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Potential Peatland Environments in Libya: Ecosystem Assessment and Sustainable Management Strategies

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keywords

Peatlands, Remote Sensing, GIS, Ecosystem Services, Sustainable Development, Libya.

Abstract

Peatlands are valuable wetland ecosystems that provide a wide range of services, from carbon storage and water to biodiversity and climate regulation. While Libya is mainly an arid country, some areas with a permanent or seasonal water surplus, depressions, wetlands, lagoons, oases, and periodically saturated grounds may generate conditions suitable for the formation of peat and organic soils. The current study was conducted to evaluate the potential peatland areas in Libya using remote sensing and geographic information system (GIS) analysis. The study used Sentinel 2 normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and normalized difference moisture index (NDMI), Sentinel 1 backscatter, digital elevation model (DEM), topographic wetness index (TWI), slope, elevation, drainage accumulation, closed depressions, proximity to wetlands, and water persistence data. The data were combined in a GIS environment using a multi-criteria approach to assess the potential peatland index (PPI) and identify the areas with the most suitable conditions for peatland formation. The study found that the highest potential peatland areas were associated with coastal lagoons, wetlands, sabkhas, shallow depressions, inland oases, and other water bodies with a consistent moisture surplus and appropriate geomorphological conditions. These areas were found near the Farwa Lagoon, Tawergha, Benghazi wetlands, Qasr Ahmed Lagoon, Ain al-Ghazala, and other inland wetlands. The potential peatland areas in Libya were found to be closely linked to water sources, low topographic positions, vegetation, and surface moisture. Peatlands in these areas could serve as significant carbon reservoirs, provide water and habitat for biodiversity, and protect the local community from droughts and floods. However, the current study only identified the areas with the potential for peatland formation. Further research is needed to confirm the presence of peat deposits and assess their characteristics, such as depth, carbon content, and hydrological regime. The current findings may help understand the distribution of peatlands in Libya and support the development of conservation and management strategies for these valuable ecosystems.

البيئات المحتملة لأراضي الخث في ليبيا: تقييم النظام البيئي واستراتيجيات الإدارة المستدامة

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الكلمات المفتاحية

أراضي الخث، الاستشعار عن بُعد، نظم المعلومات الجغرافية، خدمات النظم البيئية، التنمية المستدامة، ليبيا.

الملخص

أجريت هذه الدراسة لتقييم المناطق المحتملة لوجود أراضي الخث في ليبيا باستخدام تقنيات الاستشعار عن بعد وتحليل نظم المعلومات الجغرافية. وقد اعتمدت الدراسة على بيانات متنوعة شملت: مؤشر الغطاء النباتي، ومؤشر المياه، ومؤشر الرطوبة المستمدة من القمر الصناعي "سنتينل-2"؛ وبيانات التشتت الخلفي من القمر الصناعي "سنتينل-1"؛ ونموذج الارتفاع الرقمي؛ ومؤشر الرطوبة الطبوغرافية؛ بالإضافة إلى بيانات الانحدار، والارتفاع، وتراكم التصريف المائي، والمنخفضات المغلقة، والقرب من الأراضي الرطبة، واستمرارية وجود المياه. دُمجت هذه البيانات في بيئة نظم المعلومات الجغرافية باستخدام نهج متعدد المعايير لتقييم "مؤشر احتمالية وجود أراضي الخث وتحديد المناطق الأكثر ملاءمة لتكوّنها. وأظهرت النتائج أن المناطق ذات الاحتمالية الأعلى لوجود أراضي الخث ترتبط بالبحيرات الشاطئية، والأراضي الرطبة، والسبخات، والمنخفضات الضحلة، وواحات المناطق الداخلية، وغيرها من المسطحات المائية التي تتميز بفائض رطوبة مستمر وظروف جيومورفولوجية ملائمة. وتوزعت هذه المناطق بالقرب من بحيرة فروة، وتاورغاء، وأراضي بنغازي الرطبة، وبحيرة قصر أحمد، وعين الغزالة، وغيرها من الأراضي

