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Geology of Northeastern Nigeria and Its Prospects for Geothermal Energy: A Review

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Abstract: *Geothermal energy offers a sustainable and environmentally friendly alternative to conventional fossil fuels, yet remains underexplored in many developing regions, including Nigeria. This study investigates the geothermal energy potential of Northeastern Nigeria through geological analysis and digitization of existing geological maps using Geographic Information Systems (GIS). The study area, located predominantly in Bauchi State and parts of Plateau and Gombe States, is bounded by latitudes 9°30'N to 11°00'N and longitudes 9°00'E to 11°00'E. It encompasses diverse lithological units ranging from the Precambrian Basement Complex to Cretaceous and Tertiary sedimentary formations, as well as Tertiary–Quaternary volcanic rocks and intrusive granitic complexes. Key geothermal indicators identified include hot springs, tectonic basins, uranium mineralization, and radiogenically enriched granites associated with elevated heat flow. Digitization involved georeferencing scanned analog geological maps, manual vectorization of lithological and structural features, and integration of spatial data into a GIS geodatabase. Attribute information was assigned based on map legends and standardized geological symbology, enabling further spatial analysis. The presence of Younger Granite ring complexes enriched in heat-producing elements (U, Th, K) and the occurrence of anomalously high heat flow values (70–90 mW/m²) suggest a significant geothermal gradient, especially in structurally deformed zones. This study provides foundational digital geological data and highlights key zones with high geothermal prospectivity. The results support future geophysical exploration and policy development toward sustainable energy exploitation in Nigeria's northeastern region.*

Keywords: *Geothermal Energy; Geological Map Digitization; GIS; Northeastern Nigeria; Younger Granites*

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1.0 Introduction

The increasing global demand for sustainable and clean energy has intensified interest in geothermal energy as a viable alternative to fossil fuels. Geothermal energy is a renewable resource derived from the natural heat of the Earth's interior, offering a consistent and environmentally friendly power source with minimal carbon emissions (Lund & Boyd, 2016). While traditionally associated with tectonically active regions such as the Rift Valley and the Pacific Ring of Fire, recent studies have shown that regions with suitable geological and structural conditions outside these areas can also host significant geothermal resources (Noorollahi *et al*., 2007).

Northeastern Nigeria, situated within the West African Craton and forming part of the extensive Chad Basin, comprises diverse geological units, including Precambrian basement rocks, Cretaceous sediments, and intrusive bodies such as granites and rhyolites (Obaje, 2009). These features—particularly the fractured basement terrain, deep sedimentary basins, and widespread tectonic lineaments—provide a geologically favorable environment for geothermal exploration. The occurrence of hot springs, high radiogenic heat production, and crustal heat flow anomalies in some parts of the region further suggests latent geothermal potential (Obaje, 2009).

This study focuses on the digitization of geological maps of Northeastern Nigeria using GIS tools. It aims to create spatially accurate, queryable, and updateable digital geological datasets that can support geothermal energy prospecting and other geoscientific applications in the region.

1.1 Digitization of Geological Maps

The digitization of geological maps using Geographic Information Systems (GIS) has become a transformative tool in modern geoscience, allowing for the efficient integration, visualization, and analysis of spatial geological data. Traditional geological maps, often produced in hardcopy format, are invaluable for understanding the distribution of lithological units, structural features, and geologic processes. However, these static maps have limitations in terms of accessibility, scalability, update capability, and analytical integration with other geospatial datasets (Longley *et al*., 2015). Digitizing such maps into GIS-compatible formats not only preserves them but also enhances their utility for a wide range of applications including mineral exploration, environmental assessment, land use planning, and natural hazard management.

Geological map digitization involves the conversion of analog geological data—such as lithological boundaries, faults, folds, and stratigraphic contacts—into digital vector formats like shapefiles or geodatabases. This process typically includes map georeferencing, vectorization, attribute assignment, and database creation within GIS software environments such as ArcGIS or QGIS (Longley *et al*., 2015). Georeferencing aligns the scanned geological map with real-world coordinates, ensuring spatial accuracy, while vectorization converts geological features into editable line and polygon features. The resulting datasets are dynamic, searchable, and interoperable with remote sensing, topographic, geophysical, and geochemical datasets.

