Journal of Scientific and Human Dimensions
مجلة الأبعاد العلمية والإنسانية
ISSN: 3106-1702
Volume 2, Issue 3, 2026 Pages: 950-961
Journal homepage: https://jshd.com.ly/index.php/jshd/en

Spatial Distribution, Geological Controls, and Sustainable Exploration Framework for Copper Mineralization in Libya: A GIS-Based Preliminary Assessment

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التوزيع المكاني والضوابط الجيولوجية وإطار الاستكشاف المستدام لتمعدن النحاس في ليبيا: تقييم أولي باستخدام نظم المعلومات الجغرافية

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Received: June 27, 2026	Accepted: August 25, 2026	Published: September 16, 2026

Abstract:
Although Libya has several geodynamic settings favorable for copper mineralization, its metal endowment potential has been less studied than its hydrocarbon resources. This study provides a basis for future copper mineral exploration studies and performs an initial analysis of potential areas for copper mineralization using a GIS-based approach. A geographic information system was constructed using digitalized topographic data, structural data, mineral occurrence data, and geological data. For the identification of prospective areas with high, moderate, and low exploration potential, a set of geological units was selected, large sedimentary basins were isolated, and Precambrian basement rocks were identified. Moreover, an inventory of volcanic rocks, fractures, and copper mineralization occurrences was performed. The results of the analysis demonstrated that northwest Libya (Ghadames–Nalut) and Kufra Basin have a moderate potential for exploration. Copper mineralization in Libya is mainly concentrated in the areas of the SW and SC, including the Precambrian basement rocks, Tibesti–Haruj, and the Murzuq Basin. Thus, these promising areas are associated with the tectonic structures and cover only partly by sedimentary rocks. In central and northern Libya, copper occurrences are rarely found, which may be due to both a lack of interest in their exploration and their actual scarcity. The report provides a conceptual framework for geological and environmental research in the context of sustainable development, recognizing community life, economic impact, governance, innovation, and ecological integrity. The study aims to provide a regional overview of copper exploration in Libya to support future geological, geochemical, geophysical, remote sensing, and exploratory drilling activities. Sustainable copper exploration and development in Libya will help the country achieve economic sustainability by 2040.

Keywords: Copper ores, Spatial Distribution, Mineral Exploration, Sustainable Development, Libya.

الملخص

على الرغم من تمتع ليبيا ببيئات جيوديناميكية مواتية لتكوّن تمعدنات النحاس، إلا أن إمكاناتها من الموارد المعدنية لم تحظَ بنفس القدر من الدراسة والبحث مقارنة بمواردها الهيدروكربونية. وتُشكل هذه الدراسة أساساً لأعمال التنقيب المستقبلية عن النحاس، حيث تقدم تحليلاً أولياً للمناطق المحتملة لوجود تمعدنات النحاس باستخدام نهج يعتمد على نظم المعلومات الجغرافية. وقد تم بناء نظام للمعلومات الجغرافية بالاستناد إلى بيانات طبوغرافية وهيكلية وجيولوجية، بالإضافة إلى بيانات حول مواقع التمعدن. ولتحديد المناطق الواعدة ذات احتمالات التنقيب العالية والمتوسطة والمنخفضة، تم اختيار مجموعة من الوحدات الجيولوجية، وعزل الأحواض الرسوبية الكبيرة، وتحديد صخور القاعدة التي تعود إلى حقبة ما قبل الكمبري؛ كما شمل العمل حصر الصخور البركانية والصدوع ومواقع تمعدن النحاس. وأظهرت نتائج التحليل أن شمال غرب ليبيا (منطقة غدامس-نالوت) وحوض الكفرة يتمتعان باحتمالات تنقيب متوسطة، في حين تتركز تمعدنات النحاس في ليبيا بشكل رئيسي في المناطق الجنوبية الغربية والجنوبية الوسطى، بما في ذلك صخور القاعدة (ما قبل الكمبري)، ومنطقة تبستي-هاروج، وحوض مرزق. وترتبط هذه المناطق الواعدة بالبياى التكتونية، وتتميز بكونها مغطاة جزئياً فقط بالصخور الرسوبية. أما في وسط وشمال ليبيا، فتُعد حالات ظهور النحاس نادرة، وقد يُعزى ذلك إما إلى نقص الاهتمام بالتنقيب عنها أو إلى ندرتها الفعلية. ويقدم التقرير إطاراً مفاهيمياً للبحوث الجيولوجية والبيئية في سياق التنمية المستدامة، مع مراعاة الجوانب المتعلقة بحياة المجتمع، والأثر الاقتصادي، والحوكمة، والابتكار، والسلامة البيئية. وتهدف الدراسة إلى تقديم لمحة عامة إقليمية حول التنقيب عن النحاس في ليبيا لدعم الأنشطة المستقبلية في مجالات الجيولوجيا، والكيمياء الجيولوجية، والجيوفيزياء، والاستشعار عن بعد، والحفر الاستكشافي. ومن شأن عمليات التنقيب عن النحاس وتطويره بشكل مستدام في ليبيا أن تساعد البلاد على تحقيق الاستدامة الاقتصادية بحلول عام 2040.

الكلمات المفتاحية: خامات النحاس، التوزيع المكاني، التنقيب عن المعادن، التنمية المستدامة، ليبيا.

