation
Wuntin Dada, Bauchi	3.45	35.09	9.71	Active, very strong fertility island
Matsango, Katagum	0.53	2.67	1.21	Equilibrating - mound flux to control soil
Wuntin Dada Control	—	—	—	Enriched control (equilibration complete)

Enrichment ratio >1 = mound richer than control; ratio <1 = equilibration/translocation to control soil active.

The extraordinary enrichment ratios at Wuntin Dada, Bauchi LGA (N: 3.45×; P: 35.09×; K: 9.71×) classify this site as a strongly active fertility island with immediate agronomic value. These ratios are among the highest reported for West African termite mound soils, confirming the fertility island function as especially potent in the Bauchi transition zone, where the combination of moderate rainfall, near-neutral pH, active organic matter mineralization and deep K-rich subsoil access by N. walkeri creates optimal conditions for NPK accumulation.

The sub-unity N ratio (0.53) and near-unity P and K ratios at Matsango, Katagum, combined with elevated NPK in Federal Lowcost Katagum control soils, indicate that NPK translocation from mound to adjacent soil is well advanced in Sudan savannah sites. This 'equilibration signal' identifies sites where farmers can benefit from mound-derived NPK in adjacent plots without deliberate mound excavation simply by positioning crops within 1–2 m of active or recently degraded mound structures.

4. Quantitative Bioindicator Validation: Amplification Factors

Table 2 summarizes the mound-to-control amplification factors across all analytical dimensions, providing a quantitative basis for the bioindicator framework.

Table 2. Mound-to-Control Amplification Factors Across All Analytical Dimensions

Parameter	Max. Mound Value	Adj. Control Value	Amplification Factor	Bioindicator Tier
P (mg/kg)	105.97	3.02	35.1×	Tier 3 - fertility status
K (Cmol/kg)	2.72	0.28	9.7×	Tier 3 - fertility status
N (%)	0.252	0.073	3.5×	Tier 3 - fertility status
Moisture content (%)	27.80	12.00	2.3×	Physical - water retention
Organic matter (g/kg)	4.50	2.33	1.9×	Physical - soil carbon
Fe_2O_3 (%, Bauchi LGA)	11.68	5.02	2.3×	Tier 2 - geological anomaly
SiO_2 gradient (%)	83.91 (Katagum)	65.34 (Bogoro)	+28% N→S	Tier 1 - regional geochemistry

Amplification factor = mound value / adjacent control value. N→S = south-to-north increase.

The amplification factors in Table 2 confirm that all three bioindicator tiers are supported by quantitative evidence from the multi-parameter dataset. The strongest amplification occurs for P (35.1×) in Tier 3, confirming that N. walkeri mounds are exceptionally powerful fertility indicators for P-limited savannah soils. The Tier 2 Fe_2O_3 amplification (2.3×) is more modest but geographically specific confined to Bauchi LGA and therefore highly informative as a local geological anomaly indicator. The Tier 1 SiO_2 gradient (+28% from south to north) is the most spatially extensive signal, spanning the full ecological range of the study.

5. Operational Protocol for Termite Mound Geochemical Surveys in Northern Nigeria

Based on the three-tier bioindicator framework and the methodological experience of this study, we propose an operational protocol for systematic mound geochemical surveys in northern Nigerian savannah contexts.

Step 1: Survey Design: establish a sampling grid of 5 km × 5 km across the survey area. At each grid point, identify the dominant termite mound type using the FAO/IUCN termite species key for West African savannahs. If both N. walkeri and C. acinoformis mounds are present, sample both; otherwise sample the dominant species.

Step 2: Sample Collection: collect 500 g composite mound material from three sampling positions (0°, 120°, 240°) at 30 cm depth per mound; collect 500 g control soil from an undisturbed location 10 m from the mound base at 15 cm depth. Label and seal samples.

Step 3: Laboratory Analysis: the minimum analytical dataset for Tier 1–3 assessment comprises: SiO_2, Al_2O_3, Fe_2O_3, K_2O by XRF (Tier 1 and 2); total N by Kjeldahl (Tier 3); available P by colorimetry (Tier 3); exchangeable K by AAS (Tier 3); and pH by electrode (agricultural context). Heavy metal screening (Fe, Zn, Pb, Cr, Mn, Cd by AAS) is recommended for sites near road corridors or industrial activity.

Step 4: Tier Classification: compare oxide data against regional baseline values from this study and Mujinyawa *et al*. [9] to identify Tier 2 anomalies. Compute NPK enrichment ratios to classify Tier 3 fertility status (ratio >2 = active fertility island; ratio 1–2 = moderate enrichment; ratio <1 = equilibrating). Use SiO_2–Al_2O_3 ratio to classify Tier 1 ecological zone (ratio >4 = Sudan savannah; 2–4 = transition; <2 = Guinea savannah).

Step 5: Mapping and Reporting: interpolate results using kriging or inverse distance weighting to produce continuous maps of Tier 1 (geochemical zone), Tier 2 (anomaly distribution) and Tier 3 (fertility island density and intensity). Overlay with existing geological maps, satellite imagery and agricultural extension data to produce integrated soil geochemical and fertility management maps.