Digitized geological maps also support 3D geological modeling, spatial interpolation, and multi-criteria decision analysis, which are critical for georesource assessments and geotechnical investigations. Moreover, integrating geological maps with high-resolution satellite imagery and digital elevation models (DEMs) allows for more detailed structural and lithological interpretations (Jordan *et al*., 2003). The application of spatial analysis techniques, such as buffer analysis, overlay operations, and terrain modeling, further enhances geological understanding and predictive modeling.

In developing countries, where many geological maps remain in analog form and are often inaccessible to the public or researchers, digitization serves as a key step toward democratizing geoscience data. Open-source GIS platforms and global initiatives, such as OneGeology and the African Geochemical Baselines project, are promoting the digitization and dissemination of geological information for education, exploration, and sustainable development (Jackson, 2008).

2.0 Methodology

2.1 Data Acquisition and Scanning

Analog geological maps of the study area were sourced from the Nigerian Geological Survey Agency (NGSA) and other government repositories. These maps were produced at a scale of 1:100,000 and contained detailed lithological, structural, and stratigraphic information. The hardcopy maps were scanned using high-resolution flatbed scanners at 600 dpi to ensure clarity and precision in subsequent georeferencing and vectorization processes (Balogun, 2019).

2.2 Georeferencing

The scanned maps were imported into a GIS environment (ArcGIS 10.8) and georeferenced using control points obtained from topographic map sheets and known geographic features (e.g., river junctions, road intersections). A first-order affine transformation was applied, and Root Mean Square Error (RMSE) was used to assess georeferencing accuracy. Only georeferenced maps with RMSE < 10 meters were used for further analysis, in line with established practices (Longley *et al*., 2015; Jordan *et al*., 2003).

2.3 Vectorization

Manual vectorization was performed to digitize geological features such as lithological boundaries, faults, fold axes, and stratigraphic contacts. This was done using the Editor tool in ArcGIS, with each feature class (e.g., rock units, faults) stored in separate vector layer. The digitization process followed a heads-up digitizing approach, where features were traced directly from the georeferenced raster maps (Longley *et al*., 2015). Polygon topology rules were enforced to ensure data integrity, such as "no overlaps" and "must not have gaps" for lithological units.

2.4 Attribute Assignment and Symbology

Each digitized feature was assigned attribute information, including rock type, formation name, lithology, age, and structural classification. This information was extracted from the map legend and embedded metadata and stored in the attribute tables of each feature layer. Standardized geological symbology was applied to conform with the International Commission on Stratigraphy (ICS) and FGDC (Federal Geographic Data Committee) geologic mapping guidelines (Jackson, 2008).

2.5 Spatial Database Development

All vectorized and attributed layers were compiled into a geodatabase to facilitate easy query, retrieval, and integration with other spatial datasets such as satellite imagery, digital elevation models (DEMs), and geophysical data. The geodatabase structure followed a hierarchical model organizing data by themes: lithology, structure, and stratigraphy. Metadata for each layer was created according to ISO 19115 standards to ensure transparency and reproducibility (Longley *et al*., 2015).

2.6 Accuracy Assessment and Validation

The quality of the digitized maps was evaluated through overlay analysis with recent geological data, satellite imagery (Landsat 8, Sentinel-2), and field verification where possible. Positional accuracy and topological consistency were reviewed using the Topology Checker in QGIS and ArcGIS Topology Rules. Cross-validation with previous digital geological datasets ensured consistency and minimized digitization errors.

2.7 Study Area

The study area is located predominantly within Bauchi State, extending slightly into parts of Plateau and Gombe States (Figure 1). It is geographically bounded by longitudes 9°00′ E to 11°00′ E and latitudes 9°30′ N to 11°00′ N, and covers a total of twelve geological map sheets, namely: Kailatu – 127, Madaki – 128, Ganjuwa – 129, Dukku – 130, Toro – 148, Bauchi – 149, Alkaleri – 150, Ako – 151, Maijuju – 169, Balewa – 170, Yuli – 171, and Futuk – 172. The selection of this area was because of previous findings on geothermal indicators in Northeastern Nigeria (Mohammed *et al*., 2024; Usman *et al*., 2025 a-b), and was delineated based on the regional geological map of Northeastern Nigeria (Figure 2). The works suggested that the presence of Younger Granite ring complexes enriched in heat-producing elements (U, Th, K) and the occurrence of anomalously high heat flow values (70–90 mW/m²) suggest a significant geothermal gradient, especially in structurally deformed zones.