1. Introduction

Copper ores are naturally occurring rocks or mineral aggregates that contain economically viable amounts of extractable copper. Native copper is uncommon, and most copper, in the form of sulfides, oxides, carbonates, and silicates, occurs in various types of ore. Copper ores contain metallic copper, and it can be extracted from them for use in electrical wiring, electronics, construction, transport, energy production, and elsewhere (Guilbert and Park, 1986; Robb, 2005; Sillitoe, 2010). Numerous authors have assessed copper ores in several countries (e.g., Calagari, 2004; Yongqing et al., 2008; Pour and Hashim, 2011; Cioacă et al., 2014; Ochoa-Landín et al., 2017; Mernagh et al., 2020; Liu et al., 2023; Wang et al., 2026).

Libya is characterized by a wide range of geological formations that start from the Precambrian rocks in the south and are represented by Paleozoic, Mesozoic, and Cenozoic sedimentary rocks in the central and northern parts of the country. The main geological structures and tectonic elements include Ghadames Basin, Murzuq Basin, Kufra Basin, Sirte Basin, Gargaf Arch, Tibesti-Haruj uplift, and many others (Fig. 1). The processes of uplift, subsidence, faulting, tilting, and unconformity have had a significant impact on the geology of Libya. In spite of such a broad range of deposits, metal exploration remained underprioritized for the vast majority of the time, compared to hydrocarbons. Thus, the United States Geological Survey (USGS) accounted for all of Libya's metal resources (Goudarzi, 1970), while subsequent discoveries and assessment reports reiterated the country's geologic variability, which could be used for further mineral resource assessment. However, the country's current national level of mineral resource production does not appear to be high on a global scale, implying that the region has potential but does not possess significant concentrations of economic mineral resources at present.

Geological exploration of copper resources (e.g., Dhahri et al., 2024; Asr, 2026) and archaeological research of the ancient usage of copper (e.g., Duckworth et al., 2015) are the two primary categories of earlier research on copper in Libya.

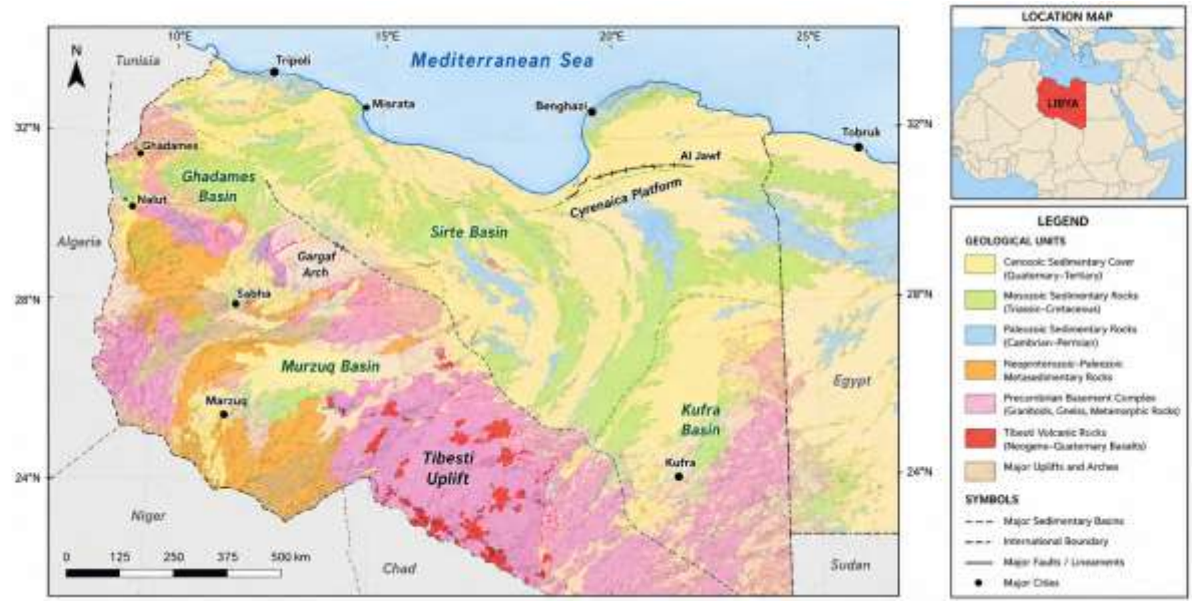

Fig. 1: Location and generalized geological framework of Libya.

An efficient way to investigate the connection between mineral occurrences and geological controls is using spatial analysis. Host-rock type, basement exposure, faults and shear zones, volcanic and magmatic activity, hydrothermal alteration, sedimentary settings, and geochemical anomalies are all very significant aspects in copper exploration. This study incorporates a number of these factors and therefore offers a starting point for locating advantageous areas. Consequently, the goal of this study is to assess the geological importance and spatial pattern of copper favorability, instead of estimating Libyan copper reserves. The specific objectives are: (1) To examine the geographical pattern of mapped copper occurrences, prospects, and geochemical anomalies; (2) To investigate the relationship between copper favorability and major geological units ; (3) To evaluate the influence of Precambrian basement rocks, volcanic terrains, sedimentary basin margins, and structural zones; (4) To identify regions showing relatively high, moderate, and low preliminary exploration potential; (5) To compare the geological characteristics of the principal prospective regions, including southwestern Libya, the Tibesti region, Murzuq Basin margins, northwestern Libya, and the Kufra region; (6) To establish a preliminary framework for future GIS-based mineral prospectivity mapping; and (7) To recommend geological, geochemical, geophysical, remote-sensing, and drilling investigations required to verify the interpreted targets.

