



10.22034/JAPB.2025.168

Remote Sensing Assessment of Vegetation Dynamics Using Sentinel-2 Indices in the Geo-Ecological Landscape of Gonabad

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Article Received: 17 Nov. 2025, Revised: 30 Nov. 2025, Accepted: 28 Dec. 2025

Abstract

Background: Monitoring vegetation and soil conditions in arid regions is essential for understanding ecological stability and guiding sustainable land management. This study evaluates the spatial and temporal dynamics of vegetation vigor, soil salinity, and mineral composition in the Gonabad region of northeastern Iran. **Method & Material:** We employed Sentinel-2 Level-2A imagery to analyze eight spectral indices during summer 2025: Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Salinity Index (NDSI), Clay Minerals Ratio (CMR), Ferrous Minerals Ratio (FMR), Chlorophyll Index Green (CIgreen), Chlorophyll Index Red-Edge (CIrededge), and Green Normalized Difference Vegetation Index (GNDVI). These indices captured vegetation performance, hydrological stress, and surface mineral variability. **Result:** Results indicated persistently low NDVI (0.08–0.10) and negative NDWI (−0.19 to −0.21) values, consistent with severe aridity. A gradual NDSI increase reflected progressive soil salinization. Chlorophyll-sensitive indices, (CIgreen, CIrededge) peaked in late August, suggesting short-term vegetation recovery. Spatially, polygons G1 and G7 exhibited higher vegetation vigor, indicating micro-environmental resilience. **Conclusion:** The integrated assessment highlights the interplay between water scarcity, salinity, and vegetation stress. We recommend a hybrid management strategy combining traditional qanat irrigation with modern systems, cultivation of drought-tolerant species, and establishing green belts. Supported by continuous monitoring, these measures can strengthen ecological resilience in Gonabad.

Keywords: Arid ecosystems, Chlorophyll indices, Remote sensing, Soil salinity, Vegetation dynamics

1. Introduction

Vegetation cover plays a fundamental role in maintaining ecological balance and is a key indicator of ecosystem health, particularly in arid and semi-arid environments where vegetation dynamics are highly sensitive to climatic fluctuations and anthropogenic pressures (14, 36). Monitoring vegetation patterns and their responses to environmental stressors has become essential for understanding ecosystem stability and resilience (13, 30). Recent advances in satellite-based remote sensing allow for consistent, large-scale, and long-term observation of vegetation cover without the need for extensive ground measurements (4, 23). Among the available Earth observation platforms, Sentinel-2 provides high-resolution multispectral data that facilitate accurate estimation of biophysical variables and vegetation indices such as NDVI, SAVI, LAI, and FAPAR, which are widely applied to assess plant vigor, chlorophyll content, and canopy structure (11, 31).

Temporal variations in these indices enable the detection of vegetation degradation, disturbance, and recovery, offering insight into the ecological consequences of land-use and climate interactions (22, 42). Water-related indicators such as NDWI complement vegetation metrics by linking canopy greenness and productivity to moisture availability and hydrological fluctuations (24, 40). In arid regions with limited field data, remote

sensing-based approaches provide a defensible and cost-effective alternative for ecological assessment, especially when combined with spatial analysis tools such as the Sentinel Application Platform (SNAP) and ArcGIS (10, 28).

The geo-ecological landscape of Gonabad, located in northeastern Iran, features a complex mosaic of mountainous terrain, plains, saline riverbeds, and anthropogenically altered lands, making it an ideal area for studying vegetation dynamics and ecohydrological responses (26, 46). Accordingly, this study aims to assess vegetation cover, degradation, and recovery in the Gonabad region using Sentinel-2 derived optical indices. By integrating vegetation and moisture indicators within a spatial analysis framework, this research provides an operational remote sensing approach to support sustainable ecological management in arid landscapes (1, 8).

2. Materials and Methods

2.1. Study Area

The study area covers approximately 155 km² within the Gonabad region, located in the southeastern part of Khorasan Razavi Province, Iran. Geographically, it lies between 34.29°–34.49° N latitude and 58.55°–58.79° E longitude, situated in the eastern foothills of Kuh-e Siah (Black Mountain) (Figure 1).

