Journal of Insights in Basic and Applied Sciences
مجلة رؤى في العلوم الأساسية والتطبيقية
ISSN: 3106-1737
Volume 2, Issue 3, 2026, Pages: 688-698
Journal homepage: https://jibas.com.ly/index.php/jibas/en

Integrated Remote Sensing and GIS Approach for Phosphate Exploration in Eight Documented Areas in Libya

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نهج متكامل يجمع بين الاستشعار عن بُعد ونظم المعلومات الجغرافية لاستكشاف الفوسفات في ثماني مناطق موثقة في ليبيا

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Received: June 28, 2026	Accepted: August 28, 2026	Published: September 16, 2026

Abstract:
Although phosphate deposits have been identified in a number of formations in Libya, their geological controls, spatial distribution, and exploitation potential have not yet been adequately assessed. With an emphasis on the recorded events in Al Fuqaha, Sabha, Idri, Hasi Anjiwal, Tikiumit, Wadi Tanezzuft, Anay, and Gharyan, this study offers a combined remote sensing and GIS-based method for evaluating phosphate prospectivity in Libya. The Sentinel-2 images were processed using the true- and false-colored composites, spectral band rations including B11/B12, B12/B8, and B11/B4, and principal component analysis (PCA) to detect lithological and mineralogical spectral anomalies. The digital elevation model (DEM) helped extract the elevation data, hillshade, slope, lineaments, lineament density, and drainage. The spectral data and detected lithological, geological, and structural were combined, and a weighted-overlay analysis was performed to produce a phosphate prospectivity map. The map was classified into very high, high, moderate, low, and very low potential classes. The phosphate occurrences are primarily controlled by sedimentological and structural factors. The areas that can be considered highly prospective for phosphate exploration were detected, and they are related to the spectral anomalies associated with specific lithology and structural geology. This study proved that multispectral and GIS-based methods are appropriate for regional phosphate exploration in Libya. The detected high and very high prospects need to be prioritized for follow-up geological, geochemical, and mineralogical surveys and, if possible, a drilling campaign.

Keywords: Phosphate Deposits, Mineral Exploration, Prospectivity Mapping, Libya.

الملخص
على الرغم من تحديد وجود رواسب الفوسفات في عدد من التكوينات الجيولوجية في ليبيا، إلا أن الضوابط الجيولوجية، والتوزيع المكاني، وإمكانات الاستغلال لهذه الرواسب لم تخضع بعد لتقييم كافٍ. ومن خلال التركيز على المواقع المعروفة في كل من الفقهاء، وسبها، وإدري، وحاسي أنجيوال، وتيكيوميت، ووادي تانزفت، وآناي، وغريان، تقدم هذه الدراسة منهجية مشتركة تعتمد على الاستشعار عن بُعد ونظم المعلومات الجغرافية لتقييم احتمالات وجود الفوسفات في ليبيا. وقد عولجت صور القمر الصناعي سنتينل-2 باستخدام التركيبات اللونية الحقيقية والكاذبة، ونسب النطاقات الطيفية، وتحليل المكونات الرئيسية للكشف عن الشذوذات الطيفية المرتبطة بالخصائص الصخرية والمعدنية. كما ساعد نموذج الارتفاع الرقمي في استخلاص بيانات الارتفاع، وتظليل التضاريس، ودرجة الانحدار، والخطيات وكثافتها، وشبكة التصريف المائي. وجرى دمج البيانات الطيفية مع السمات الصخرية والجيولوجية والتركيبية المكتشفة، ثم أُجري تحليل التراكب الموزون لإنتاج خريطة توضح احتمالات وجود الفوسفات؛ حيث صُنفت المناطق وفقاً لمستويات الاحتمالية إلى: عالية جداً، وعالية، ومتوسطة، ومنخفضة، ومنخفضة جداً. وتخضع أماكن تواجد الفوسفات في المقام الأول لعوامل رسوبية وتركيبية. وقد حُددت المناطق التي تُعد واعدة للغاية لاستكشاف الفوسفات، حيث ترتبط هذه المناطق بالشذوذات الطيفية المصاحبة لخصائص صخرية وتركيبية جيولوجية محددة. وأثبتت الدراسة أن الأساليب المعتمدة على التصوير متعدد الأطياف ونظم المعلومات الجغرافية تُعد ملائمة لأعمال الاستكشاف الإقليمي للفوسفات في ليبيا. وتستدعي المناطق التي أظهرت احتمالات عالية وعالية جداً إعطاءها الأولوية لإجراء مسوحات جيولوجية وجيوكيميائية ومعدنية تكميلية، وتنفيذ حملة حفر استكشافية إن أمكن ذلك.

الكلمات المفتاحية: رواسب الفوسفات، استكشاف المعادن، خرائط التوقعات المعدنية، ليبيا.