Northeastern Nigeria is geologically significant due to the coexistence of hot springs, tectonic basins, Tertiary–Quaternary volcanic rocks, and widespread uranium mineralization, all of which provide compelling evidence for latent geothermal energy potential. These geological features suggest the presence of an active or recently active geothermal regime, especially in structurally complex and thermally anomalous zones. The integration of these indicators makes the area highly prospective for further geothermal energy exploration. (Usman *et al*., 2025 a-b).

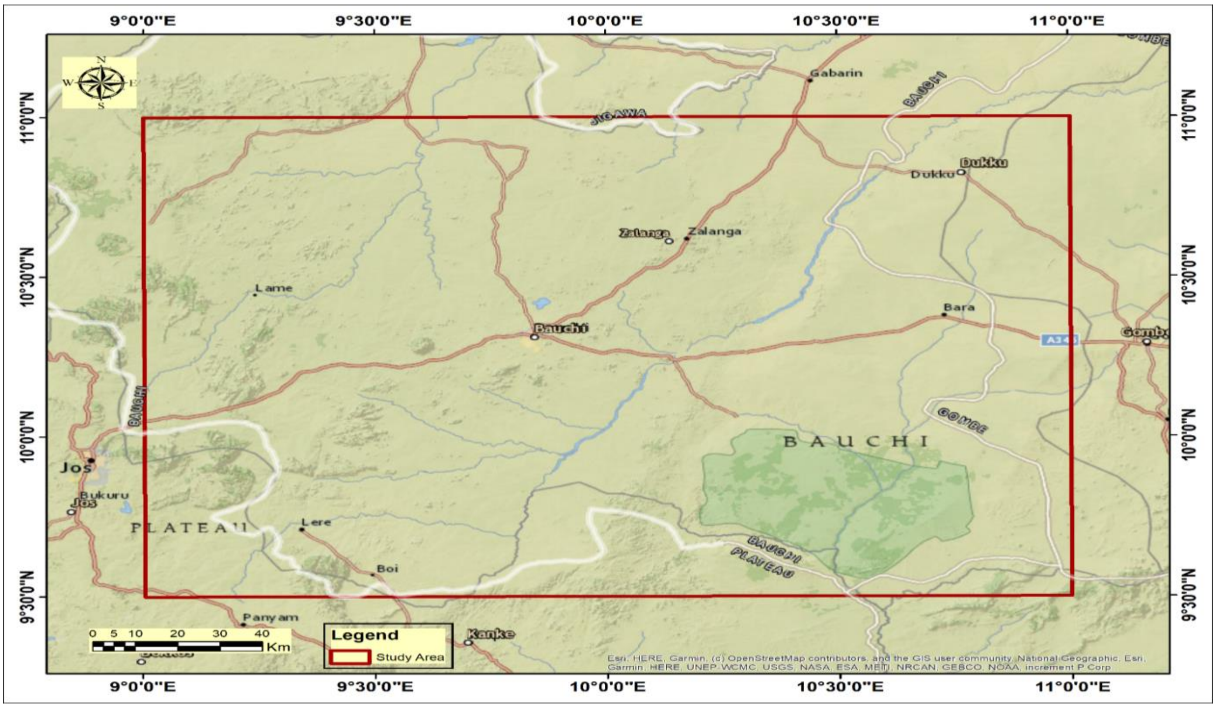

Fig. 1: Location map of the study area

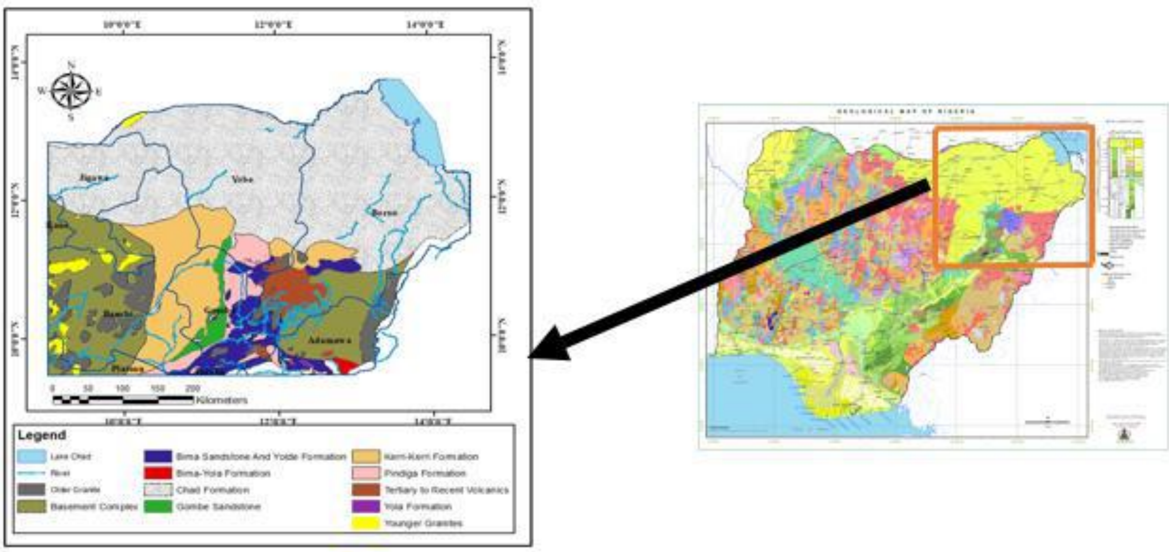

Fig. 2: Northeastern Geological Map (NGSA, 2011)

3.0 Results and Discussion

Geologically, the study area spans from the Precambrian Basement Complex to Cretaceous and Tertiary sedimentary formations (Figure 3). The western part of the region is predominantly underlain by the Basement Complex, consisting of migmatite-gneiss, granite gneiss, and biotite granite. These lithologies are products of the Pan-African orogeny and exhibit significant metamorphic and structural features (Obaje, 2009; Tijani, 2023). The area lies along the northeastern margin of the West African Rift

System, occupying a transitional zone between the Precambrian basement rocks of the Jos Plateau and the Cretaceous–Tertiary Benue Basin. The Upper Benue Trough (UBT), part of this basin system, is a Cretaceous rift formed during the breakup of Africa and South America (Wright, 1985). The regional structural grain trends predominantly northeast–southwest (NE–SW), reflecting early Cretaceous rift–rift–transform interactions that segmented the West African Craton (Fitton, 1987).

The stratigraphic succession of the Gongola Basin, a sub-basin within the UBT, records a complex depositional history transitioning between continental and marine environments. From oldest to youngest, the sequence includes the Bima Formation, Yolde Formation, Pindiga Formation, Gombe Formation, and the Kerri-Kerri Formation. Each unit displays unique lithological characteristics and represents distinct depositional settings shaped by tectonic and paleoenvironmental changes throughout the Cretaceous to Paleocene.