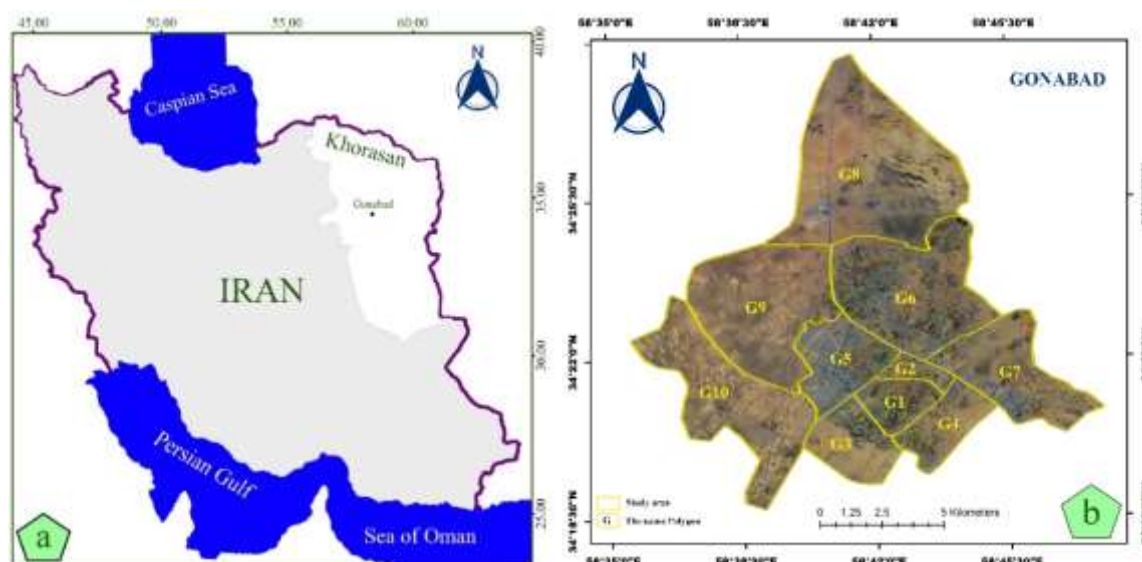


Figure 1. Geographic location of the study area in the geo-ecological landscape of Gonabad, northeastern Iran. Map (a) shows the national context, highlighting the position of Gonabad within Khorasan Province. Map (b) presents the detailed spatial layout of the study area, divided into 10 sampling polygons (G1–G10), with the Pajga route marked in yellow. This spatial framework supports the remote sensing-based assessment of vegetation cover, degradation, and recovery using Sentinel-2 indices across multiple time periods.

This region is characterized by an arid to semi-arid climate, with low and irregular rainfall, high evapotranspiration rates, and substantial seasonal temperature variations. Elevation across the study area ranges from approximately 900 to 2400 meters above sea level, forming pronounced topographic, hydrological, and ecological gradients.

The landscape comprises mountainous terrain, alluvial plains, ephemeral riverbeds, saline depressions, and human-modified agricultural lands. Vegetation is mainly composed of *Tamarix* shrubs (salt cedar) and sparse xerophytic grass species adapted to drought, salinity, and poor soil conditions. The spatially fragmented vegetation cover, coupled with seasonal fluctuations in soil moisture and salinity, makes the Gonabad region an ideal site for assessing vegetation cover dynamics, degradation, and recovery through Sentinel-2 based optical indices.

2.2. Data Source and Preprocessing

This study utilized Sentinel-2 Level-2A imagery, which provides atmospherically corrected surface reflectance data, making it particularly suitable for monitoring

vegetation and soil moisture in arid environments (15). The dataset offers spatial resolutions of 10–20 m across visible, near-infrared (NIR), and shortwave infrared (SWIR) spectral bands. Cloud-free images corresponding to the main vegetation phenological stages during the summer of 2025 (specifically 26 June, 25 August, and 21 September 2025) were selected to ensure consistent temporal coverage of vegetation dynamics. Since Level-2A products are preprocessed by the European Space Agency (ESA) using the Sen2Cor atmospheric correction algorithm, no additional radiometric or atmospheric adjustments were required. The selected images were clipped to the Gonabad study area (155 km²) using ArcGIS 10.8. Spectral bands were resampled to a uniform 10-meter resolution where necessary using the nearest neighbor method to maintain data consistency for vegetation index calculations. All data processing steps were performed exclusively within SNAP and ArcGIS software environments. The overall methodological framework of this study, illustrating the data processing and analytical workflow from Sentinel-2 preprocessing to index extraction and interpretation, is presented in Figure 2.