1. Introduction

Because phosphorus is a necessary component for plant growth and has no viable replacement in agriculture, phosphate deposits are among the most significant non-metallic mineral resources. Phosphoric acid and phosphate fertilizers are produced from the majority of mined phosphate rock. Moreover, phosphate is utilized in a number of industrial applications and animal feed additions. Phosphate deposits can be found in a variety of geological settings and are widely dispersed throughout the world (Baioumy, 2005; Holmkvist et al., 2010; Nielsen et al., 2015; Asfahani, 2019; Teles and Campos, 2023; Gao et al., 2026). More than 1,600 phosphate mines, deposits, and occurrences were recorded by Chernoff and Orris (2002), indicating the wide global spread of phosphate mineralization.

Libya has a varied sedimentary succession from the Paleozoic to the Cenozoic. Phosphate was discovered as one of the nation's resources by previous geological investigations. According to World Atlas (2019), the Late Ordovician Melaz Suqran Formation hosts 109,000 tons of phosphate in the Tikiumit area. Lagna (1997) reported the occurrence of phosphorites in the Triassic Abu Shaybah Formation in the Gharyan area. Petrological observations indicate that the deposits were originally formed as phosphate-rich mud that was reworked and redeposited as phosphate sands in a shallow marine environment. The phosphorite deposits were deformed and fractured during later tectonic movements, which affected the phosphorite beds, and created faults and doming structures. Dhahri et al. (2024) suggested that phosphate rock is one of the key mineral resources that can be found in Libya. They explained that Libya’s phosphate rock resources are poorly studied and evaluated regarding economic feasibility, with significant unexplored areas located in remote desert regions. They proposed that additional studies should be carried out to fully assess the potential of phosphate resources, including geological mapping, mineralogical and geochemical analyses, remote sensing, field surveys, and techno-economic evaluations. Shaltami et al. (2025) employed the chemical data of Galecic (1984), Parizek et al. (1984), Protic (1984), Radulovic (1984), Roncevic (1984), Seidl and Rohlich (1984), and Woller (1984) to assess the geochemical and industrial characteristics of the phosphate deposits in the Al Fuqaha, Sabha, Idri, Hasi Anjiwal, Tikiumit, Wadi Tanezzuft, and Anay areas. The study revealed that: (1) The phosphate occurrences were identified in the Late Ordovician Melaz Suqran, Late Silurian Akakus, Middle-Late Devonian Awainat Wanin, Early Carboniferous Marar, Early Carboniferous Assedjefar, Late Permian-Early Triassic Zarzaitine, and Late Cretaceous-Late Paleocene Zimam formations; (2) Three rock types, including Phosphorite, phosphatic and phosphatized rocks, were determined; (3) Most phosphorite samples were predominantly of marine origin, while the others were detrital; (4) The phosphatic rocks were low-grade, while the phosphorites varied from medium- to high-grade; (5) The Marar Formation in the Tikiumit area met all fertilizer industry requirements, except it needed a removal process of Fe_2O_3; and (6) Artificial bones could be produced from the Awainat Wanin Formation in the Sabha area, but the Ca/P ratio had to be adjusted correctly.

Fig. 1 provides the geological setting of Libya, including distribution of the reported phosphate occurrences, main sedimentary basins, geological provinces, and corresponding geological age. The locations where phosphate was found were identified in the southwestern and northwestern parts of Libya, namely Al Fuqaha, Sabha, Idri, Hasi Anjiwal, Tikiumit, Wadi Tanezzuft, Anay, and Gharyan. The proximity to the large sedimentary basins such as Murzuq, Ghadames, Sirte, and Al Kufrah indicates that phosphate occurrences are closely related to the geology of the area and its basin location.