الرطبة الداخلية. كما تبيّن وجود ارتباط وثيق بين المناطق المحتملة لأراضي الخث في ليبيا ومصادر المياه، والمواقع الطبوغرافية المنخفضة، والغطاء النباتي، ورطوبة التربة السطحية. ويمكن لهذه المناطق أن تعمل كمخازن هامة للكربون، وتوفر المياه والموائل للتنوع البيولوجي، فضلاً عن حماية المجتمعات المحلية من مخاطر الجفاف والفيضانات. ومع ذلك، اقتصرت الدراسة الحالية على تحديد المناطق التي تتوفر فيها احتمالية لتكوّن الخث، مما يستدعي إجراء المزيد من الأبحاث لتأكيد وجود رواسب الخث وتقييم خصائصها، مثل العمق ومحتوى الكربون والنظام الهيدرولوجي. وقد تساهم هذه النتائج في فهم توزيع أراضي الخث في ليبيا ودعم تطوير استراتيجيات الحفظ والإدارة لهذه النظم البيئية القيّمة

1. INTRODUCTION

Peatland refers to wetlands that are predominantly characterized by waterlogged conditions, hence low levels of decomposition in the soil. Some peatlands are formed when the production of plant materials exceeds their consumption. First, peatlands are wetlands that are flooded or permanently waterlogged, thus promoting the formation of saturated soils. Secondly, they involve low decomposition of plant matter. Thirdly, peatlands are characterized by the fact that their soils are progressively deep and organic. Fourthly, peatlands are associated with depressions that promote percolation and wetland complexes. Fifthly, there is a perennial or seasonal shortage of water that is adequate for the development of wetlands. Lastly, they provide critical resources such as carbon and extensive habitat for sustaining a wide range of wildlife species and supporting the wetlands' ecosystem functions (Kremenetski et al., 2003; Hope et al., 2005; Kværner and Snilsberg, 2008; Zhaojun et al., 2011; Akumu and McLaughlin, 2014; Dohong et al., 2017; Lupascu et al., 2020; Fatimah et al., 2023; Liu et al., 2026). Libya's mineral, petroleum, groundwater, and coastal resources have garnered far more interest than peat. This disregard does not always mean that peat-forming conditions are completely absent. Libya features many wetlands connected to the Mediterranean coast, including shallow depressions, oases, sabkhas, springs, seasonal streams, and coastal lagoons. Many potentially significant wetland settings, such as Farwa Lagoon, the Taourgha/Tawergha complex, Sebkhet Sultan, Sebkhet Karkoura, Benghazi Lake, Sebkhet Al Kouz, Sebkhet Temimi, and Ain Al-Ghazala, were identified in a previous national wetland survey. Nevertheless, little research has been done on Libya's peatlands (e.g., Cremaschi and Di Lernia, 1998; Parish et al., 2008; Cremaschi and Zerboni, 2009; Cremaschi et al., 2010). In Libya, wetlands have a far more robust and well-documented scientific history than peatlands. The literature discusses the significance of coastal sabkhas, lagoons, lakes, marshes, wadis, springs, interior playas, and paleolakes for migratory birds (Pergent et al., 2002; Defos du Rau et al., 2003; Azafzaf et al., 2005; Smart et al., 2006; Bourass et al., 2013; Shaltami et al., 2017, 2025; Maitieg et al., 2022; Etayeb et al., 2023; Alsayd and Alkrekchi, 2024; Alfaghi et al., 2025).

The present Ramsar List for Libya includes two Ramsar sites, while the latest national report designates other wetlands, including Farwa Island, Shash wetland, and Ain Al-Ghazala, as wetlands of regional importance. Nevertheless, the mere presence of a wetland is not necessarily an indicator of the presence of peat, since salt flats and sabkhas, while rich in evaporite minerals, tend to have only a thin organic layer. By contrast, freshwater or saline marshes, springs, swamps, vegetated lagoons, and permanently inundated depressions are more likely to have anaerobic conditions that promote the accumulation and preservation of organic matter. Accordingly, there is a need to identify, using remotely sensed data, those wetlands that have the greatest probability of supporting peat formation, which then require ground-truthing and laboratory analysis.

2. OBJECTIVE

The primary goal of this research is to explore and assess potential peatland environments in Libya by utilizing remote sensing and GIS technologies to determine their significance for sustainable development and environmental management. The following objectives are set:

(1) To identify potential peatland environments related to coastal wetlands, lagoons, sabkhas, oases, depressions, and other water-rich environments in Libya.