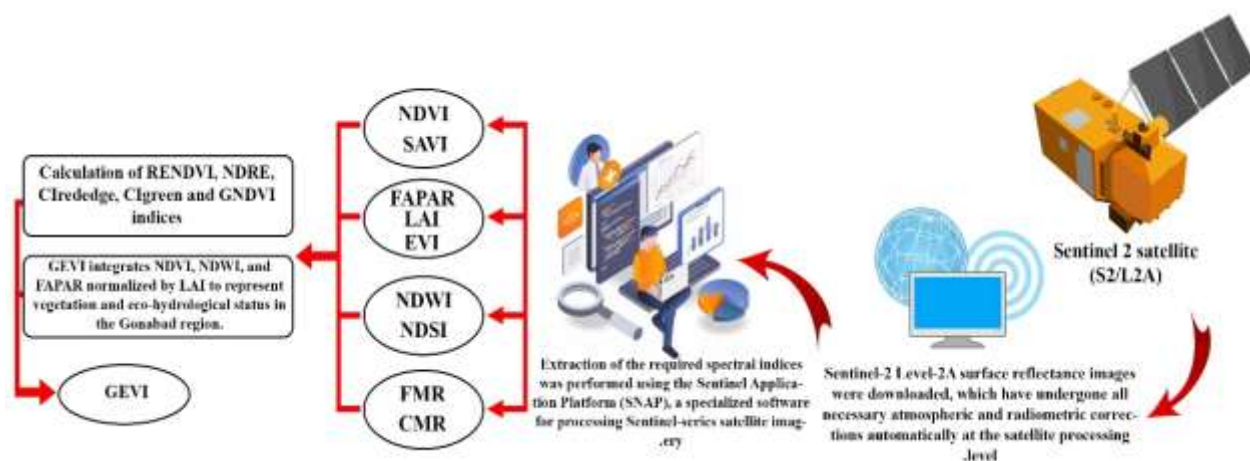


Figure 2. Flowchart for downloading and extracting Sentinel-2 image data to calculate the desired research indicators

2.3. Vegetation, Soil and Mineral Indices

This study utilized multispectral imagery from the Sentinel-2 mission, a key component of ESA Copernicus program for global terrestrial monitoring (21, 37). The twin satellites, Sentinel-2A and Sentinel-2B, launched on 23 June 2015 and 7 March 2017 respectively, operate in the same sun-synchronous orbit, phased 180° apart (3, 43). This configuration provides a high revisit frequency,

which is essential for consistent temporal coverage (5, 44). The mission's Multispectral Instrument (MSI) captures data in 13 spectral bands spanning the visible (VIS: 400–700 nm), near-infrared (NIR: 700–1000 nm), and shortwave infrared (SWIR: 1000–2400 nm) regions, with varying spatial resolutions: four bands at 10 meters, six bands at 20 meters, and three atmospheric correction bands at 60 meters (Table 1) (16, 32).

Table 1. Information about Sentinel-2 bands

Band Number	Band Name	Central Wavelength (nm)	Bandwidth (nm)	Spatial Resolution (m)
B1	Coastal Aerosol	443	20	60
B2	Blue	490	65	10
B3	Green	560	35	10
B4	Red	665	30	10
B5	Vegetation Red Edge	705	15	20
B6	Vegetation Red Edge	740	15	20
B7	Vegetation Red Edge	783	20	20
B8	Near Infrared (NIR)	842	115	10
B8A	Narrow NIR	865	20	20
B9	Water Vapor	940	20	60
B10	Shortwave Infrared (SWIR) - Cirrus	1375	30	60
B11	Shortwave Infrared (SWIR)	1610	90	20
B12	Shortwave Infrared (SWIR)	2190	180	20