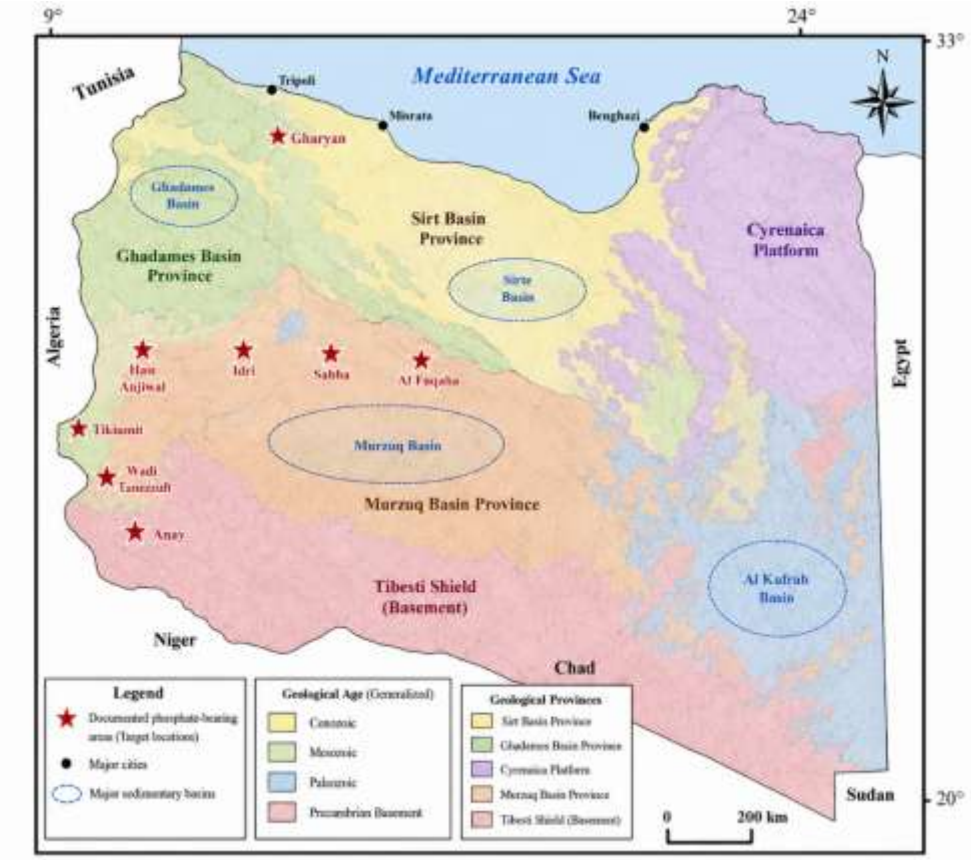

Fig. 1: Location and geological map of phosphate-bearing areas in Libya.

2. Objective

The primary goal of this research is to evaluate and delineate phosphate exploration potential in Libya by using remote sensing and GIS. The precise goals are to:

(1) Determine the spatial distribution pattern of phosphate occurrences, including the deposit sites of Al Fuqaha, Sabha, Idri, Hasi Anjiwal, Tikiumit, Wadi Tanezzuft, Anay, and Gharyan.
(2) Expose the spectral lithology of the identified phosphate occurrences using the multiband Sentinel-2 satellite images
(3) Apply the principal component analysis (PCA) and various band ratios to extract subtle anomalies of phosphate mineralization that could indicate phosphate-bearing rock distribution.
(4) Identify the outcropping lithology and sedimentary structures using the false-color composites of the Sentinel-2 multispectral data.
(5) Use the digital elevation model (DEM) to generate elevation, slope, aspect, lineaments, lineament density, and drainage density for the study site.
(6) Combine the spectral, geological, lithological, geomorphological, and structural evidence of phosphate mineralization to determine the phosphate prospects.
(7) Prepare the phosphate prospectivity map, which will distinguish the study area into five classes of phosphate exploration potential, ranging from very high to very low.
(8) Determine the priority phosphate exploration targets for the follow-on field campaign and geochemical survey.

(9) Propose a strategy for the phosphate prospecting and development for achieving the economic growth of the country by 2040.

3. Methodology

The initial stage of the research involved the compilation of the geological map, reported phosphate occurrences, Sentinel-2 imagery, and digital elevation model (DEM) for Libya. The imagery was then atmospherically corrected and enhanced to generate spectral band ratios (B11/B12, B12/B8, and B11/B4), and principal component analysis (PCA) for the identification of lithological and mineralogical anomalies. False color-composite images and spectral data were then used to extract exposed sedimentary rocks and favorable lithological units. The DEM data were used to generate elevation, hillshade, slope, lineaments density and lineaments, and drainage network maps. The extracted spectral, lithological, geological, and structural information was integrated using a weighted-overlay/prospectivity approach. This enabled the generation of phosphate prospects potential classes, which included very high, high, moderate, low, and very low. The phosphate occurrences were then overlaid on the map to verify the identified prospects. Finally, the top priority areas were recommended for field campaigns consisting of geochemical surveys to confirm the presence of phosphate deposits. The final conceptualized phosphate development map was then used to demonstrate the potentiality of sustainable phosphate exploration and development for Libya's economy by 2040.

4. Results and Discussion

The Sentinel-2 true-color image using B4–B3–B2 (Fig. 2) highlights the ground covered by the surface of a natural color. It can be seen that the exposed rock surfaces, desert, drainage, sediment accumulation, and various other large-scale geomorphological features are revealed. The known phosphate occurrences are seen to be associated with different surface environments, thus, providing an opportunity to compare the phosphate's geological setting. Although the true-color image does not reveal the presence of phosphates, it helps to distinguish exposed rock formations from non-consolidated sediments, evaluate them, and assess their accessibility. The image shows the value of a multispectral approach, combined with a closer look at specific features in spectral space, for regional reconnaissance.

The false-color composites of B12–B8–B4, B11–B8–B4, and B12–B11–B4 (Fig. 3) facilitate a better separation of lithologies, compared to the natural color composite, which is explained by the fact that rocks and minerals often have diagnostic absorption bands in the SWIR range. As a result, one can distinguish exposed sedimentary formations, lithological contacts trace, weathering patterns, and structural trends. The areas with the recorded phosphate occurrences have characteristic spectral features that can be used as spectral markers; however, the spectral differences should be interpreted with caution as actual minerals need to be identified in the field and the laboratory.