(2) To evaluate vegetation, surface-water, and soil-moisture parameters using Sentinel-2's NDVI, NDWI, and NDMI.

(3) To detect consistently wetland areas and surface water using backscatter data from multi-temporal Sentinel-1 SAR observations.

(4) To evaluate the effect of topography and drainage on peat formation using elevation, slope, TWI, closed-depression analysis, and other metrics.

(5) To analyze the relationship between identified potential peatlands and coastal and inland wetlands, including lagoons, oases, and depressions.

(6) To evaluate the impact of multiple environmental variables on the potential for peat formation using a GIS-based multi-criteria assessment.

(7) To prioritize areas for further field verification and investigation of peatlands and organic soils.

(8) To analyze the contribution of potential peatlands to sustainable development and environmental management.

3. METHODOLOGY

The authors used remote sensing and GIS technologies to delineate potential wetland and peatland areas in Libya. First, cloud-free Sentinel-2 MSI Level-2A scenes were used to create true-color (B4-B3-B2) and false-color (B8-B4-B3) composite images to visually detect wetlands, vegetation, water bodies, moisture stress, lagoons, marshes, and oases. Second, normalized difference water index (NDWI) and normalized difference moisture index (NDMI) were calculated from the Sentinel-2 scenes to identify surface water and areas with high vegetation moisture using multi-temporal analysis. Third, the Sentinel-1 SAR data were processed to obtain VV and VH backscatter coefficients to delineate persistent surface wetness areas with potential wetlands as pixels with higher backscatter coefficient values. Fourth, a digital elevation model (DEM) was used to calculate the topographic wetness index (TWI), drainage accumulation, and closed depressions, which were used to delineate areas with

potential water accumulation and low-lying regions. Lastly, an environmental suitability analysis was carried out using the GIS spatial analysis function to combine the wetness indices, vegetation, moisture, and topography layers to estimate the potential peatland index (PPI). The final PPI map divided Libya into five categories: very high, high, moderate, low, and very low potential peatland areas. The study identified potential peatlands that require ground survey and soil analysis to confirm whether the area has peat deposits.

4. Results and Discussion

The Sentinel-2 true-color image (Fig. 1) represents an overall view of the main potential wetland environments within the country. Thanks to the use of the natural colorbands, it is possible to distinguish vast areas of dry land deserts and identify locations of surface water bodies, wetlands, vegetation, and coastal areas. The farthest north coast of Africa can be seen at the very bottom of the image. Most of the Mediterranean coastal zone is characterized by a mild climate, which allows for the presence and formation of various wetland environments. They can be seen as isolated patches and lines of dark and light blue tones, green colors, and brownish areas, which are different from the overall sandy appearance of the Sahara Desert. The most prominent potential wetlands are highlighted within the red-outlined areas of Farwa Lagoon, Tawergha, Benghazi, and Qasr Ahmed Lagoon. Farwa Lagoon is located in northwestern Libya, and it is a coastal lagoon characterized by the presence of saline and freshwater ecosystems. Other coastal areas highlighted within the red-outlined zones represent local accumulations of dark and greenish colors, which are different from the overall yellow-brown coloration of the desert. The inland water bodies highlighted in purple were also delineated as potential wetland areas. They are presented as isolated patches of vegetation and appear to be sporadically distributed throughout the territory of the Sahara Desert. Farwa Lagoon, Tawergha, Benghazi, and Qasr Ahmed Lagoon are some of the most prominent potential wetlands in Libya, which will be prioritized during the next step of the PPI analysis. Coastal lagoons, inland salt marshes, and man-made reservoirs identified in the image can be environments where organic matter will accumulate and form peatlands, which are wetland ecosystems with high carbon content. However, the current analysis based on the remote sensing data cannot verify the presence of peat in the selected areas. According to the methodology, remote sensing data can indicate potential peatland areas, which have to be validated by the field measurements and laboratory analyzes.

