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Geological Framework and Exploration Potential of Manganese Mineralization in Libya: A Comparative Study of Nalut–Jabal Nafusa, Wadi Urari and Shati Valley

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ABSTRACT

A conceptual prediction framework for assessing the potential for manganese exploration in three important areas—Nalut–Jabal Nafusa, Wadi Urari, and Shati Valley—is presented in this paper. Geological mapping, remote sensing investigation, structural analysis, mineral information, and spatial evaluation of regulating factors impacting manganese mineralization are all included into the methodology. The Nalut–Jabal Nafusa region exhibits potential for fault-controlled mineralization and manganese deposits supported by carbonate. An interesting site connected to structural pathways and sedimentary deposits on the edge of the Ghadames Basin is Wadi Urari. Due to local tectonic features regulating mineral accumulation and iron-bearing Carboniferous strata, the Shati Valley region exhibits considerable promise. The obtained results can serve as an initial guide to the areas of priority exploration, mineral assessments, and geochemical surveys. In addition to the potential mineralization sites, sustainable manganese production can also help Libya achieve economic diversification through processing, creating jobs, and contributing to critical mineral supply chains for hydrogen-based energy systems. However, detailed research, environmental impact assessments, and economic evaluations are required before any significant commercial production can commence.

الإطار الجيولوجي وإمكانات استكشاف تمعدن المنجنيز في ليبيا: دراسة مقارنة لمناطق نالوت-جبل نفوسة، ووادي أوباري، ووادي الشاطئ

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الكلمات المفتاحية
تمعدن المنجنيز
استكشاف المعادن
التعدين المستدام
الاستشعار عن بُعد
نظم المعلومات الجغرافية
ليبيا

الملخص

تستعرض هذه الورقة إطاراً مفاهيمياً تنبؤياً لتقييم إمكانات استكشاف المنجنيز في ثلاث مناطق هامة: نالوت-جبل نفوسة، ووادي اوباري، ووادي الشاطئ. وتتضمن المنهجية المتبعة كلاً من: الخرائط الجيولوجية، ودراسات الاستشعار عن بعد، والتحليل البنيوي، والبيانات المعدنية، والتقييم المكاني للعوامل المتحكمة في تمعدن المنجنيز. وتُظهر منطقة نالوت-جبل نفوسة إمكانات لوجود تمعدن مرتبط بالصدوع ورواسب منجنيز ذات أصل كربونات. ويُعد وادي عراري موقعاً واعداً يرتبط بمسارات بنيوية ورواسب رسوبية عند حافة حوض غدامس. كما تظهر منطقة وادي الشاطئ آفاقاً واعدة للغاية نظراً لوجود سمات تكتونية محلية تتحكم في تراكم المعادن، فضلاً عن وجود طبقات صخرية من العصر الكربوني غنية بالحديد. ويمكن أن تشكل النتائج المحصل عليها دليلاً أولياً لتحديد المناطق ذات الأولوية للاستكشاف والتقييمات المعدنية والمسوحات الجيوكيميائية. وإلى جانب مواقع التمعدن المحتملة، يمكن للإنتاج المستدام للمنجنيز أن يساعد ليبيا في تحقيق التنويع الاقتصادي من خلال عمليات المعالجة، وخلق فرص العمل، والمساهمة في سلاسل توريد المعادن الحيوية اللازمة لأنظمة الطاقة القائمة على الهيدروجين. ومع ذلك، تظل هناك حاجة ماسة لإجراء أبحاث تفصيلية، وتقييمات للأثر البيئي، ودراسات جدوى اقتصادية قبل البدء في أي إنتاج تجاري واسع النطاق.