Fig. 2: Sentinel-2 true-color image of the main phosphate-bearing regions in Libya.

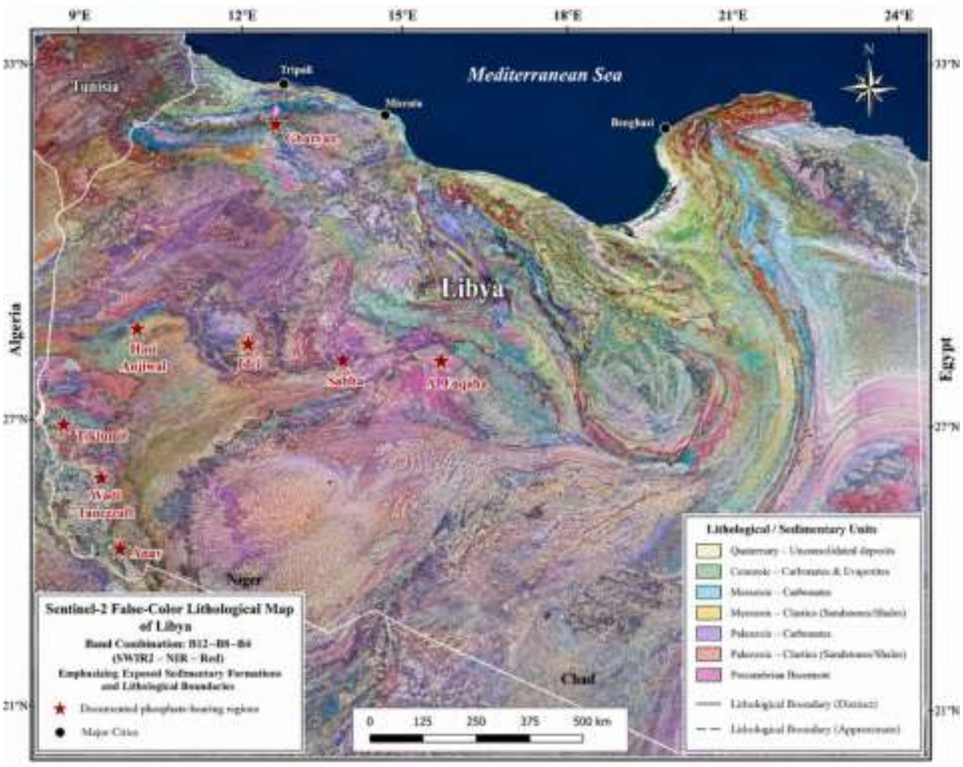

Fig. 3: Sentinel-2 false-color lithological map of Libya.

The band-ratio map (Fig. 4) is formed using the B11/B12, B12/B8, and B11/B4 ratios in order to highlight subtle mineralogical and lithological ground features. The formation of such a ratio image allows for partial compensation of the influence of slope and illumination on the reflectance of individual spectral bands; at the same time, band ratios emphasize anomalies in the spectral properties of materials. The strongest anomalies are those spectral bands that are significantly different from the surrounding areas. If such anomalies are associated with phosphate deposits, favorable lithology, and structure, they are highlighted as promising for prospecting. Therefore, the figure above is an essential tool for selecting regions with potential phosphate rock occurrences based on their spectral similarity.

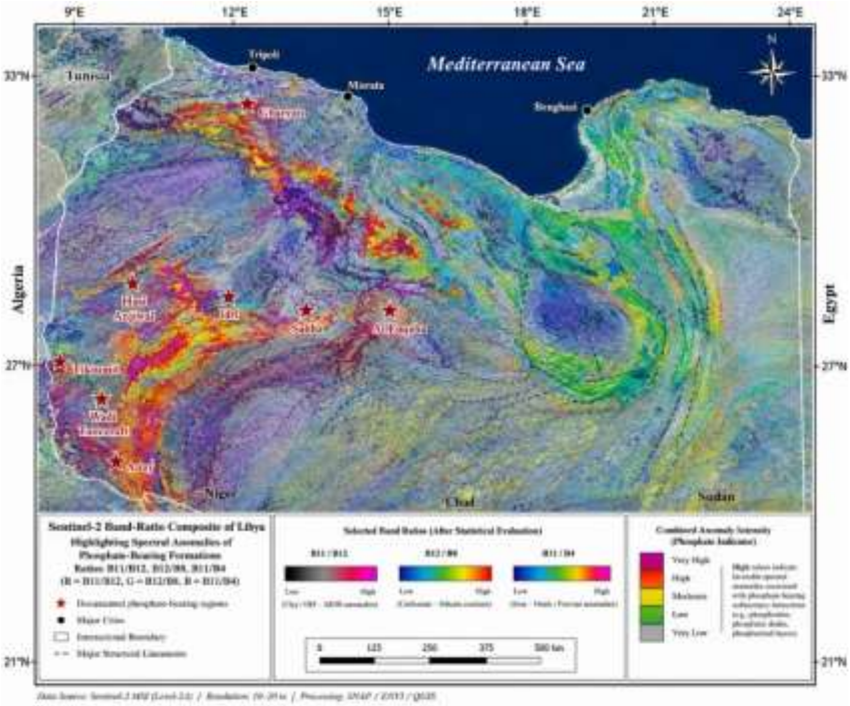

Fig. 4: Sentinel-2 band-ratio composite of Libya.