Fig. 2 effectively highlights vegetative and moisture content in Libya. In this band combination, the vegetation responses appear as green color while the desert surface takes most of the red and pink colors on the image. Water content and saline deposits present dark-blue and cyan areas on the image, which helps to identify wetlands with better precision. The coloration seen around the Mediterranean coastal areas can be associated with an increased amount of moisture as the most prominent tints of green are found near Farwa Lagoon, Tawergha wetlands, Benghazi wetlands, and Qasr Ahmed Lagoon. The localities with high potential for producing wetlands can be identified on the coastal line as far as the Qasr Ahmed Lagoon area as tine blue and dark areas found around green patches suggest the presence of water bodies, saline deposits, and salt-affected soils. Still, the concentration of wetlands shown on the figure can suggest the areas where the closest access to freshwater resources will be available, as it appears the shallow waters and associated lowlands provide the best conditions for maintaining a wetland of any size. Notably, the Ain al-Ghazala Oasis takes a distinct green color on the otherwise brown desert, which implies its relative humidity and the presence of standing water resources several kilometers below the surface. Other localities marked with dark-green spots on the map can be associated with either local wetlands or oases of smaller sizes. Another feature worth mentioning is the sharp contrast between light pink and green areas presented on the image. Due to their distinct appearance, the image allows tracing vegetated plots found next to salt-affected soils or large bodies of water with greater precision than on the true-color picture. As one can see, the figure helps identify different wetland areas for further analysis. Therefore, it will be a valuable tool for conducting further investigations. However, when assessing the presence of peatlands, vegetative content in the soil should be taken as a sign of areas suitable for organic matter accumulation rather than the direct indication of the peatland itself, as per the methods described in the attached paper. The paper explicitly notes that the satellite's capabilities can be ambiguous when distinguishing between wet mineral soils, saline deposits, aquatic and agricultural vegetation, and mixed peaty sediment. Thus, field confirmation is necessary in each case before concluding a particular location as a peatland



Figure 1: Sentinel-2 true-color image of major potential wetland environments in Libya.

Fig. 1 shows a multi-temporal Sentinel-2 moisture analysis for Libya, based on the NDWI and NDMI. The intent is to highlight areas with relative levels of consistent surface water or vegetation/wetness compared to the generally arid terrain of Libya. The figure shows a striking contrast between the blue–cyan areas of relative moisture and the yellow–orange–red areas of dryness or inconsistent moisture. It is especially important for this map in Libya,

as potential wetland areas are likely to be small and localized within a larger region of an arid to hyper-arid climate. The most prominent moister areas are those localized around the Mediterranean coastline. Farwa Lagoon, Tawergha, Benghazi wetlands, and Qasr Ahmed Lagoon all stand out as localized areas of persistent or semi-permanent surface water and/or wetlands. These coastal features all have the advantage of being low-lying areas with ready access to fresh surface water in the form of either lagoons or marine inlets. As such, they can be expected to have a higher potential to accumulate organic matter, albeit the NDMI/NDWI values cannot confirm the presence of peat deposits directly. Several other discrete blue–cyan anomalies are visible inland, with the largest concentration found near Ain al-Ghazala. This oasis has a well-defined pattern of local moisture, forming an isolated "island" within the larger region of dry land. Other isolated blue–cyan spots can be seen across western and central Libya, with similar potential for ground water to be present in these areas. It should also be noted that these specific anomalies may have more than one contributing factor, including but not limited to localized ground water, seasonal moisture, and drainage patterns that follow vegetation growth. The NDMI indicates areas of general vegetation moisture with higher accuracy, with the bluer the area, the higher the level of moisture is. According to the color legend at the bottom of Fig. 3, the bluest areas indicate the presence of permanent or semi-permanent bodies of water, while the cyan areas suggest seasonal or intermittent bodies of water. The green areas suggest moist land surfaces. The overall pattern thus suggests a set of candidate wetland regions with their seasonal and continuous zones of surface moisture around them. The figure should also help to approximate the boundaries of such wetlands, due to the transition from the bluest areas (indicating open water) to green (moist land) and then to yellow (drier land). The NDMI is used to provide additional information on the general levels of vegetation and soil moisture, as it highlights areas where moisture might be present. Similar to the NDWI, the bluer the area, the more moisture can be expected on average, with yellower and redder areas indicating dryer regions. This is especially important for the ability of NDMI to detect moisture not visible to the NDWI. For instance, there may be areas of vegetation with consistently high levels of moisture, such as the margins of vegetated wetlands, that would have higher NDMI values. This could include saline sediments, wetland vegetation communities, shallow surface water accumulations, and other similar occurrences in central and western Libya. In effect, NDMI enables the identification of a broader range of surface- and ground moisture features, including those that may only retain moisture under specific conditions. Overall, one should note that Fig. 3 was generated using a multi-temporal Sentinel-2 composite from 2022 to 2024. As such, it focuses on areas that generally have higher levels of surface moisture across multiple months, as opposed to individual instances of moisture on the ground. As such, it can be used to identify candidate wetland areas with a higher potential to hold moisture across seasons and years. The document goes into further detail on the process of selecting these multi-temporal composites to distinguish between persistent and temporary moisture. It is especially crucial to this analysis, as persistent moisture is an essential part of any wetland environment, including those with peat deposits. In effect, Fig. 3 can be used to determine the likely areas for further ground investigation into the presence of wetlands, which may then be followed up by more detailed analyses, such as ground surveys, to find potential peat deposits. The findings should be used as a guide, as the identified areas of moisture may have other causes, including but not limited to wet mineral soils, saline deposits, or aquatic plants. The document suggests that further validation efforts may include measures of soil organic carbon and loss-on-ignition, as well as wetland profile descriptions and water-table measurements if applicable.