To comprehensively assess the geo-ecological landscape of the arid Gonabad region, fourteen spectral indices were derived from atmospherically corrected Sentinel-2 Level-2A surface reflectance products (36, 41). These indices were strategically selected to capture critical and interconnected aspects of the environment, including vegetation dynamics, soil characteristics, and mineral composition (6, 9). This multi-faceted approach provides a holistic understanding of the ecosystem's condition and its susceptibility to degradation processes such as vegetation loss, soil salinization, and erosion (35, 40). The complete list of indices, their formulations, primary applications, and key references is detailed in Table 2 (20, 38, 39). For a focused analysis of vegetation vigor, soil properties, hydrological conditions, and mineral composition in the Gonabad region, eight spectral indices were further derived from Sentinel-2 Level-2A imagery (7, 25). These indices provide a multi-

dimensional understanding of the arid ecosystem's structure and its degradation status (29, 45).

2.3.1. Vegetation Vigor and Structure Indices

The NDVI was employed to evaluate vegetation greenness and canopy density, serving as a primary indicator of plant vigor and biomass productivity (33). The Green Normalized Difference Vegetation Index (GNDVI) and the Chlorophyll Index Green (CIgreen) provided refined assessments of chlorophyll concentration and photosynthetic activity, allowing improved discrimination of vegetation health and nutrient status (18). The Chlorophyll Index Red Edge (CIre) was also calculated to provide a more sensitive assessment of chlorophyll content in dense canopies by leveraging the reflectance in the red-edge region, which is highly correlated with leaf chlorophyll concentration (19). The Red-Edge NDVI (RENDVI) was utilized to

detect subtle variations in canopy structure and early-stage vegetation stress, particularly useful in semi-arid environments where vegetation is sparse and stress occurs rapidly (17).

2.3.2. Soil and Hydrological Indices

The Normalized Difference Water Index (NDWI) was applied to monitor vegetation water content and hydrological stress, reflecting the spatial variability of surface moisture across the landscape (27).

2.3.3. Soil, Hydrological and Mineral Indices

The Normalized Difference Salinity Index (NDSI) was used to detect surface salt accumulation and soil salinity patterns, which are particularly critical in arid regions prone to salinization and land degradation (2). The Clay Minerals Ratio (CMR) facilitated the identification of clay-rich zones and hydrothermally altered soils,

offering insight into soil composition and related geological processes (12). The Ferrous Minerals Ratio (FMR) was calculated to detect iron-bearing minerals such as hematite and magnetite, contributing to the understanding of the geological formations and potential mineralogical variability of the region (34). All indices were computed from atmospherically corrected surface reflectance values using standardized equations (Table 2). NDVI, GNDVI, RENDVI, CIgreen, NDWI, NDSI, CMR, and FMR were calculated using the Raster Calculator in ArcGIS 10.8. This multi-index approach provides a comprehensive framework for evaluating vegetation health, soil salinity, and mineralogical composition across the Gonabad landscape. Table 2 summarizes the mathematical formulations, primary applications, and key references for all indices employed in this study.

Table 2. Band formulas used to calculate spectral and biophysical indices of data extracted from Sentinel-2 images.

Category	Index (Abbreviation)	Formula (Sentinel-2 Bands)	Primary Application	Key Reference(s)
Vegetation Vigor & Density	NDVI	$(B8 - B4) / (B8 + B4)$	Assesses vegetation greenness and biomass.	(33)
Chlorophyll & Canopy Structure	GNDVI	$(B8 - B3) / (B8 + B3)$	Estimates chlorophyll concentration and plant health.	(18)
	CIgreen	$(B8 / B3) - 1$	Measures chlorophyll content, sensitive to leaf greenness.	(18)
	CIre	$(B7 / B5) - 1$	Estimates chlorophyll content using the sensitive red-edge region.	(19)
	RENDVI	$(B7 - B5) / (B7 + B5)$	Sensitive to variations in canopy structure and chlorophyll.	(17)
Water & Soil Moisture	NDWI	$(B3 - B8) / (B3 + B8)$	Highlights vegetation water content and detects surface water.	(27)
Soil & Mineral Composition	NDSI	$(B4 - B11) / (B4 + B11)$	Detects and monitors surface soil salinity in arid landscapes.	(2)
	CMR	$B11 / B12$	Identifies clay-rich soils and hydrothermally altered zones.	(12)
	FMR	$B11 / B8A$	Maps iron-bearing minerals (e.g., hematite, magnetite).	(34)

3. Results

The spatiotemporal analysis of vegetation and salinity indices across the geo-ecological landscape of Gonabad reveals distinct patterns of ecological change over the study period. Figure 3 illustrates the distribution of NDVI and NDSI values on three key dates: 26 June, 25 August, and 21 September 2025.