The PCA (Fig. 5) effectively isolates the multiset data set into statistically independent components, that is, PC1, PC2, PC3. PC1 usually contains the largest spectral component, while PC2 and PC3 highlight smaller details that may not be discernible in the original image. The PC1–PC2–PC3 combination is optimal for maximizing lithology and surficial material contrast. The PCA anomaly map emphasizes areas of distinct spectral character. Superimposed on the PCA plot are the locations of the known phosphate occurrences, which allows a direct comparison between the known deposits and statistically determined anomalies. Thus, the areas of PCA anomaly, which coincide with the locations of the known phosphate deposits, indicate the effectiveness of the method. On the other hand, the sites that showed similar anomalies, but no phosphate occurrence, require further geological evaluation to confirm if they are indeed analogous to the known deposits.

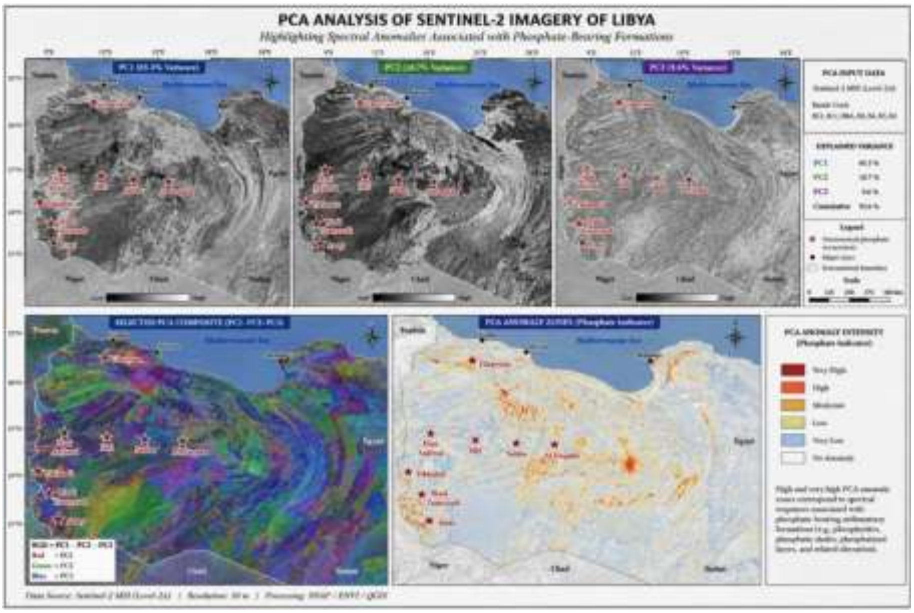

Fig. 5: Principal component analysis of Sentinel-2 imagery of Libya.

Fig. 6 shows the first level of data fusion of the spectral sets presented. It combines the band-ratio anomalies with the PCA results and lithology information to pick out those regions with spectra compatible with phosphate deposits. The most probable areas are those that show consistent anomalies in several independent methods and have the appropriate lithology to host phosphates. The chance that such an anomaly was caused by vegetation, soil moisture, topography, or some other unrelated property is lower than for locations with only one of these signs. Thus, Fig. 6 combines the individual spectral findings into a more general lithology-related discovery. The known phosphate occurrences indicated in the figure can be used as a guide to find similar deposits.