Figure 2: Sentinel-2 false-color vegetation/moisture image of Libya.

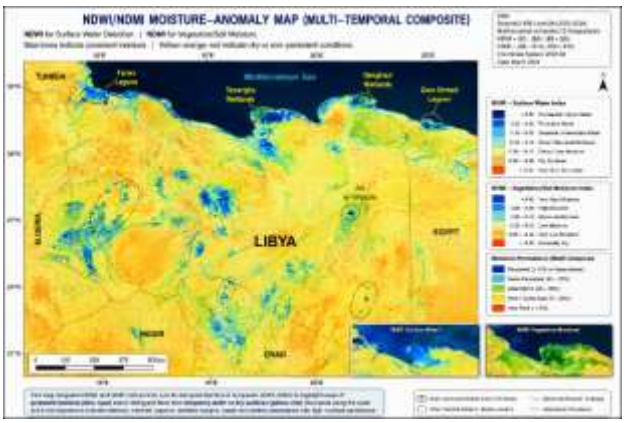


Figure 3: NDWI/NDMI moisture-anomaly map of Libya.

Fig. 4 presents a multi-temporal Sentinel-1 SAR wetness map of Libya based on the VV and VH backscatter. The map is generated to identify the spatial distribution of persistent radar response related to wet soils, surface moisture, and associated wetland vegetation. Unlike the optical products, SAR is not impacted by cloud cover, penetrating through the cloud canopy and being sensitive to moisture content below the vegetation. The map shows a noticeable contrast between the grey/yellow-dominant dry desert areas and blue/green coastal wetlands, oasis, drainage-related ecosystems, and selected inland regions,

with the strongest radar responses outlined in blue and cyan. In particular, the Mediterranean coast delineates the boundary of the country, where the most prominent wetland clusters are found. Farwa Lagoon, Tawergha wetlands, Benghazi wetlands, and Qasr Ahmed Lagoon were identified as the wettest regions in Libya with enhanced blue/cyan radar responses in both polarizations. These sites are recognized as the priority areas for wetland mapping in the current study. The most extreme examples are found around the lagoon's coastal margin, which appears to have the most contrasting surface structures compared to the surrounding desert. It is suggested that these sites contain a considerable amount of surface moisture, soil saturation, floodwater bodies, and/or dense wetland vegetation. Apart from the major coastal wetlands, several inland regions with enhanced blue/green radar responses were found. In particular, Ain al-Ghazala is presented as a local moisture anomaly with the low content of surface vegetation. Similar responses were identified as potential priority areas for exploration in western and central Libya. Accordingly, these sites can be prioritized for field validation as they might contain local groundwater discharge zones, oasis, seasonally flooded depressions, or saline marshes. The single composite of January 2022 – December 2024 was utilized, which minimizes the impact of individual dates and outlines the persistent wetness areas with enhanced SAR backscatter in blue/green colours. Both polarizations were combined to retrieve wetness information from two independent channels, with VV being sensitive to surface roughness/moisture and VH polarization responding to vegetation structures. As such, the merged SAR wetness map highlights the areas with either persistent roughness/moisture (VV), vegetation-related response (VH), and/or combined wetness and vegetation response in both polarizations (green). The SAR Wetness Index was used to define the five categories of wetness (very high, high, moderate, low, very low). The choice of the multi-temporal median composite is justified, as it minimizes the impact of individual observations, thereby considering only areas with consistent SAR responses throughout the observation window. This approach was applied following the objectives of the current study, which is to utilize the Sentinel-1 VV/VH backscatter for wetland discovery in priority areas. For the purposes of the peatland assessment, the presented SAR wetness map provides additional independent information on areas with enhanced surface moisture unrelated to cloud cover. The intersection of high SAR wetness and high optical NDWI/NDMI, vegetation content, low topographic position, and persistent surface water bodies can be used to prioritize sites for the field validation as potential peatlands or organically rich soils. This is especially the case for Libya, where the majority of the country is covered with non-foliated vegetation, which complicates the identification of moisture content and wetland ecosystems. It is suggested that the current findings can be utilized to complement the existing optical screening in the PPI framework. However, a high SAR wetness score was not confirmed to indicate the presence of peatlands or organic soils. Radar response is impacted by various factors, including surface roughness, vegetation structures, soil type, moisture, and others. As such, the presented sites should be considered as potential wetland organic soil areas for further validation.