Introduction

Manganese ores are natural deposits of manganese minerals or rocks with the content of more than 10% of manganese. Manganese is an essential metal due to its strong affinity for oxygen and its ability to improve the properties of other metals. Manganese and its alloys have a wide range of

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applications, with about two-thirds of global manganese production being used directly in the iron and steel industries. Manganese is a critical component of steel as it removes oxygen and sulfur from molten iron, thus improving the strength, hardness, and resistance of steel alloys. Manganese is becoming more important in batteries, fertilizers, chemicals, and other industrial applications. Manganese deposits are rarely simple. They contain various manganese minerals besides oxides, carbonates, silicates, iron minerals, silica, and clay [1-8].

Unlike the extensive studies devoted to iron ore and hydrocarbons, research on manganese ores is poorly represented in the literature. Most of the available information comes from reconnaissance studies carried out at the dawn of exploration. More recent satellite- and GIS-based geochemical and quantitative mineral prospectivity assessments of manganese mineralization in Libya are also scarce. One of the earliest contributions was made by Goudarzi [9] who studied the iron formations in the Shati Valley, Fezzan. While his primary goal was to understand the genesis of major iron ore deposits forming the Shati group, manganese occurrences were also described in detail as they were found associated with the iron ores. In particular, the study area was found to host Carboniferous hematite deposits in which manganese ores were generated during localized enrichment processes along fault zones. Goudarzi [9] postulated that the reason for these enrichments was connected to the Tertiary volcanic activity observed in the region, in particular, the basaltic province of Brach, with magma intrusion being a possible mechanism for introducing manganese into the iron formations through fault structures. Goudarzi [10] reported manganese as one of the minerals in Libya, which was present in the country, but its exploration was limited compared to major iron deposits from the Shati Valley. The areas reported to have manganese occurrences included (1) Northwest Libya or Tripolitania referred to as Jabal Nafusa, (2) Wadi Urari and its surrounding regions, and (3) the Shati Valley in Fezzan, which was found to have manganese deposits alongside iron ore. Manganese was reported to occur as lenses, veinlets, and fracture fills, with some localities having reached up to 23% Mn, although this was not an indication of an average grade of a mine deposit. It is also noted that manganese nodules in the Cambrian Hasawnah Formation, from Jabal Al Hasawnah were first discovered by Jurak [11]. DeYoung [12] regarded manganese in Libya as a strategically important mineral resource. Finally, Dhahri [13] observed that although the country has a geology capable of supporting several metallic mineral deposits, many of them were poorly explored.

The distribution of documented manganese occurrences in the three primary study regions—Nalut–Jabal Nafusa, Wadi Urari, and Shati Valley–Fezzan—is depicted on the geological framework map (Fig. 1). These manganese deposits were found commonly associated with carbonate, iron formations, and tectonic-related geology. The Nalut-Wadi Urari province is underlain by Cretaceous and Jurassic carbonate rocks, where manganese occurrences were observed in fracture zones, karstic features, and iron-stained limestone. Meanwhile, the Shati Valley area has manganese deposits found mostly within Paleozoic-Tertiary iron formations. Moreover, most manganese occurrences were found to be related to major fault systems and lineaments, which may have facilitated the migration of mineralizing solutions.

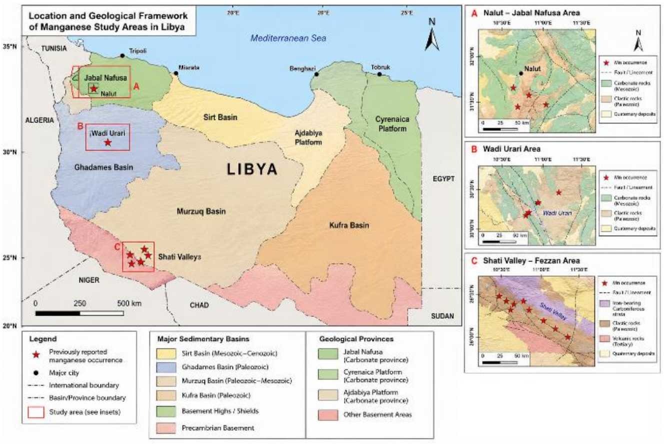

Figure 1: Location and geological framework of the manganese study areas in Libya.