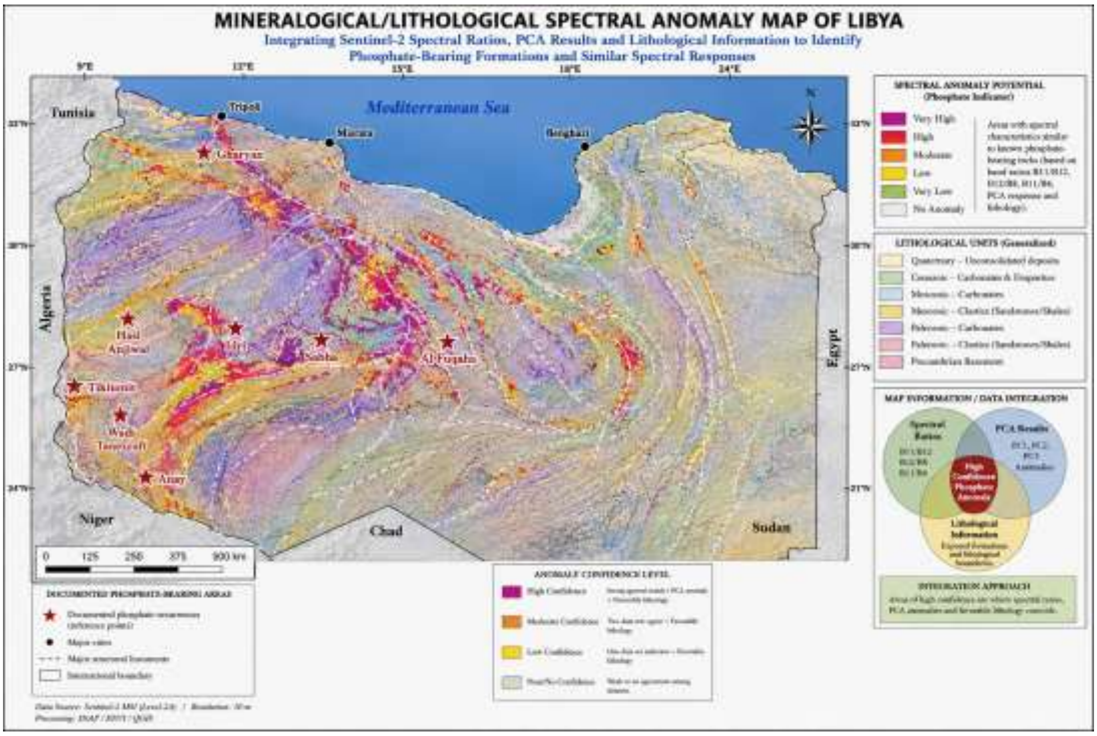

Fig. 6: Mineralogical/lithological spectral anomaly map of Libya.

The DEM-based analysis (Fig. 7) includes elevation, hillshade, slope, extracted lineaments, lineament density, and drainage. All of the layers can demonstrate the area's topographic-governed distribution and arrangement of exposed rocks and drainage pattern. The hillshade layer enhances the visualisation of ridges, escarpments, valleys, and structural discontinuities. The slope layer highlights the steepest places. The lineaments layer shows the preferred directions of fractures, faults, joints, and lithological contacts. The most possible directions of structural discontinuities are demonstrated by the lineament density layer. Finally, the drainage layer aids in understanding the area's structural control by showing the relationship between fault lines and lithology. For instance, it can be seen on the lineaments layer that such geological structures as fractures or faults have a linear nature. Hence, in the places with a high density of lineaments, particular attention should be paid to finding phosphate deposits.

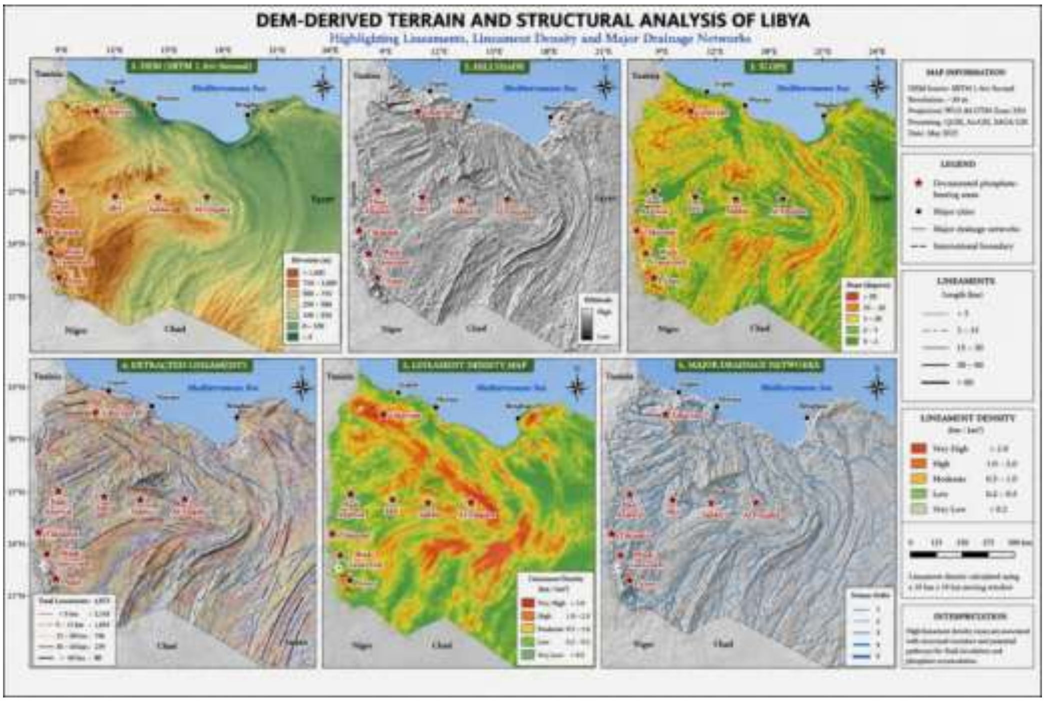

Fig. 7: DEM-derived terrain and structural analysis of Libya.