2. Methodology

2.1. Data Compilation: The available geological surveys and published reports were used to prepare regional geological maps, published literature, mineral occurrences, structural features (faults, lineaments) and topography/base maps of Libya.

2.2. GIS Database Preparation: All the data were compiled in a common projection coordinate system and then imported into a GIS software environment as digital data sets.

2.3. Geological Framework Map: The generalized geological map of Libya was prepared by digitizing and displaying the lithology, sedimentary basins, basement complexes, volcanic rocks, prominent faults and other relief features.

2.4 Copper Occurrence Map: The copper deposits and prospects, geochemical anomalies and targets were plotted as point features in the GIS environment. They were extracted from the published reports and literature.

2.5 Spatial Analysis: The spatial arrangement of geological units, basement outcrops, fault corridors, basin margins and mineral occurrences were analyzed in order to delimit areas prospective for copper mineralization.

2.6 Prospectivity Assessment: A qualitative GIS based assessment was carried out based on the presence of suitable host rocks, structural controls, mineral occurrences and geochemical data sets to prioritize the areas for detailed exploration.

2.7 Cartographic Visualization: Finally, the thematic maps were prepared using a standard symbolization, legend, north arrow, scale bars, grid lines, inset figures and other features for effective illustration and publication.

3. Results and Discussion

3.1. Preliminary Evaluation

Placed together with the nation's key geological units, sedimentary basins, faults and shear zones, and copper-potential areas, Fig. 2 finally represents the distribution pattern of reported and interpreted copper mineralization occurrences for Libya. It should be noted that this map cannot be considered as a definitive list of economically viable copper resources but is used to provide a basis for research. Indeed, based on the accompanying paper, copper-related points, deposits, prospects, occurrences, geochemical anomalies, and targets needing verification are included in the map. Thus, the map clearly demonstrates the significant variance in the areal distribution of copper occurrences, with the highest concentration found in the countries western, south-western, and southern regions. In turn, central and northern Libya were only marginally associated with copper occurrences. The distribution pattern was approximately similar to the areas of outcrops of Precambrian basement rocks, intrusive and volcanic rocks, major faults, shear zones, and basin margins. Similarly, the accompanying paper revealed that southern and western Libya had the greatest concentration of copper-target clusters. Hence, instead of identifying a broad regional pattern, it seems that the map shows a strong relationship between individual copper occurrences and tectonic complexity.

It is also essential to evaluate the symbols according to their level of certainty (Table 1). Due to the fact that finding copper mineralization or geochemical anomaly does not always guarantee the presence of a mineral deposit, this information is highly relevant. It should also be noted that before assessing the economic significance, it is necessary to acquire data on geological, mineralogical, geochemical, grade, and tonnage as well as drilling information.

Northwestern Libya, in particular the Ghadames Basin and Ghadames-Nalut region, is characterized by a significant number of copper symbols. Fig. 2 represents the variety of copper-related symbols: (1) Major copper deposits; (2) Copper prospects; (3) Copper occurrences; (4) Geochemical anomalies; and (5) Items requiring additional research. The pattern reflects a transition from basement/structural provinces to sedimentary cover. The report suggests that northwest Libya is only a 'limited exploration province'. Therefore, the relative absence of copper findings compared to southern Libya may be explained by the combination of limited exploration, sediment cover, insufficient geochemical surveys, and concealed mineralization.