Objective

This study's primary goal is to create a conceptual prediction framework for evaluating Libya's potential for manganese deposits by combining geological data, remote sensing findings, structural investigation, and manganese discoveries. The particular goals are:

(1) Determine the main geological settings conducive to manganese occurrences in Nalut–Jabal Nafusa, Wadi Urari, and Shati Valley.

(2) Assess the relationship between manganese occurrences and lithology, faults, lineaments, and depositional environments.

(3) Develop a conceptual manganese prospectivity map indicating the priority areas for exploration in the study region.

(4) Determine the significance of manganese prospecting for future metal resources and sustainable industrial development in Libya.

(5) Establish a preliminary exploration framework for the future mineralization potential assessment of the study area.

Methodology

Geographic Information Systems (GIS) have demonstrated its capability to provide data; researchers have utilized them in numerous studies across various fields, including engineering, education, environment, agriculture, geospatial science, remote sensing, etc… [14-30].

The authors assessed the potential for manganese mineralization in Libya by interpreting remote sensing and GIS data. First, satellite Sentinel-2 MSI imagery was processed using specific bands, false color composites, band ratios (B4/B2, B4/B3, B11/B8, and B11/B12), and Principal Component Analysis (PCA) to highlight iron oxides, hydroxyls, and manganese mineralization zones. Additionally, a digital elevation model (DEM) was employed to determine geomorphological features (drainage, slope, lineaments), hillshade, and aspects. Then, the obtained data were combined with geological data including rocks, iron formations, carbonate, faults, and manganese occurrences. Finally, manganese prospectivity and target-zone maps were generated using a GIS-based multi-criteria analysis by considering spectral mineralogical anomalies, alteration zones, geological settings, lineament density, and proximity to faults. The final maps highlight areas with high manganese mineralization potential that can be prioritized for field validation, geochemical surveys, and mineral exploration.

Results and Discussion

The Sentinel-2 imagery (Fig. 2) was used to identify the differences in geology. The true-color composites (B4-B3-B2) were constructed to highlight the color of exposed rocks, carbonate units, and landforms while also visualizing drainage patterns. The bright areas with a few vegetation covers indicate regions with significant surface rock outcrops. The false-color composites (B12-B8-B4) were constructed to emphasize the spectral contrast between different lithological units and materials altered by hydrothermal processes. Exposed rock deposits of iron minerals and manganese oxides were detected as unique spectral features in the shortest wavelength infrared band. The altered mineral deposits with hydroxyl groups were highlighted in the composite. It can be observed that the mineralized zones are mainly distributed along the faults and drainage ways, suggesting that these areas were formed by hydrothermal activity.

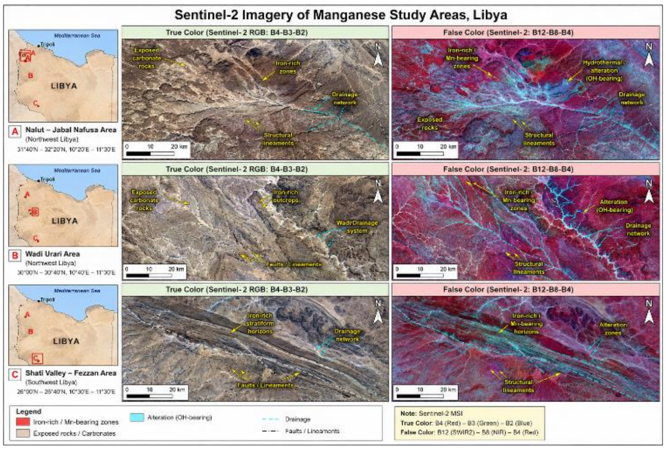

Figure 2: Sentinel-2 true-color and false-color imagery of the manganese areas.