Fig. 8 is the main exploration map, which aggregates all the evidence classes into the final prospectivity class. The map shows five classes from very high → high → moderate → low → very low. Very high and high classes are associated with the spectral anomalies, PCA evidence, favorable lithology, moderate to high density of structures, and particular geomorphology. The phosphate occurrences reported in the literature are shown as markers to check whether they fall within the high prospectivity areas. It can be seen that the phosphate deposits are not randomly distributed throughout the study area but rather follow specific structural-sedimentary lineaments. Thus, it can be concluded that favorable conditions for phosphate occurrences were controlled by a combination of sedimentary, structural, spectral-hydrological, and geomorphological factors. The prospectivity classes should be used as a priority list for further exploration efforts. It is recommended to prioritize very high classes by organizing field surveys and taking samples for laboratory analyses. If the results are positive, it will be possible to drill-test deposits in the highest prospectivity areas.

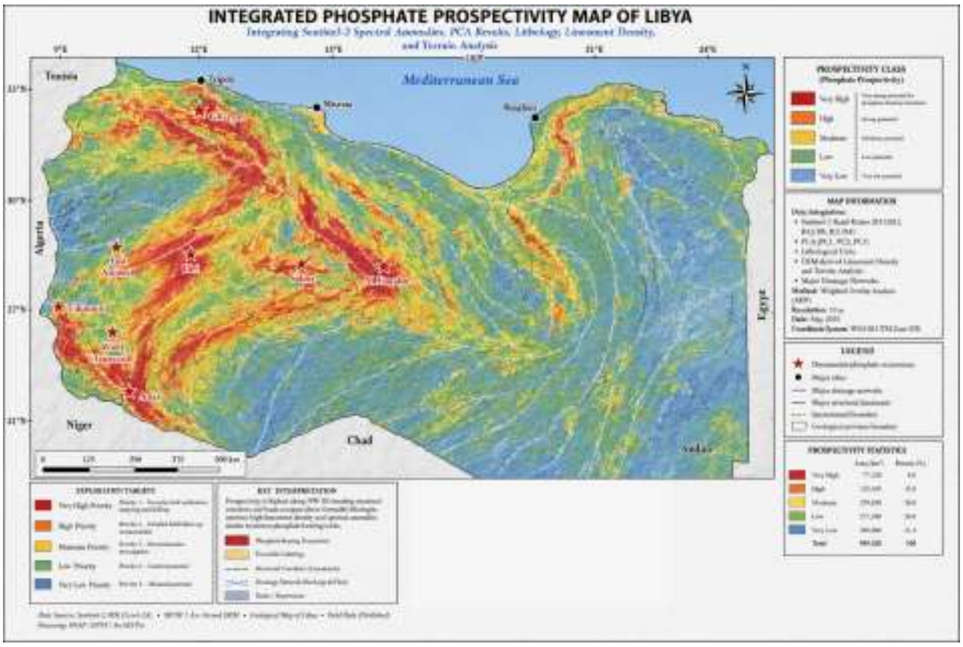

Fig. 8: Integrated phosphate prospectivity map of Libya.

Fig. 9 provides an extrapolation of the outcomes of geological prospectivity assessment to the socioeconomics, indicating the potential benefits that can accrue to society from discovering new phosphate occurrences through mineral exploration. The figure shows that phosphate resource development has the potential to diversify the state's economy and provide direct and indirect benefits to the local economy, including jobs, infrastructure, industrial processing, fertilizer manufacturing, and exports. The figure also demonstrates that such benefits would require substantial downstream processing and integration into the regional economy, which involves complex technical and socioeconomic questions. Therefore, the 2040 benefit projection should be regarded as an approximate planning-level target rather than a specific economic forecast. In addition to phosphate discoveries, time, effort, and expenditures would have to be invested in water management, environment protection, mining, and processing, as well as in workforce training, technological upgrades, and regulatory oversight.