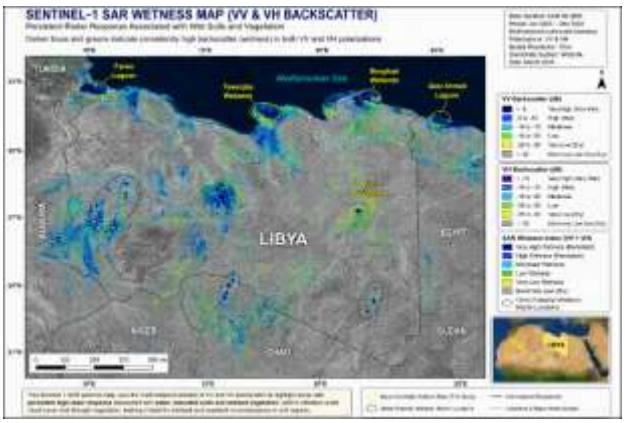


Figure 4: Sentinel-1 SAR wetness map of Libya.

Fig. 5 combines DEM-derived hillshade, TWI, drainage accumulation, and closed depressions to approximate regions in Libya that are conducive to water accumulation, holding capacity, and associated organic-matter development. The figure thus represents the topographic component of the potential peatland evaluation. Firstly, the hillshade layer serves as an essential presentation of the topographic model, providing the basic understanding of the study area. The image shows the elevation and slope-related differences ranging from higher elevations and steep slopes in the northern part of the country and western Libya to lower relief areas in the central part and the Saharan regions. Such variations are critical to note because lower areas and depressions that experience stagnation and discharge of water are more likely to host organic deposits. Next, the TWI layer shows the areal variation of topographic wetness, ranging from extremely high (blue and cyan colors) to low (yellow and white). High values generally correspond to the identified drainage lines, low areas in valleys, coastal plains, and depressions. Local maxima are found near the coast in association with wetlands, lagoons, and inland oasis clusters. The layer thus implies the potential for the frequent or prolonged presence of water. It should be noted that the TWI is evaluated in combination with other factors through the identification of the drainage-accumulation layer. This layer highlights the flow pathways and flow accumulation, i.e., the concentration of water. The visual analysis of the layer suggests that the drainage network in Libya is not uniform throughout the region. In particular, water flow seems to converge to specific points, which can be seen in the shapes of the valleys, plains, basins, and depressions. Drainage accumulation is critical in Libya because it represents areas capable of holding water for a certain period after discharge. For an arid region characterized by a lack of humidity, such sites may become vital ecosystems with increased organic-matter development. Thus, a combination of the TWI and drainage-accumulation layers can be used to find areas