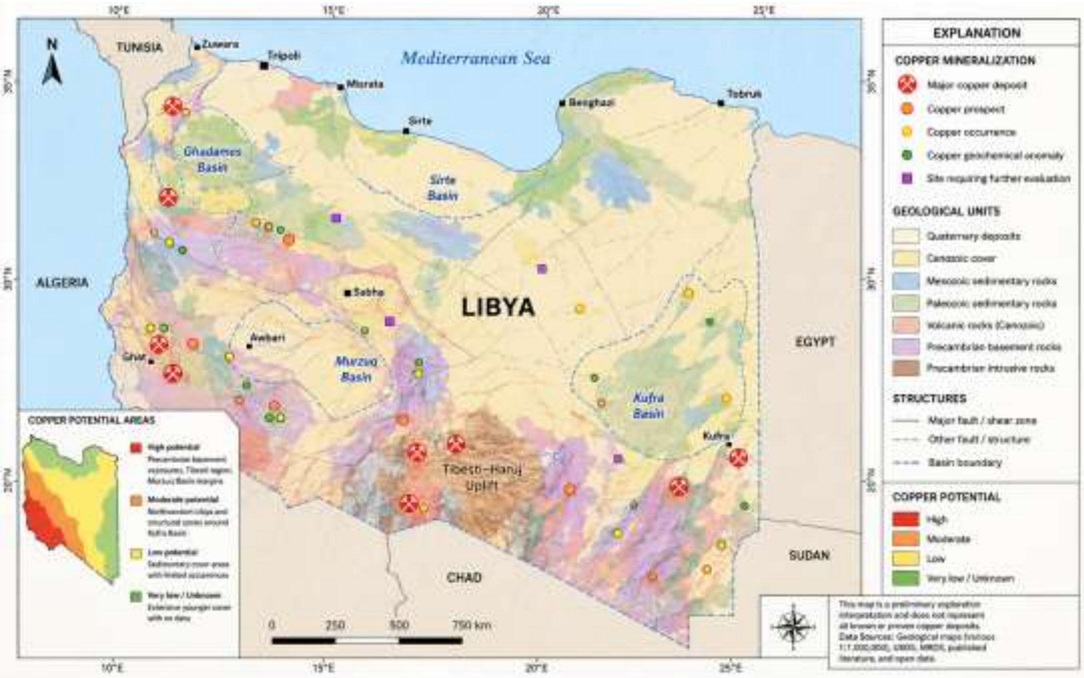

Fig. 2: Spatial distribution map of copper ores in Libya.

Table 1: Description and interpretation of the spatial distribution map symbols used for copper mineralization in Libya

Map symbol	Meaning	Interpretation
Major copper deposit	Strongest reported evidence	Highest priority, but still requires independent verification
Copper prospect	Favorable geological/mineral indication	Requires additional exploration
Copper occurrence	Reported or interpreted copper mineralization	Economic significance remains uncertain
Geochemical anomaly	Elevated Cu or associated elements	Requires analytical and field confirmation
Site requiring further evaluation	Location needing investigation	Insufficient evidence for classification

There is a noticeable concentration of copper-related symbols in the southwest of Libya, near Ghat, Awbari, and the western part of the Murzuq Basin. One of the main trends found on the map is associated with this area. It is also rich in structures of various kinds, as well as Precambrian basement and intrusive rocks. Copper mineralization prospects are predicted to be significant in the region. The report notes that the discovered concentration of copper symbols alone is not enough to confirm the resource's potential. However, the area of the basement in the southwest was highlighted as a priority for further exploration. Therefore, it is necessary to conduct detailed geological, geophysical, and exploratory work, study rock, soil, and sediment properties.

Due to the extensive number of copper-related occurrences found around its periphery and close to basement rocks, the Murzuq Basin holds a particular interest. Based on the map, it is possible to suggest that mineralization is focused in the basin margins and structurally complex belts. This localization can be explained by the fact that such zones may include various geological structures that play an important role in mineralization processes. These structures may include (1) Faults and fractures; (2) Basement discontinuities; (3) Lithological contacts; (4) Intersections of structures; and (5) Possible pathways for mineralizing solutions. Therefore, the study suggests that the Murzuq Basin has a moderate to high discovery potential due to the presence of multiple geological structures associated with mineralization. It was claimed that such areas should be prioritized during further research, as they may include either hydrothermal or sediment-hosted copper occurrences.

Another region considered interesting for exploration is the Tibesti–Haruj Uplift. The uplift and the area to the south have several symbols associated with copper occurrences. In particular, Precambrian basement, volcanics, intrusives, prominent structural elements, and possible magmatic-hydrothermal systems are observed in the geological sections of the area. The report classifies the Tibesti region as a priority due to the concentration of copper targets near fault zones, volcanic structures, basement outcrops, and various types of alteration. Hydrothermal vein deposits, mineralization of a structural nature, magmatic-hydrothermal systems, volcanogenic deposits, and supergene enrichment of copper are several of the promising models suggested for the area.

The Kufra Basin and southeast Libya contain several copper occurrences, prospects, and anomalies. These are scattered throughout the basin compared to the discoveries in southwest Libya. Nonetheless, the mineralized provinces could be found along structural and basin-margin faults. As per the report, the most promising locations for further copper exploration in southeast Libya are (1) Basin-margin faults; (2) Basement highs; (3) Structural intersections; (4) Sandstone and shale; (5) Successions; and (6) Hydrothermal alteration. Thus, it can be concluded that the Kufra basin has a moderate potential for copper exploration, but the possibility cannot be accurately defined due to insufficient geochemical and drilling data.

The central Sirte Basin and most part of northern Libya have fewer copper symbols than other areas. There are also fewer reported copper occurrences because the region is predominantly covered by Cenozoic, Mesozoic, and Paleozoic sedimentary rocks. However, the fact that certain regions or geological structures do not appear on the map does not mean that they are not present. Geological formations and minerals are often located far below the surface covered by sedimentary layers. The study explains that the possible reason for the absence of copper in the area is due to a lack of exploration and concealment by geological sediments. For this reason, geophysical methods are considered very effective in such cases.

One of the most interesting aspects of Fig. 2 is the apparent relationship between copper occurrences and intrusive and Precambrian basement rocks. Many copper symbols are observed to be located within or adjacent to: Precambrian basement → volcanic belts → large faults/shear zones → intrusive rocks → basin margins. This supports the hypothesis that tectonic and lithological factors play an important role in the distribution of copper deposits in Libya. Notably, the study also identifies sedimentary basin margins, Tibesti rocks, and Precambrian basement as highly prospective areas for copper mineralization.