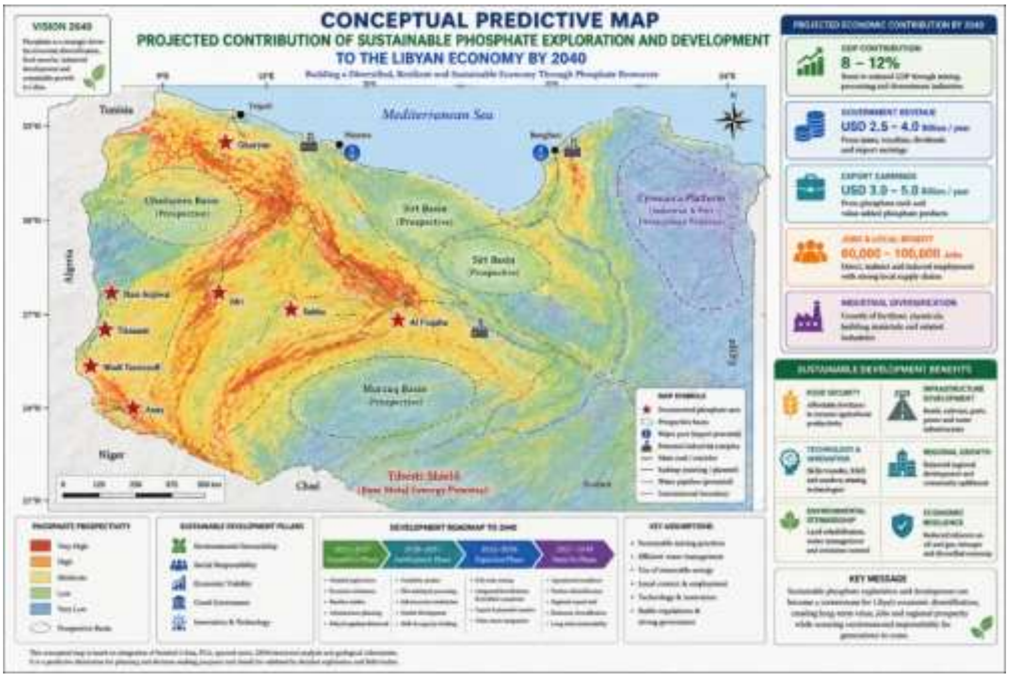

Fig. 9: Conceptual predictive map of sustainable phosphate development toward 2040.

5. Conclusions and Recommendations

This study provides an example of using Sentinel-2 remote sensing data, PCA, band ratio, geological features, and a DEM with a structural analysis to identify phosphate prospectivity. The phosphate occurrences found in Libya are mainly associated with large sedimentary basins and their structural subregions located in the western part. Using true-color images, it was possible to highlight sedimentary formations, geological contacts, and rock weathering belts. These features are well presented on the false-color image. Furthermore, applying the band ratio analysis and performing a PCA allowed distinguishing the regions with unique spectral characteristics. The fact that several spectral methods highlighted the same areas with anomalous spectrometry data along with positive lithology associations proves their favorability for phosphate exploration. The DEM-derived information on geomorphology, lineaments, structures, and drainage, together with the findings on the phosphate occurrences' properties, allowed the identification of the key factors affecting phosphate prospectivity. The final visualized model highlights the target areas that are found to have the highest concentration of spectral anomalies revealed, phosphate minerals, sedimentary structures, and geomorphological formations. The model can be used to prioritize phosphate exploration with respect to the defined classes, namely very high, high, moderate, low, and very low. It is necessary to note that the model is not intended to estimate the amount of phosphate resources or their economic value but rather provides a prioritization framework for phosphate exploration. Accordingly, the areas delineated as the ones of the highest priority should be subjected to detailed field surveys to confirm the initial hypotheses. The identified phosphate occurrences, once explored and extracted, can contribute to the regional economic growth by diversifying the local economy, providing employment opportunities, supporting local infrastructure, manufacturing, and fertilizer production, and facilitating the export potential. However, this is only possible with the adequate phosphate rock exploitation and the necessary environmental, water, and land use management and considering the social, technological, work-force, and policy-related aspects.

The following are the main recommendations:

(1) Focus on the most promising areas for further fieldwork investigation, especially those areas that show spectral, lithological, and structural anomalies.
(2) Carry out field geological mapping and field verification works to confirm the presence of phosphate deposits indicated by spectral anomalies.
(3) It is essential to collect samples from the most perspective sites and conduct geochemical analyzes, including the determination of P_2O_5 content, major- and trace-element composition, and other relevant indicators.
(4) Determine the host rocks and their association with phosphate minerals using geological and mineralogical methods.
(5) Compare the discovered phosphate anomalies with the known phosphate occurrences based on their geological setting and spectral characteristics to improve the prospectivity of the model.
(6) Use high-resolution satellite imagery and hyperspectral data, and other available data, to identify phosphate deposits and separate them from other types of anomalies.
(7) Combine the obtained prospectivity results with other available geological, geochemical, geophysical, and borehole data to select the most promising sites for drilling.
(8) Initiate drilling campaigns and resource estimation only after the positive results of geological and geochemical investigations in the highest priority areas.
(9) Assess the economic viability and processing needs of the phosphate occurrences identified as well as their impact on the environment, water resources, and infrastructure.
(10) The phosphate mining should be environmentally and economically sustainable while considering water management, land use, waste management, air quality, workforce development, and other critical factors. The authors emphasize that economic development will require significant investments in water management, phosphate processing, workforce training, and environmental protection.

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