Step 6: Cost Assessment: the estimated cost per sample point (including laboratory analysis at ATBU Bauchi rates) is NGN 25,000–45,000, compared to NGN 150,000–250,000 for a conventional pit-profile soil survey at the same point density — representing a 5–6-fold cost saving. At a 5 km × 5 km grid density across Bauchi State's officially reported land area of 49,119 km², the total survey would require approximately 1,965 sample points — feasible as a single- to two-year programme with total survey costs of approximately NGN 49–88 million, substantially less than the NGN 295–491 million cost of a comparable conventional soil survey at the same point density.

Statistical Reporting Note

Sample sizes across the four synthesized datasets are: n = 9 communities (3 per LGA) for the oxide, heavy-metal and NPK analyses, with 2 mound species plus 1 control soil per community; the 81 XRF analyses reported in Section 3 reflect 27 composite field samples analysed in triplicate. Pearson correlations reported at the LGA level (e.g., Zn-Cr, Cd-Zn, SiO_2-Al_2O_3) are calculated from n = 3 LGA means (2 degree of freedom).

6. Conclusion

This synthesis study has validated a three-tier geochemical bioindicator framework for *Nausititermes walkeri* and *Coptotermes acinoformis* mound soils in Bauchi State across four analytical dimensions oxide geochemistry, heavy metal distribution, NPK content and physical properties. Tier 1 (regional signal): the oxide order $SiO_2 > Al_2O_3 > Fe_2O_3$ and its spatial gradient from Guinea savannah (high Al_2O_3, low SiO_2) to Sudan savannah (high SiO_2, low Al_2O_3) provides a reproducible, species-independent bioindicator of regional parent material and weathering intensity. Tier 2 (local anomaly signal): Fe_2O_3 enrichment in Bauchi LGA mounds (amplification factor 2.3×) provides a bioindicator of Jos Plateau Fe-rich geological influence and K_2O enrichment in Guinea savannah mounds signals deep K-bearing subsoil mineral content. Tier 3 (fertility status signal): NPK enrichment ratios of up to 35.1× (P), 9.7× (K) and 3.5× (N) in N. walkeri mounds at Wuntin Dada confirm very strong active fertility island function in the Bauchi transition zone. An operational survey protocol with 5–6× cost advantage over conventional soil survey is proposed. These findings establish termite mounds as scientifically validated, cost-effective and readily accessible bioindicators for soil geochemistry mapping, mineral exploration and agricultural fertility assessment in the Guinea and Sudan savannah zones of northeastern Nigeria.

References

[1] Abiyot, L. D., Wondimu, T. A., & Amsalu, T. F. (2016). Soil physico-chemical properties in termite mounds and adjacent control soil in Borana Zone. *American Journal of Agriculture and Forestry, 4*(3), 69–74. https://doi.org/10.11648/j.ajaf.20160404.11

[2] Agarwal, M. K. (1978). Iron and aluminium in termite mounds. *Journal of Soil Science, 29*(4), 505–514.

[3] Boyer, P. (1973). Action de certains termites constructeurs sur l'évolution des sols tropicaux. *Annales des Sciences Naturelles, Zoologie, 15*, 329–498.

[4] Chandra, L., & Sekhar Reddy, L. (2014). Termite mound as an effective geochemical tool in mineral exploration: A study from chromite mining area, Karnataka, India. *Research Journal of Chemical Sciences, 4*(5), 85–90.

[5] Jouquet, P., Guilleux, N., Chintakunta, S., & Subramanian, S. (2022). Soil physical modifications and microbial priming effects by termite bioturbation: A global meta-analysis. *Geoderma, 420*, 115879.

[6] Lavelle, P. (1997). Faunal activities and soil processes: Adaptive strategies that determine ecosystem function. *Advances in Ecological Research, 27*, 93–132. https://doi.org/10.1016/S0065-2504(08)60007-0

[7] Macleod, W. N., Turner, D. C., & Wright, E. P. (1971). *The geology of the Jos Plateau: Explanation of 1:100,000 sheets nos. 147, 148, 168, 169, and 189 and 190. General geology* (Vol. 1). Geological Survey of Nigeria.

[8] Markert, B. A., Breure, A. M., & Zechmeister, H. G. (Eds.). (2003). *Bioindicators and biomonitors: Principles, concepts and applications*. Elsevier.

[9] Mujinyawa, P. A., Abubakar, M. S., & Bashir, S. (2013). Chemical characterization of termite mound soils from Borno State. *Nigerian Journal of Basic and Applied Sciences, 21*(4), 271–278.

[10] Nwachukwu, C. E., Obiora, S. C., & Eze, U. O. (2022). Termite mound geochemistry as a mineral prospecting tool in southeastern Nigerian basement complex. *Journal of African Earth Sciences, 194*, 104641.

[11] Sileshi, G. W., Arshad, M. A., Konate, S., & Nkunika, P. O. Y. (2023). Restoring degraded dryland soils with termite ecosystem services: A review of evidence from Africa. *Agronomy for Sustainable Development, 43*, 15.