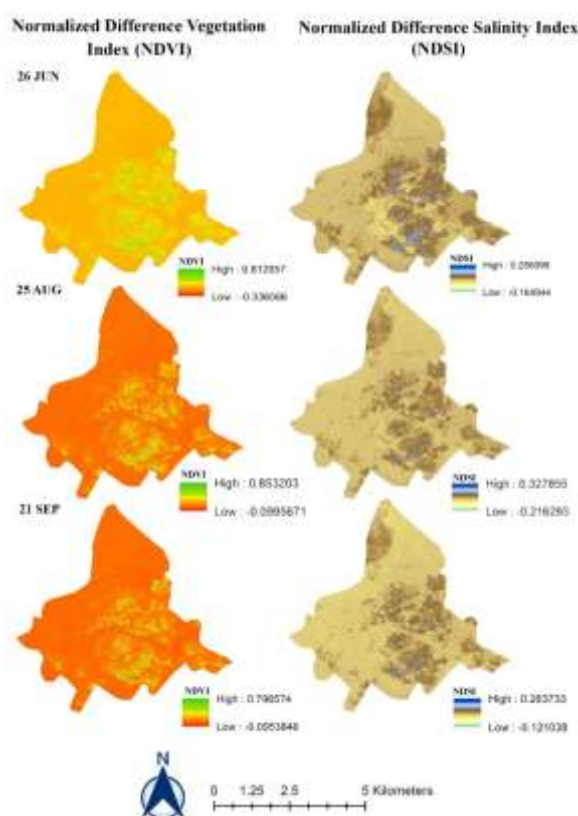


Figure 3. Spatiotemporal distribution of vegetation cover (NDVI) and surface soil salinity (NDSI) across the study area in Gonabad on three dates: 26 June, 25 August, and 21 September 2025. NDVI maps (left) illustrate seasonal variations in vegetation density, where green areas indicated higher vegetation coverage and red areas indicated sparse or degraded cover. NDSI maps (right) show the extent of surface salinity, with blue tones representing higher salinity levels and brown tones indicating lower salinity. The maps revealed an inverse relationship between vegetation density and surface salinity, supporting the assessment of ecological degradation and recovery dynamics.

Figure 3 presents the spatiotemporal distribution of vegetation cover and surface soil salinity, illustrating distinct ecological patterns across the Gonabad study area during the summer of 2025. The following subsections provide a detailed quantitative analysis of these patterns.

3.1. NDVI

NDVI maps reveal a distinct seasonal pattern in vegetation cover across the study area. On 26 June, vegetation density was moderate, with NDVI values ranging from -0.14 to 0.81 . By 25 August, the index increased (-0.10 to 0.85), reflecting peak vegetation growth during the late summer period. A slight decline was observed by 21 September (-0.05 to 0.79), which may indicate the onset of senescence, reduced photosynthetic activity, or early signs of ecological degradation. These temporal variations suggest dynamic vegetation responses to seasonal climatic conditions and surface soil properties.

3.2. NDSI

NDSI maps reveal moderate levels of surface salinity across the study area. On 26 June, NDSI values ranged from -0.15 to 0.26 , with salinity hotspots appearing in

central and southern zones. By 25 August, NDSI peaked (-0.21 to 0.33), likely due to increased evaporation and salt accumulation during the dry season. A noticeable decline in NDSI values was observed on 21 September (-0.12 to 0.18), possibly reflecting post-irrigation effects or reduced surface salt exposure.

3.3. Soil Mineral Composition (CMR and FMR)

The spatial distribution of clay-related and iron-related mineral indices reveals notable temporal variations in surface soil composition across the study area, as illustrated in Figure 4. CMR maps showed moderate to high values throughout the region, with a slight increase observed in late August (range: 0.64 to 1.98) compared to late June (0.72 to 1.69) and a subsequent stabilization in September (0.78 to 1.71). These fluctuations may reflect seasonal changes in surface moisture, sediment exposure, or soil texture dynamics. FMR maps indicated more pronounced variability. The highest values were recorded in August (0.34 to 3.84), which suggests increased surface oxidation or mineral exposure during the driest period. In contrast, lower FMR values in June and September (minimum ~ 0.41) may have corresponded to reduced surface reflectance or partial vegetation cover masking mineral signatures. These mineral indices provide complementary insights into soil conditions that influence vegetation dynamics, water retention capacity, and ecological resilience. Their temporal behavior supports the interpretation of seasonal soil stress and potential degradation risks in arid environments.