Four potential areas for copper exploration are identified on the map, based on the geological setting and the number of reported copper occurrences: **(1) High potential:** Precambrian basement outcrops, Tibesti area, and the Murzuq basin margins; (2**) Moderate potential:** northwest Libya and particular structures within the Kufra basin; **(3) Low potential:** large areas underlain by sedimentary cover that have only few copper occurrences reported; and **(4) Very low/unknown potential:** regions with extensive cover of recent sediments and limited copper data. Thus, the map should not be interpreted as an assessment of copper resources but rather as a prioritization of exploration targets.

Fig. 3 suggests the most promising areas where further research efforts should be oriented. The Southwestern Precambrian basement should be given the highest priority. Then, the Tibesti–Haruj area is considered high priority, while the Murzuq Basin margins are also prioritized as a high discovery potential zone. The Northwestern Libya/Ghadames–Nalut is a moderate priority area, and the Kufra Basin margins are also regarded as a moderate priority zone. The paper recommends applying high-resolution magnetic and radiometric surveys, IP/EM geophysics, ASTER and Sentinel-2 remote sensing, soil and stream-sediment geochemistry, GIS-based prospectivity analysis, and machine learning methods to delineate targets.

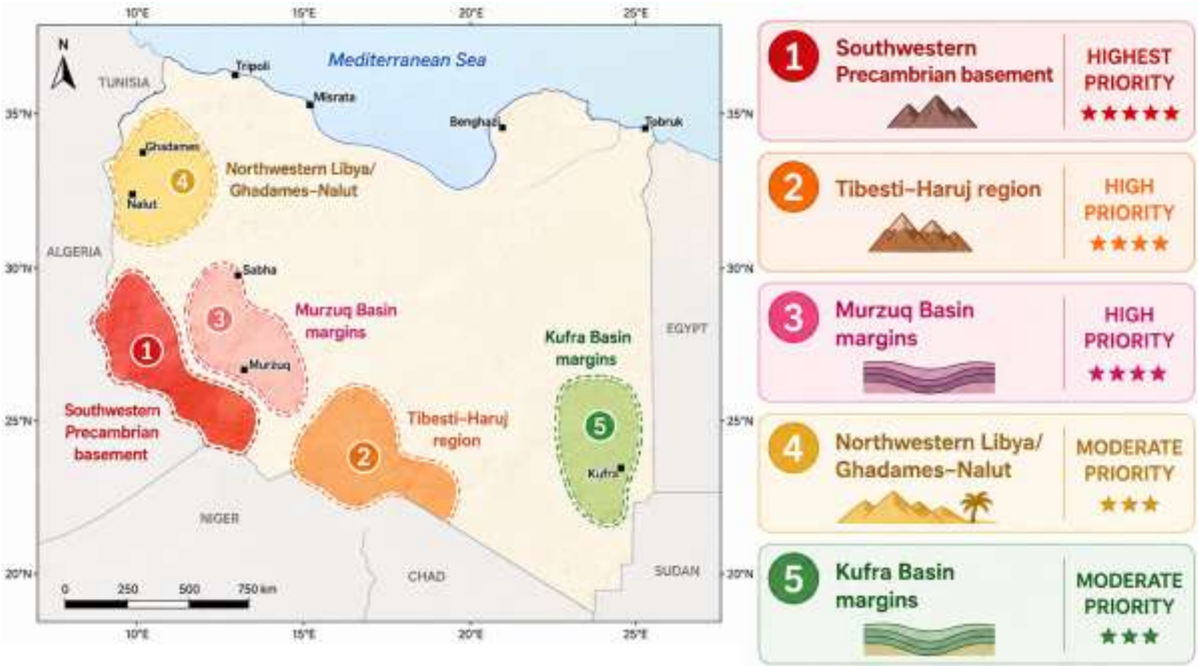

Fig. 3: The key priority areas for copper deposits in Libya.

3.2. Sustainable Exploration

A conceptual framework for sustainable exploration of copper deposits is presented in Fig. 4. Within a single conceptual model, exploration geology, ecological sustainability, social responsibility, economic feasibility, governance, and technological development, as well as strategic resource development considerations, have been integrated. The key message is that responsible exploration and sustainable resource development, as well as long-term socio-economic benefits, should be the objectives of future copper exploration in Libya rather than the mere identification of resources.