The band-ratio analysis (Fig. 3) was carried out to extract additional information from the image and enhance certain spectral features associated with manganese prospecting: (1) B4/B2 – iron oxide index – pixels with high values of this index indicate areas with a high content of ferric iron, which can be an indicator of iron oxide deposits; (2) B4/B3 – ferric iron enhancement – allows the visualization of areas with increased concentration of ferric iron; (3) B11/B12 – SWIR mineral detection index – used to identify areas with different mineral content; and (4) B11/B8 – alteration index – allows the identification of hydroxylated minerals. The coincidence of spectral responses with the location of manganese occurrences indicates that the spectral indicators of the Sentinel-2 sensor can be used to search for this type of deposit.

The principal component analysis (PCA) is presented in Fig. 4. The PCA separates the image into several bands with different characteristics, which can be seen from the following information about each component: (1) PC1 – 48.6%: it emphasizes the most significant spectral variations, including Fe and Mn anomalies; high PC1 values indicate the exposed mineralized objects and structures; (2) PC2 – 23.1%: related to the alteration mineralization; (3) PC3 – 12.7%: connected to the lithology, in particular, carbonates; (4) PC4 – 7.6%: related to the other lithology variations. Based on the PCA results, it can be concluded that Mn anomalies are distributed along the structural zones and appeared in the places of mineralized rock exposures.

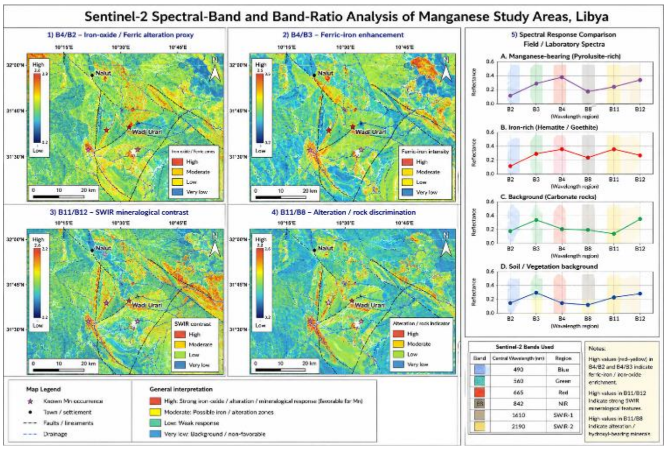

Figure 3: Sentinel-2 spectral-band and band-ratio analysis of the manganese areas.

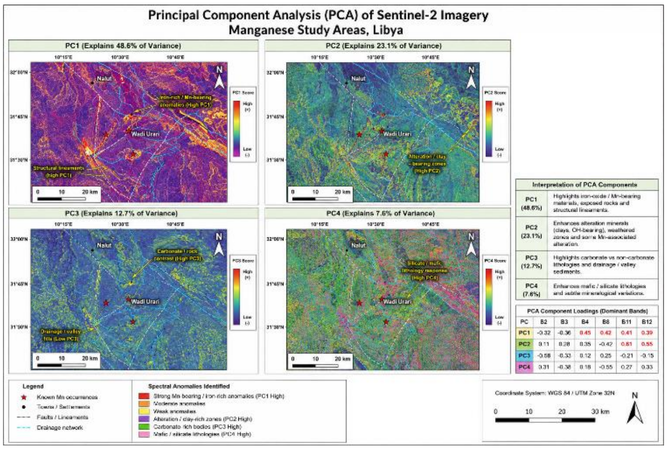

Figure 4: Principal component analysis of Sentinel-2 imagery of the manganese areas.

Fig. 5 presents the anomaly maps of manganese prospecting using spectral indices. The ferric iron anomaly maps (B4/B2) indicate the zones with increased content of iron oxides. These areas are associated with the Wadi Urari and Shati Valley, which are manganese occurrences. This suggests that the manganese prospecting areas are related to the zones of iron oxide enrichment. The hydroxyl alteration maps (B11/B8) were used to detect the altered regions. The altered areas combined with the iron oxide zones were prioritized for manganese prospecting. The manganese prospecting areas were classified into three priority levels. The first priority level (high) includes the regions with significant anomalies of iron and alteration. The second priority level (moderate) includes the areas with partial anomalies that require additional verification. The third priority level (low) represents the regions with minor anomalies or no anomalies at all.