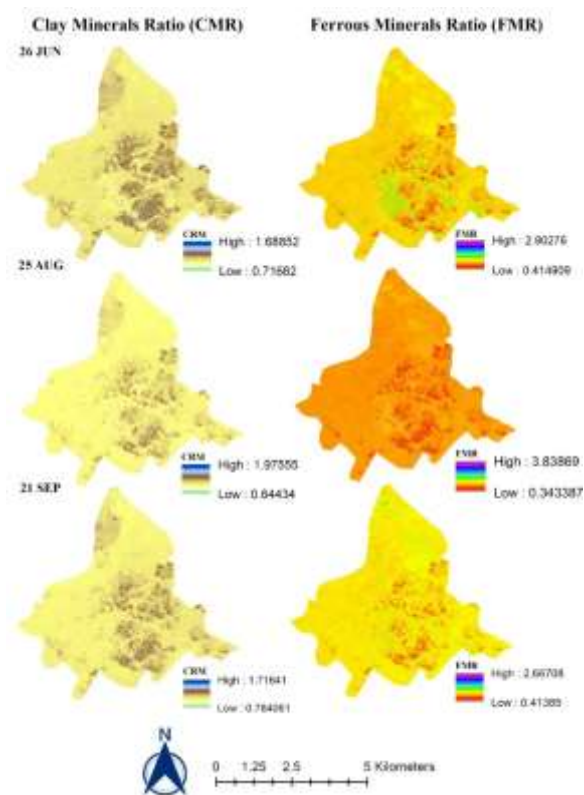


Figure 4. Spatiotemporal distribution of CMR and FMR across the study area in Gonabad on three dates: 26 June, 25 August, and 21 September 2025. CMR maps (left) illustrate variations in surface clay content, where darker tones indicated higher clay mineral ratios. FMR maps (right) show the distribution of iron-bearing minerals, with red tones representing higher ferrous mineral concentrations. The maps highlighted seasonal

shifts in soil composition, which supports the interpretation of surface texture dynamics and mineral exposure relevant to ecological and land management assessments.

3.4. Quantitative Assessment of Vegetation Indices

A quantitative analysis of key vegetation indices was conducted to precisely evaluate temporal trends in chlorophyll activity and canopy density across the study

area. CIgreen, CIrededge, and GNDVI were selected for detailed temporal profiling due to their high sensitivity to photosynthetic activity and plant health. Figure 5 illustrates the average values of these selected vegetation indices for each defined polygon across the three observation dates, highlighting areas with the most dynamic physiological responses.