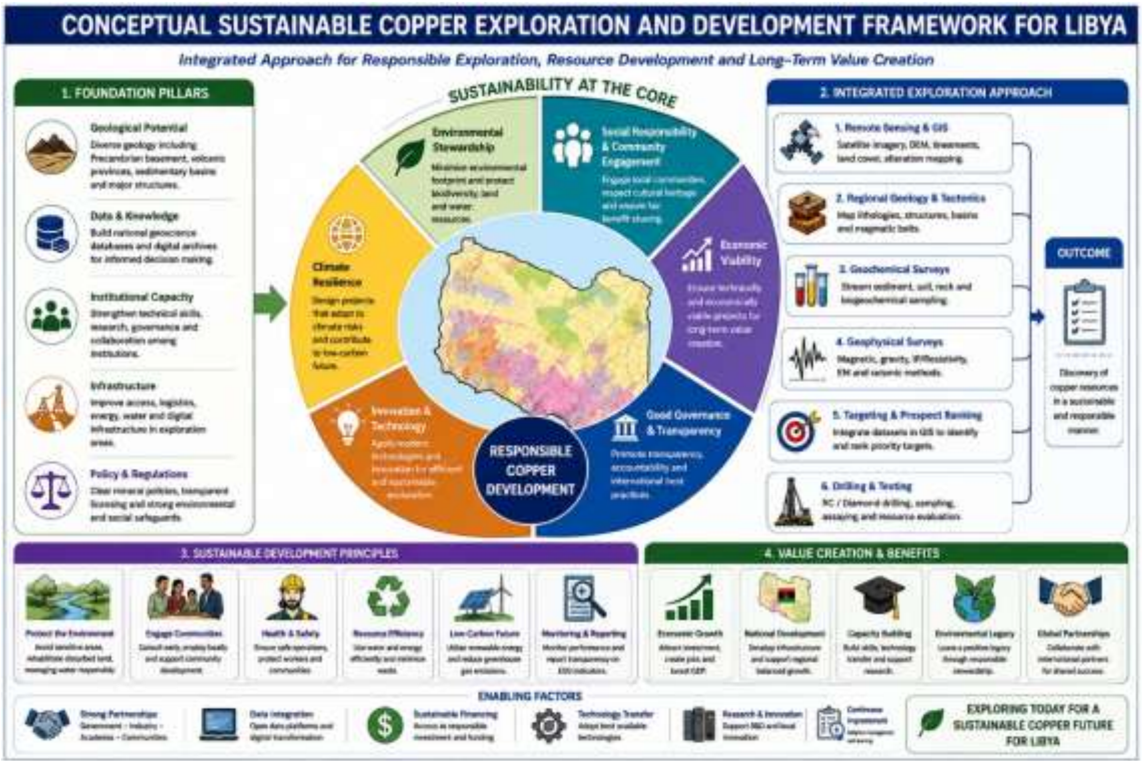

Fig. 4: Conceptual sustainable copper exploration and development framework for Libya.

Five key conditions for sustainable copper exploration are outlined on the left side of the figure. The geological potential of Libya, as a region with a wide range of geological environments, from Precambrian basement rocks, volcanics, and sedimentary basins to various structural provinces, is recognized as a critical factor. A sound knowledge of potentially prospective geological settings in Libya underpins the identification of targets for copper exploration. The need to develop national capacities in geoscience information is determined by data and knowledge. It reduces uncertainties in exploration and contributes to informed decision-making, facilitated by accessible digital databases, as well as comprehensive geological, geochemical, geophysical, and remote sensing information. Institutional capacity was identified as a priority area for enhancing the technical expertise, research capabilities (including governance), and collaborative activities of Libyan institutes. Another important finding was the need to upgrade infrastructure (transport, logistics, energy, water, and digital) to support exploration activities, particularly in remote areas and in the southern and southeastern parts of the country, for example. Finally, legislation, through mineral policies, licensing frameworks, and protection mechanisms for ecosystems and communities, emerges as an essential pillar by providing the institutional framework for responsible mineral exploitation. By focusing on responsible copper exploration and development, the central part of the figure is linked to six key sustainability pillars: governance, institutional strengthening, financing, infrastructure, social environment, and geological environment.

The framework is focused on reducing the impact of copper exploration and development on the environment. In particular, this refers to the need to preserve biodiversity, land, water, and wilderness areas. This priority is set as a high priority because many of the sub-regions where copper can be found are located in ecologically sensitive desert and mountain areas. This is particularly important for Libya, given the potential for copper mining in desert and mountain areas. The framework also highlights the importance of engaging local communities in the exploration process. In this context, respect for cultural heritage, equitable sharing of benefits, and consultation with local communities is identified as an important principle. In other words, it is necessary to involve local communities in the benefits of mining, not just expect them to accept the consequences of mining operations.

Technical and financial viability are also important criteria for copper mines. Rather than searching for resources without considering resource economics, infrastructure, capital investments, and market conditions, the strategy focuses on project realization that ensures sustainable economic benefits. Accountability, transparency, and implementation of international standards are essential aspects of sustainable development. They are particularly relevant for natural resources, as they contribute to responsible governance, reporting, verification, environmental permits, mineral leases, and concessions. Exploration efficiency can also be increased by using modern technologies like GIS, geomining, remote sensing, geochemical surveys, geophysics, database technologies, and other innovative exploration methodologies. This will help identify targets accurately and avoid additional expenses and disturbances associated with excavation.

The framework incorporates climate resilience, thus emphasizing processes that are adaptable to the hazards brought about by climate change and that contribute to carbon emission reduction while promoting the creation of a copper deposit exploration scheme and the identification of mineral prospects that considers copper's broader implications beyond mineralization.

A six-step exploration and assessment workflow is presented on the right side in Fig. 4: (1) Remote sensing and GIS; (2) Regional geology and tectonics; (3) Geochemical surveys; (4) Geophysical surveys; (5) Targeting and prospect ranking; and (6) Drilling and testing. The six principles that underpin exploration and, by implication, potential mine development are articulated in the lower part of the figure (Table 2). Generally, the principles suggest that sustainability should be considered throughout the entire process of mineral exploration and development, and not as an afterthought once a mineral deposit has been found.