The DEM analysis (Fig. 6) provided information about the topography and identified the main structural elements such as fault planes, fractures, and lineaments. These were found to be strongly associated with the manganese occurrences as the structural features could provide the pathway for mineralization. The slope and aspect maps showed the landform's morphological variability, whereas the lineament density map emphasized the areal distribution of lineaments. The areas with dense structural lineaments and faults were considered as the priority zones for exploration since such structures can serve as the channels for mineralization.

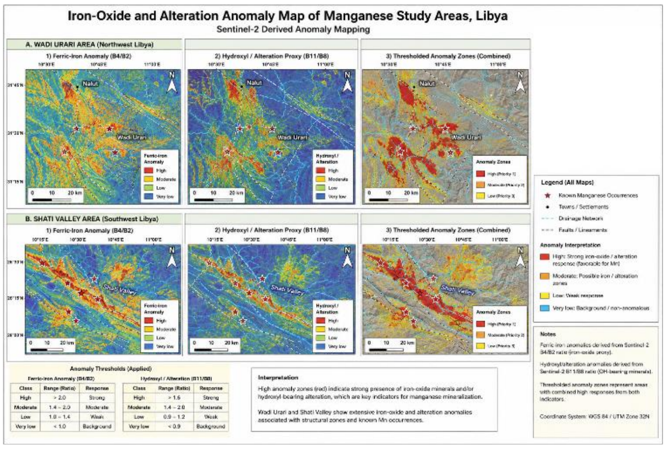

Figure 5: Iron-oxide and alteration anomaly map of the manganese areas.

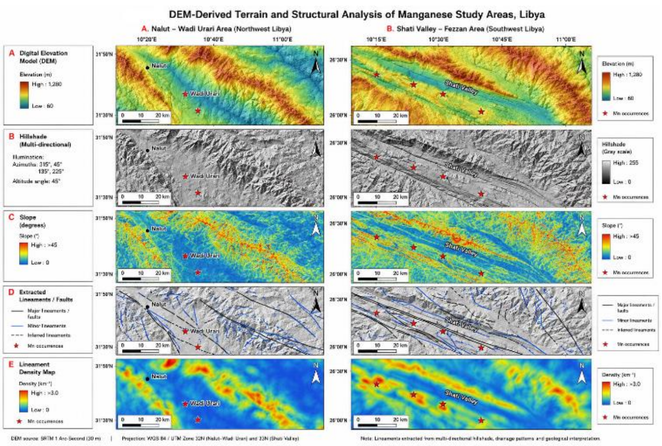

Figure 6: DEM-derived terrain and structural analysis of the manganese areas.

Fig. 7 displays the relationship between manganese occurrences and host geology. Manganese in the Nalut – Wadi Urari region was found to be commonly associated with carbonate deposits. This may be explained by the fact that fractures and weathering are typical for this area, which favors the accumulation of manganese. In turn, in the Shati Valley region, manganese occurrences are related to ferruginous and iron formations, thus providing the necessary conditions for its endogenous enrichment. The concentration of manganese along faults and geological boundaries further supports the association between this metal and both rock types and structural geology.

Several layers of data are combined in the prospectivity map (Fig. 8): (1) Spectral anomalies; (2) Iron oxides; (3) Alteration zones; (4) Suitable lithology; (5) Lineament density; (6) Distance from faults; and (7) Manganese deposits. The study areas are separated into five prospectivity classifications on the map. The areas with very high and high prospectivity are mostly found in Wadi Urari and Shati Valley, where a number of advantageous characteristics coincide. The most promising areas for further investigation are these zones. There are fewer supporting geological and spectral signs in locations with moderate and poor prospectivity.