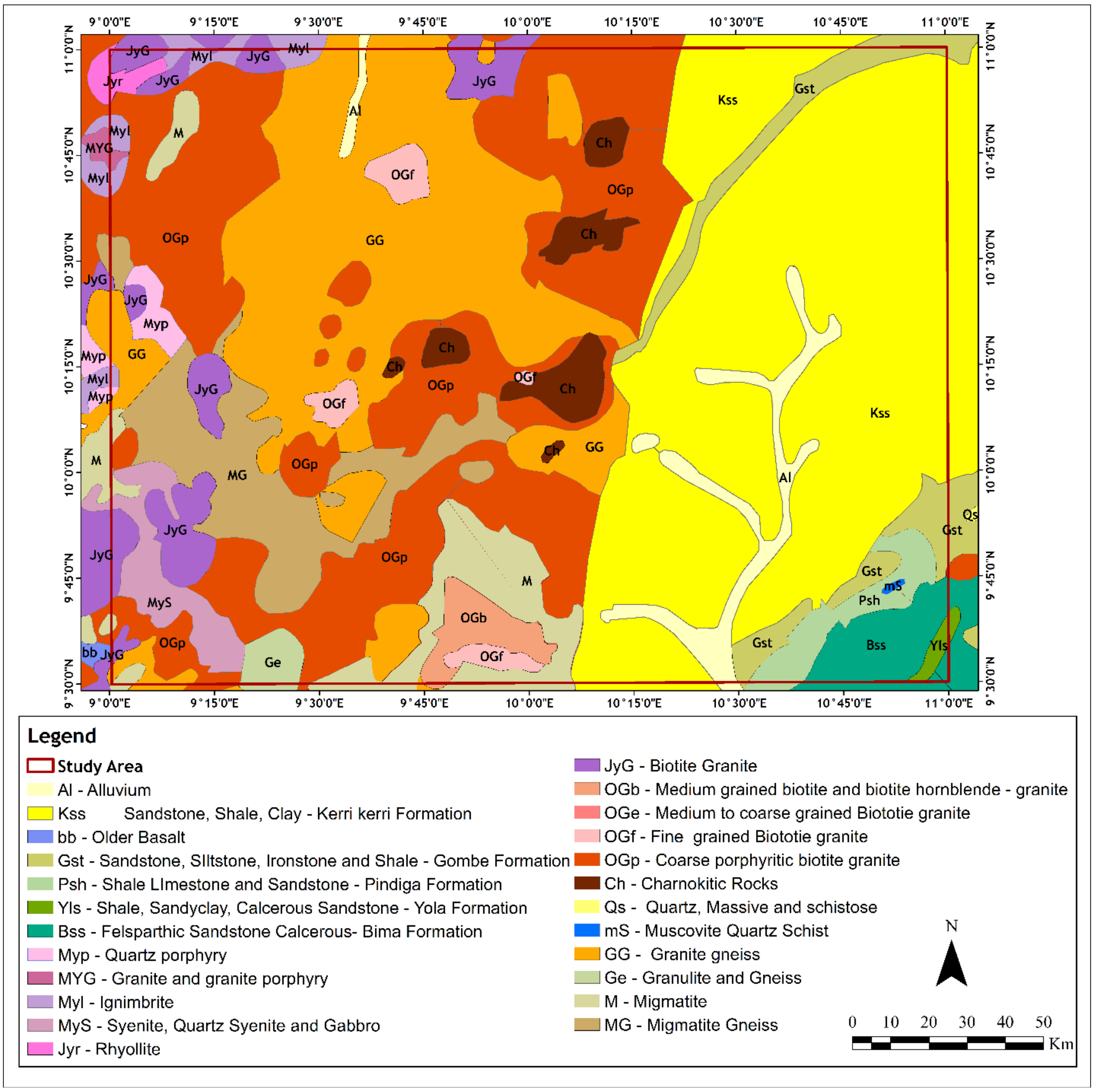

Fig. 2. Geological map of the study area

3.1 Bima Formation (Late Aptian–Early Albian)

The Bima Formation represents the earliest Cretaceous deposit in the Gongola Basin and lies unconformably on the Precambrian Basement Complex (Nwojiji *et al.*, 2014; Shettima *et al.*, 2020). It is stratigraphically subdivided into Lower, Middle, and Upper members. The Lower Bima comprises conglomeratic sands and gravelly sandstones, indicative of fluvial and lacustrine depositional environments (Hamis *et al.*, 2024). The Upper Bima is characterized by trough and tabular cross-bedded sandstones interbedded with clay, suggesting sedimentation in a braided river system.

3.2 Yolde Formation (Cenomanian)

The Yolde Formation overlies the Bima Formation and marks the onset of a significant marine transgression in the Gongola Basin. It is composed of alternating sandstones and shales, where the sandstones are fine to medium-grained and light brown in color, and are intercalated with shale and limestone layers (Garba *et al*., 2024). This lithological assemblage reflects a transitional depositional environment from continental to shallow marine conditions.

3.3 Pindiga Formation (Late Cenomanian–Santonian)

The Pindiga Formation records full marine conditions and is primarily composed of marine shales, siltstones, and limestones. Notable members include the Kanawa Member, characterized by marine shales and limestones, and the Fika Member, consisting of deep marine blue-black shales (Nwojiji *et al*., 2013; Didi *et al*., 2024). These facies indicate a gradient of marine environments from shallow shelf to deeper offshore settings (Hamis *et al*., 2024).