with a prolonged presence of water. Finally, the closed depressions layer identifies the topographic lows with no external drainage. The depressions are differentiated based on depth from less than 0.5 m to more than 2 m. The layer indicates that there are several areas in Libya with a significant number of depressions, including those not associated with coastal wetlands. However, it is noteworthy that such sites may not always hold water in an arid climate due to a lack of precipitation or a confined groundwater system. As a result, closed depressions in Libya should be considered as potential water accumulations rather than reliable wetlands. Generally, the analysis suggests that the best sites for water accumulation in Libya are associated with multiple factors identified in the DEM data. In particular, areas with high TWI, drainage-accumulation, and closed depressions (Fig. 5) should be prioritized. When such sites overlap with the moisture and vegetation indices identified in Figs. 2-4, they are likely to represent the best conditions for peatland formation with high accuracy. For instance, a site associated with high TWI, drainage-accumulation, and closed depressions and high values of NDWI, NDMI, and SAR wetness with evidence of vegetation will be more promising than isolated wet areas found in the northern parts of the country. As such, the analysis aligns with the general approach to the study of potential peatlands, which recommends using DEM-derived topographic variables in conjunction with optical and SAR data.



Figure 5: DEM-derived topographic wetness and closed-depression map of Libya.

Fig. 6 depicts the PPI map of Libya that summarizes various remote-sensing, radar, topographic, and hydrological indices to show suitable places for potential peatlands or peat-like soils. It should be noted that the map is for delineation and prioritization purposes, not final confirmation since the study notes that remote sensing cannot conclusively confirm the presence of peat. The map shows five categories of potential: (1) Very high; (2) High; (3) Moderate; (4) Low; and (5) Very low. As seen on the map, the northwestern portion and coastal regions have the most significant potential. Very high and high potential areas are concentrated mainly in the northern coastal region of Libya around some of the potentially extensive or already identified wetlands that host organic-matter-rich ecosystems. This is because these sites have more favorable agro-climatic, topographic, and hydrological conditions, including moisture and suitable water regimes. Meanwhile, the central and southern part of Libya – mainly the Sahara desert – had the lowest potential to develop peatlands or peat-like soils due to the dryness of the region and the lack of moisture and vegetation. The highest values of PPI were associated with the large coastal wetlands in Libya, including: (1) Farwa lagoon; (2) Tawergha wetlands; (3) Benghazi wetlands; and (4) Qasr Ahmed Lagoon. Each of these wetland sites had a combination of the most favorable conditions, including proximity to water, lower elevations, wetland vegetation, and higher moisture. The coastal wetlands in Libya have better conditions for developing peatlands than the interior wetlands. This is due to the availability of perennial or seasonal water, which is crucial for peatland formation. It can be argued that these wetland sites are the priority regions in Libya for further investigation and conservation efforts since they have the highest PPI scores. Finally, the PPI map also shows regions with moderate to high potential for hosting peatlands or peat-like soils. These areas are found in western Libya, central Libya, and western and southern coastal Libya around inland depressions and water bodies. One of the most critical inland areas is Ain al-Ghazala oasis. Other than coastal wetlands and large depressions such as Benghazi, these zones also have moisture regimes that favor peatland formation. Fig. 6 offers the best synthesis of the analysis since it combines the various indices and indicators used in the study. The map summarizes the following remote-sensing, radar, topographic, and hydrological data: (1) NDVI; (2) NDWI; (3) NDMI; (4) Sentinel-1 SAR; (5) TWI; (6) Elevation; (7) Slope; (8) Proximity to wetlands; and (9) Water persistence. All of these data are crucial in understanding potential peatlands or peat-like soils in Libya. For example, (1) NDVI – normalized difference vegetation index; (2) NDWI – normalized difference water index; (3) NDMI – normalized difference moisture index; and (4) Sentinel-1 SAR are used to ascertain vegetation biomass, water presence, vegetation moisture, and overall land cover information. Furthermore, (5) TWI – topographic wetness index; (6) Elevation; and (7) Slope are employed to depict the potential for water accumulation, which supports peatland formation, and topographic barriers for water movement. Lastly, (8) Proximity to wetlands and (9) Water persistence demonstrate that the most suitable conditions for peatland/peat-like soil formation in Libya are found in extensive coastal wetlands with low topographic relief and consistent or seasonal water saturation. Generally, Fig. 6 represents the culmination of the analysis and is a prioritization map based on the combined evidence. It integrates the previous figures (Figs. 1–5) to show the most critical areas for further follow-up and investigation. In essence, it incorporates both wetland proximity and water persistence to depict where the highest potential regions are for hosting peatlands. As per the study, these areas are the most suitable for conservation and research attention since they have vegetation productivity, water regime, low relief, and appropriate sediment texture for peat formation.