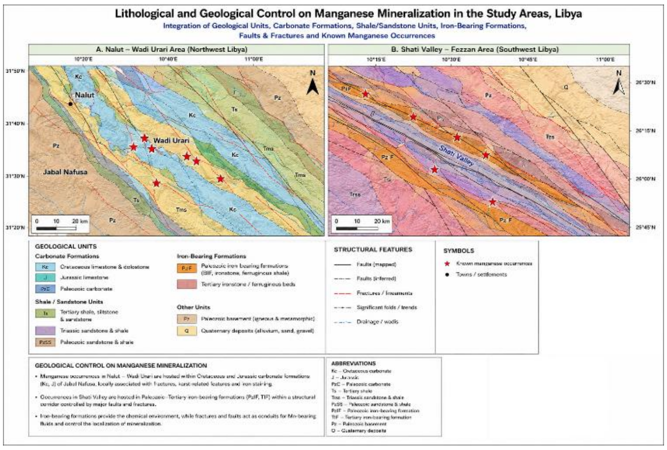

Figure 7: Lithological and geological control on manganese mineralization in the study areas.

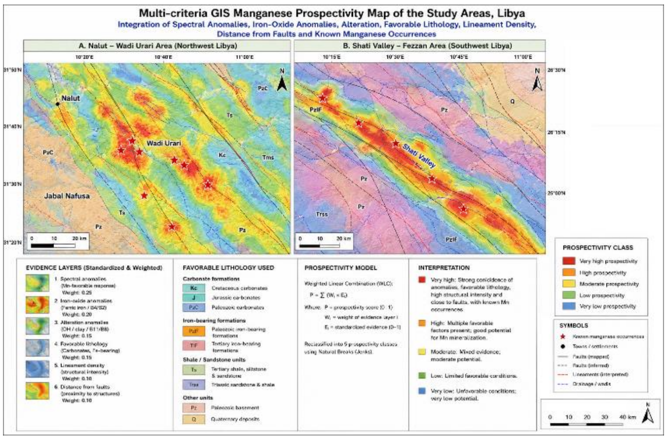

Figure 8: Multi-criteria GIS manganese prospectivity map of the manganese areas.

Interpretation of the detailed target maps (Fig. 9) indicated the key exploration targets within the identified prospective zones. The indicated targets A, B, and C were characterized by intersected spectral anomalies, favorable host rocks, high density of structures, and proximity to the known manganese occurrences. These targets were recommended for further field verification and detailed assessment of the mineralization potential.

Fig. 10 represents a resource to economy development pathway whereby indications of manganese resources through geological and remote sensing surveys lead to exploration and drilling activities which in turn lead to manganese resources. These resources are then mined to supply industries with raw materials for processing into value-added products that ultimately contribute to both domestic and international markets. The proposed development stages from 2024–2026 (foundation), 2027–2030 (development), 2031–2035 (investment), and 2036–2040 (growth and leadership) focus on a stepwise transition from exploration and discovery to beneficiation, processing, manufacturing, and value addition. The main idea is that Libya could benefit considerably from processing manganese rather than selling it as raw material to other countries. Most importantly, the map should be described as a conceptual predictive/ economic scenario and not actual reserves found and/or proven. The prioritized areas should undergo field investigations, geochemical and mineralogical assessments, drilling, resource evaluations, feasibility studies, and environmental impact analyses before they can be certified as economically viable.