Table 2: Sustainable development principles for responsible copper exploration and development in Libya

Principle	Main objective
Protect the environment	Avoid sensitive areas, rehabilitate disturbed land, and manage water responsibly
Engage communities	Consult local communities and support locally appropriate development
Health and safety	Protect workers and surrounding communities
Resource efficiency	Use water and energy efficiently and minimize waste
Low-carbon future	Increase renewable-energy use and reduce greenhouse-gas emissions
Monitoring and reporting	Continuously monitor performance and transparently report ESG indicators

Five possible consequences of responsible copper development are also identified by the framework: (1) Economic growth; (2) National development; (3) Capacity building; (4) Environmental legacy; and (5) International relationships. These advantages show that copper development is seen as a possible part of larger national economic and technological development rather than just as a mining activity.

The exploratory phase and sustainable development are connected by a number of facilitating factors at the bottom of the figure. These include the following: (1) Strong partnerships; (2) Data integration; (3) Funding; (4) Technology transfer; (5) Research and innovation; and (6) Continuous improvement. These factors are critical to copper prospecting and should not be overlooked. The geological factor is necessary but is not sufficient for sustainable copper development. In addition to geological resources, financial, institutional, technical, scientific, and social resources are required to ensure sustainable exploration, development, and utilization of copper.

The conceptual predictive map (Fig. 5) depicts the scenario where copper exploration and development serve as key economic growth drivers for Libya by 2040. It can be noted that the country's various regions are differently integrated into the economy. Some are projected to make greater overall contributions based on their geological characteristics, the extent of exploration and mining activities, associated processing, infrastructure development, and sustainable resource management. Thus, the western part of Libya, mainly the Precambrian basement, is considered the most economically beneficial region. Compared to other areas in the country, it can provide the highest copper endowment, host the most significant copper occurrences, and possess the best prospects for exploration and mining activities. Consequently, it is likely to become the most significant copper-producing region in Libya, generating economic benefits for the mining industry, processing plants, jobs, and exports. Meanwhile, the Tibesti-Haruj uplift and the Murzuq Basin margins are projected to be the secondary economic drivers through extensive exploration and copper production and support industries development. Enhanced infrastructure development and the establishment of processing facilities will also contribute to the overall economic growth of Libya. The Ghadames-Nalut region and the Kufra basin margins are anticipated to be a moderate economic factor at the national level. Although these areas are characterized by good geological settings, further assessments, including geological, geophysical surveys, geochemical analyses, and resource characterization, are required before any substantial economic impact is realized. Moreover, this economic impact is projected to be lower than that of other regions in the country. The map also indicates that connecting mineral resources with transportation networks, processing, and export hubs plays a critical role in ensuring copper development shapes Libya's economic growth in the future. This is primarily related to the fact that processed copper products carry much higher economic value than raw materials. Therefore the establishment of infrastructure, including transportation routes and processing facilities, should be prioritized to support the regional economy and facilitate export opportunities. As a result, more significant economic benefits from copper production will accrue to the state while supporting the regional economy. The value chains will comprise mining, processing, manufacturing, and export activities, which will generate economic benefits and promote sustainability at local and national levels. Furthermore, it must be noted that while copper development has the potential to diversify the national economy, it will also bring vital social benefits to Libya. It includes job opportunities, enhanced export revenue, regional economic development, expanded industrialization, and cleaner energy production, among others. These benefits are likely to accrue from investment in sustainable mining operations that follow best practices and principles of sustainable mining, responsible governance, resource management, and community engagement while promoting economic growth and regional development. It is essential to note that the conceptual predictive map should be viewed as an informative tool that provides a theoretical basis for future economic growth prospects rather than a primary source for making economic decisions. This is because the potential economic contribution will mainly depend on the number of copper deposits discovered and their proven endowment, among other factors. Additionally, it is important to consider the extent to which these resources will be explored and developed to meet national economic growth needs. The market potential and demand for copper, government policies, regulatory frameworks, investment initiatives, regional stability, political security, and other factors are also critical determinants of the economic impact and must be considered. Thus, the conceptual predictive map (Fig. 5) should be used as an informative tool that provides an initial indication of the potential economic impact that could be realized if copper exploration and development are prioritized using the described economic growth principles.