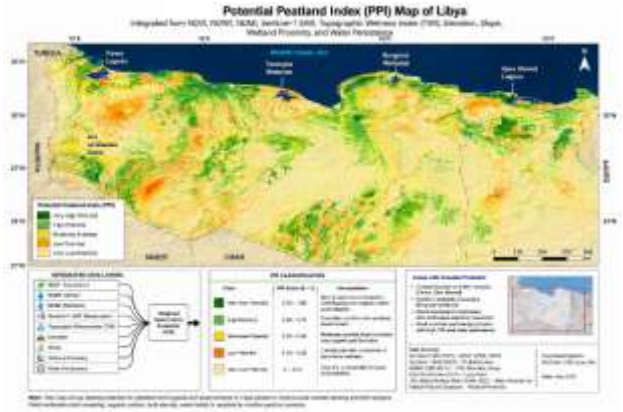


Figure 6: Potential peatland index map of Libya.

The main point of the authors in Fig. 7 is to convey that potential peatlands in Libya should be regarded as valuable ecosystems that provide water security, carbon sequestration, biodiversity, climate stability, disaster risk reduction, and sustainable livelihood. The figure implies a simple conceptual model: Remote sensing + GIS + Field verification → identification of potential peatlands → protection of peatland hydrology and biodiversity → preservation of carbon and water storage function → resilient ecosystem → sustainable development. The reverse side of the spectrum is Drainage +ground water depletion + conversion + pollution + climate change → peatland degradation →loss of carbon and water resources → increased vulnerability.



Figure 7: Conceptual framework illustrating the relationship between potential peatlands and sustainable development in Libya.

One of the critical notes here is that the author has indicated these are potential peatlands or "potential peat-forming wetlands" until there is field/laboratory research establishing the presence/absence of peat, its thickness, organic carbon content, and decomposition status. Thus, remote sensing can identify land cover types associated with peatlands (e.g., wetness, vegetation, moisture), but it cannot directly confirm the presence of peat. Generally, Fig. 7 is an excellent conceptualization for conducting a GIS- and remote-sensing-based assessment of peatlands in Libya. It also demonstrated how peatland conservation in the study region fits into broader environmental-development goals.

5. Conclusions and Recommendations

The combined analysis of remote sensing and GIS data shows that despite the predominantly dry climate, there are habitats with sufficient moisture and topography for peatland or organic soils in Libya. The analysis using optical, radar, and topographic data can be used to identify such areas. The maximum potential was found in the coastal lagoons and wetlands, low-lying coastal depressions, margins of sabkhas, inland oases, and some drainage and closed-depression systems. The sites associated with wetlands, lagoons, surface water, lowland depressions, and oases indicated by multiple criteria include Farwa Lagoon, Tawergha wetlands and saltmarshes, Benghazi wetlands, Qasr Ahmed Lagoon, and Ain al-Ghazala. Each of these sites has at least one criterion that can indicate the presence of organic-rich substrates, such as vegetation, surface or subsurface wetness, ground or surface water, low topography, and drainage. The comparison of the results of the analysis of the data of Sentinel-2 and Sentinel-1 with the topography data allowed the separation of areas with potential peatlands or organic soils. Although not directly confirming the presence of peatlands, the combined analysis of optical, SAR, and topographic data provides a reliable basis for prioritizing research sites. In particular, based on the Potential Peatland Index, sites with very high and high potential should be subject to further verification. It is recommended to consider the potentially suitable sites for conservation in Libya as areas of high value for sustainable development. This is justified by the fact that organic-rich substrates, if confirmed, will ensure carbon sequestration, water retention, and protection of habitat diversity and livelihood security at the local level.

The authors suggest the following recommendations:
(1) Verify high- and very-high-potential locations in the field.
(2) Give the coastal wetland systems top priority for in-depth research.
(3) Undertake an evaluation of inland options.
(4) Create a national inventory of existing wetlands and potential peatlands.
(5) Ensure that peatlands conservation is incorporated into national-level environmental planning.
(6) Prevent any drainage or reclamation of high-potential wetlands.
(7) Initiate pollution and unsustainable land-use prevention measures.
(8) Set up a long-term remote-sensing monitoring scheme.
(9) Evaluate the carbon-storage capacity of sites found to have high potential during field verification.
(10) Consider community-based approaches to wetland conservation.

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