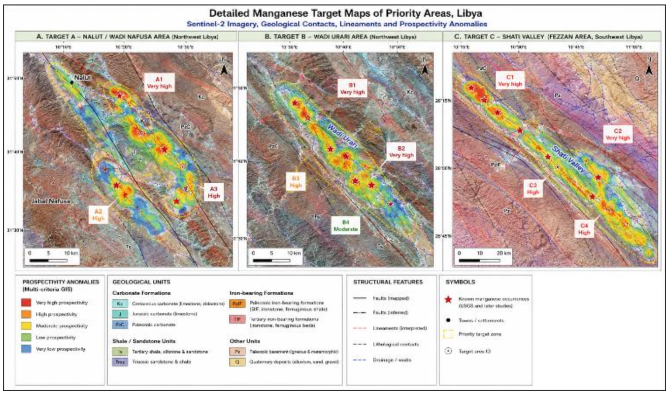

Figure 9: Detailed manganese target maps of the study areas.

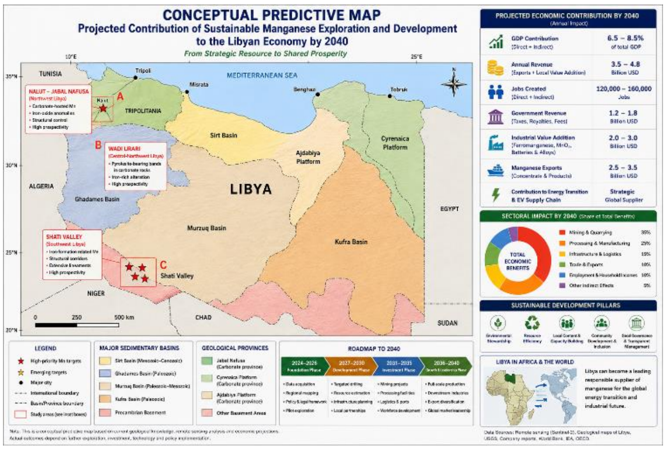

Figure 10: Conceptual predictive map illustrating the projected contribution of sustainable manganese exploration and development to the Libyan economy by 2040.

Conclusions and Recommendations

This work shows that there is potential for manganese mineralization in Libya. The predictive map delineates three main areas in which further exploration efforts should be directed, namely the Nalut–Jabal Nafusa, Wadi Urari, and Shati Valley. Nalut–Jabal Nafusa is an attractive option for manganese prospecting, with manganese deposits found in the carbonate rocks, weathering profiles, and fault zones of this area. Another manganese province with good exploration prospects is the Wadi Urari area, located on the western edge of the Ghadames Basin. It is controlled by sedimentary rocks of the basin, faults, and troughs, which have accumulated manganese mineralization. Shati Valley–Fezzan seems to be the most promising manganese province as it has iron-rich Carboniferous rocks and structures that could have controlled the formation and accumulation of manganese deposits. The combination of geological, remote sensing, and spatial data analysis can be successfully used to prioritize areas for further exploration. Although the assessment is currently theoretical, it could serve as a reliable basis for future development and detailed study. The sustainable exploitation of manganese resources could contribute to Libya's economic transformation and growth by meeting the demand for mining, processing, and manufacturing commodities and supporting the transition to net-zero emissions. However, before actual production and processing, detailed geological studies, and environmental assessments must be carried out, and infrastructure must be built.

The key recommendations are as follows:

(1) Conduct extensive geological and geochemical surveys in the identified high-potential areas to confirm manganese contents, grade, size, and economic viability.

(2) Use sophisticated remote sensing technologies such as hyperspectral sensors, Sentinel-2, ASTER, Landsat, and mineral detection algorithms to explore manganese mineralization, deposits, and alteration.

(3) Carry out geophysical surveys using magnetic, radiometric, and electrical methods to reveal concealed manganese mineralization

(4) Develop a national manganese database that will be used to store geological information, mineral resources, remote sensing data, and exploration results

(5) Encourage sustainable mining practices by incorporating environmental impact assessments, land reclamation initiatives, and appropriate waste-management policies

(6) Develop domestic processing capabilities to add value to mined minerals and diversify products instead of relying on crude mineral exports

(7) Promote research collaborations between local and international academic and mining organizations to advance mining technologies and knowledge

(8) Evaluate the opportunities for using the country's manganese reserves in the battery and renewable energy sectors.

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