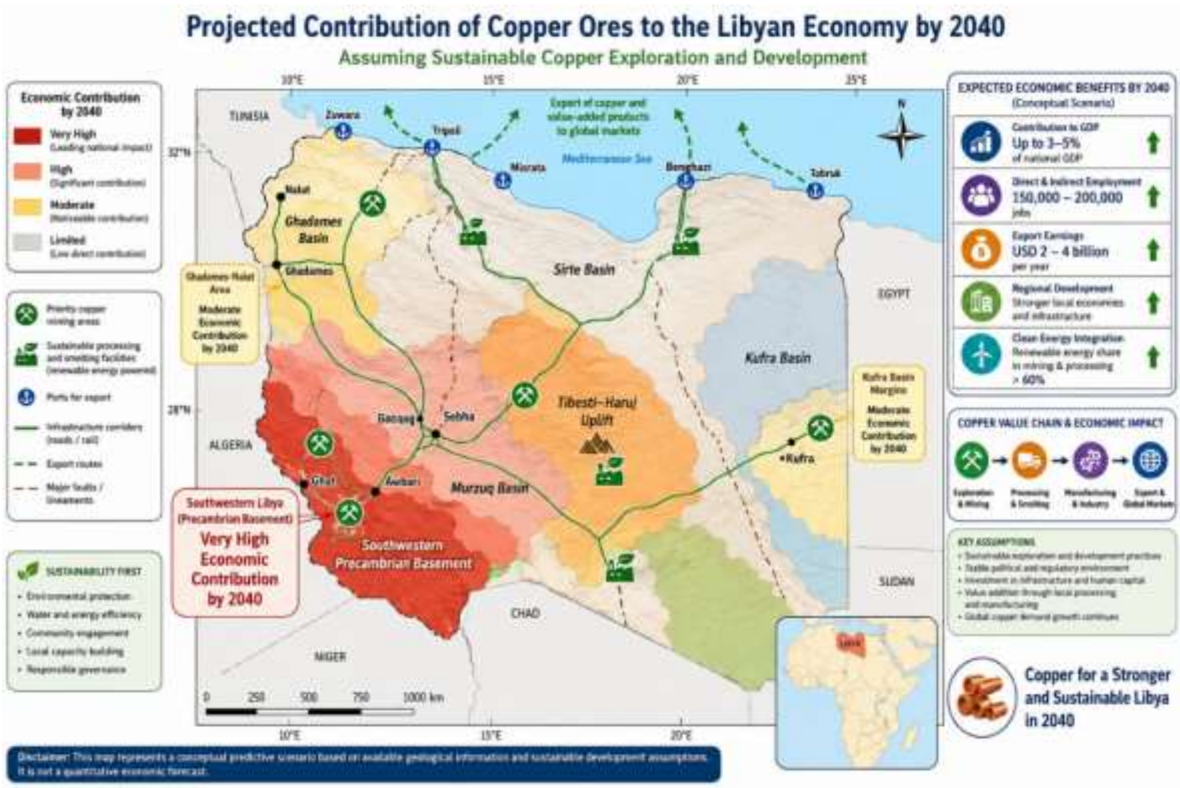

Fig. 5: Conceptual predictive map illustrating the projected contribution of sustainable copper exploration and development to the Libyan economy by 2040.

4. Conclusions and Recommendations

The key conclusions of this study can be grouped into the following points:

(1) The integration of geological, structural, and mineral occurrence data in the GIS environment allowed for the identification of the priority areas for copper mineralization in Libya.

(2) Copper occurrences are associated with Precambrian basement rocks, volcanic rocks, large fault zones, and sedimentary basin margins. This implies that lithology and tectonic structures play a key role in copper mineralization.

(3) The most promising area for copper exploration in Libya is the Southwestern part of the country. In particular, the Tibesti-Haruj uplift and the marginal areas of the Murzuq Basin are highlighted as priority ones. The Ghadames-Nalut area in Northwestern Libya and the marginal areas of the Kufra Basin can be considered as medium-priority targets.

(4) The number of copper occurrences reported in the Central and Northern parts of Libya is insufficient to conclude that these areas are barren. On the contrary, there is a possibility of discovering mineralized zones covered by thick sediments. Therefore, these regions should be explored in detail.

(5) Copper deposits, prospects, occurrences, and geochemical anomalies identified in this study should be regarded as targets for further detailed geological, geochemical, and geophysical assessments, and exploratory drilling. It is necessary to conduct these surveys to confirm the presence of economically viable mineralization.

(6) The sustainable exploration model proposed in this study allows for ensuring that copper exploration activities in Libya will be compatible with environmental, social, governance, economic, and technological goals. This is critical for achieving sustainable mineral resource development.

(7) Sustainable copper exploration and development can become one of the priorities of Libya's economic growth and diversification by 2040.

The following recommendations are proposed to support future copper exploration and sustainable resource development in Libya:

(1) Undertake detailed geological mapping in the southwestern part of the Precambrian basement, Tibesti–Haruj, the flanks of the Murzuq Basin, the Ghadames–Nalut area, and the Kufra Basin to delimit and prioritize copper prospects.

(2) Conduct extensive geochemical surveys, including soil, rock, and stream sediment sampling, to verify the locations of reported copper anomalies and discover new prospects.

(3) Obtain high-resolution airborne geophysical data, such as magnetic, radiometric, electromagnetic, induced polarization, and gravity surveys, to identify and delineate buried mineralized structures.

(4) Apply remote sensing, including ASTER, Sentinel-2, Landsat, and GIS-based data processing and machine learning techniques for mineral prospectivity analysis to prioritize targets for exploration.

(5) Perform exploration drilling in priority areas identified through the above investigations along with the corresponding laboratory analyses to confirm the presence of copper minerals.

(6) Create a national digital database that compiles all of the data gathered during the research to facilitate storage, access, and the use of information by other researchers and support further copper exploration and assessment activities.

(7) Facilitate the cooperation between universities, governmental agencies, geological surveys, and the mining industry to promote knowledge exchange, capacity building, human resources development, and technology transfer, as well as to foster mineral exploration and sustainable mining practices.

(8) Ensure the sustainable development of the mining sector by considering the relevant ESG aspects during the exploration and mining activities. For example, it is essential to minimize the impact of mining on the environment and communities, ensure responsible use of natural resources, promote transparency, and consider the impacts on the environment and local communities during the exploration and mining activities.

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