3.4 Gombe Formation (Maastrichtian)

The Gombe Formation overlies the Pindiga Formation and signifies a return to continental sedimentation. It consists of sandstones and siltstones, displaying lithofacies such as alternating beds of silty shale and fine to medium-grained sandstones, along with brick-red sandstones exhibiting tabular cross-bedding (Nwojiji *et al*., 2013). These features suggest deposition in fluvial channel and deltaic systems.

3.5 Kerri-Kerri Formation (Paleocene)

The Kerri-Kerri Formation, the youngest in the stratigraphic sequence, unconformably overlies the Gombe Formation (Nwojiji, *et al*., 2014). It comprises continental conglomerates, sandstones, siltstones, and clays deposited in fluvial to lacustrine environments (Adegoke *et al*., 1986; Abubakar *et al*., 2022). Formation thickness varies considerably, reaching up to 320 meters in tectonically active zones (Mohammed *et al*., 2024).

3.6 Discussion

This stratigraphic succession illustrates the complex depositional and tectonic history of the Gongola Basin, shaped by significant sea-level fluctuations and rift-related tectonic events from the Cretaceous to the Paleocene.

Beneath these sedimentary sequences lies the Pan-African Basement Complex (ca. 600–500 Ma), composed of high-grade migmatite–gneiss complexes and metasedimentary belts intruded by the Older Granite Suite—including equigranular biotite-hornblende granites, biotite granites, charnockites, quartz syenites, and subordinate gabbroic intrusions (Schlüter, 2008; Obaje, 2009). These plutons, emplaced during the late stages of the Pan-African orogeny, exhibit a wide variety of textures from porphyritic to medium-grained hornblende-biotite granites (Oyebamiji *et al*., 2024).

Intruding this older basement are the Younger Granite ring complexes (ca. 200–120 Ma), which include granite porphyries, rhyolitic ignimbrites, and microgranites. These intrusions, formed under anorogenic conditions, exploited pre-existing NE–SW and NW–SE basement lineaments to develop zoned ring dykes and cone sheets (Schlüter, 2008).

Geochemically, the Younger Granites are enriched in radiogenic heat-producing elements such as uranium (U), thorium (Th), and potassium (K), with heat production rates reaching up to 3.35 $\mu W/m^3$ (Yusuf *et al*., 2023). Heat flow measurements in the adjoining Benue Trough reveal values between 70–90 mW/m^2, which are anomalously high for a cratonic region. These values are attributed, in part, to radiogenic heat generation within the granitic intrusions (Salako *et al*., 2020).

4.0 Conclusion

This study has demonstrated the significant geothermal potential of Northeastern Nigeria through geological evaluation and the digitization of regional geological maps using GIS. The integration of diverse lithological units—ranging from Precambrian basement rocks to Cretaceous and Tertiary sediments, as well as Tertiary–Quaternary volcanic rocks and uranium-enriched granitic intrusions—provides compelling evidence for an active or recently active geothermal regime. The identification of key geothermal indicators such as hot springs, high heat-producing granites, tectonic structures, and anomalous heat flow values reinforces the region's suitability for geothermal energy development. The use of GIS-based digitization enhanced the spatial representation, accessibility, and analytical capabilities of geological data, creating a dynamic and queryable geodatabase that supports geothermal prospecting. These findings lay the groundwork for targeted geophysical surveys and further exploration efforts in the region.

4.1 Recommendations

1. **Geophysical Surveys**: Detailed geophysical investigations (e.g., magnetotelluric, resistivity, and heat flow measurements) should be carried out in identified hotspots to validate subsurface geothermal reservoirs.
2. **Geochemical Analyses**: Hydrochemical and isotopic studies of hot springs and groundwater should be undertaken to assess subsurface temperatures and reservoir characteristics.
3. **Exploratory Drilling**: Pilot drilling in high-potential zones is recommended to evaluate geothermal gradients and fluid flow properties.
4. **Policy and Investment**: Government and private sector stakeholders should prioritize geothermal energy in Nigeria's renewable energy agenda, encouraging investment and infrastructure development.
5. **Capacity Building and Data Sharing**: Institutions should promote training in geothermal technologies and ensure open access to geoscientific datasets to facilitate research and development.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

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Authors' Contribution

Both authors were involved in the design of the work, as well as the field and bench work. The manuscript was jointly written by both authors.