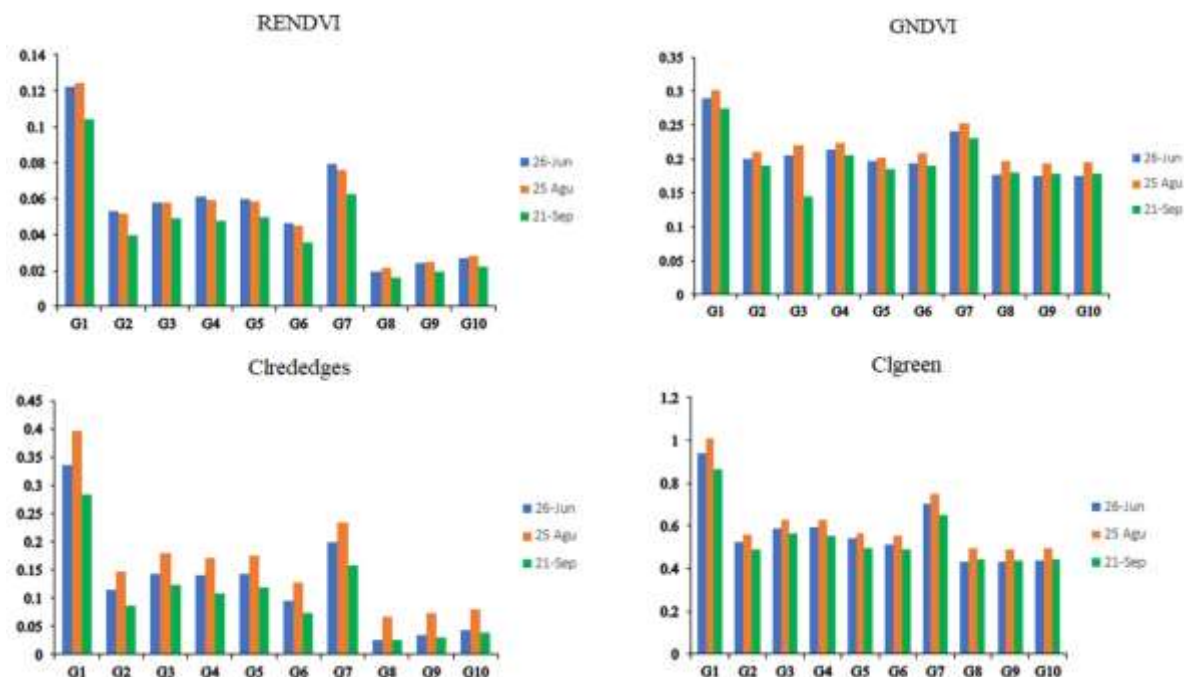


Figure 5. Temporal profiles of chlorophyll-sensitive vegetation indices (CIgreen, CIrededge, GNDVI) across different land units (polygons G1-G7) in the Gonabad study area during the summer of 2025.

3.5. Integrated Spectral Index Summary

To synthesize the spectral analysis, a comprehensive summary of key indices was compiled. Table 3 presents the average values of NDVI, NDWI, NDSI, CMR, and

FMR across the entire study area for each observation date. These integrated values provide a quantitative baseline for assessing overall vegetation health, hydrological stress, soil salinity, and surface mineral composition throughout the study period.

Table 3. Average values of key spectral indices for the Gonabad study area across three observation dates in 2025.

Date of the year	NDVI	NDWI	CMR	NDSI	FMR	RENDVI	CIrededge	CIgreen	GNDVI
20250626	0.085255	-0.19639	1.074065	0.034318	1.112059	0.043669299	0.093789389	0.523441	0.196385
20250825	0.0964	-0.21264	1.065205	0.030135	1.077431	0.043605155	0.132047388	0.574828	0.212636
20250921	0.080256	-0.19431	1.107048	0.049934	1.096452	0.035242176	0.078201028	0.509758	0.194315

4. Discussion

The spectral indices analyzed in this study provide a multidimensional perspective on vegetation health, soil conditions, and ecological variability across the study area. The values summarized in the previous section reveal spatial and temporal patterns that are critical for interpreting land suitability, environmental stress, and resource potential. In this section, we discuss the implications of these findings for agricultural planning, ecological management, and urban development. Particular attention is given to how vegetation indices such as NDVI, LAI, CIgreen, and NDSI can inform the selection of suitable crop types, medicinal plants, and orchard species under semi-arid conditions. Additionally, the role of soil-related indices (e.g., CMR,

FMR) in identifying areas prone to salinity or mineral stress is explored to support sustainable land use strategies.

4.1. NDVI

The NDVI values across all observation dates remained relatively low (0.08–0.10), indicating sparse and weak vegetation cover typical of arid and semi-arid landscapes. The minor fluctuations observed between late June and late September suggest minimal phenological activity during the dry season. Such persistently low NDVI values reflect limited biomass and reduced photosynthetic potential, largely due to soil moisture deficiency and high evapotranspiration rates. These findings are consistent with the region's climatic constraints, confirming that vegetation productivity is

primarily controlled by short-term rainfall events and soil moisture availability.

4.2. NDWI

NDWI values were consistently negative (-0.19 to -0.21), revealing extremely dry surface conditions throughout the study period. The lowest NDWI value recorded in late August corresponds to the peak of the dry and hot season, while the slight recovery in September likely reflects a marginal increase in surface moisture due to temperature decline or scattered precipitation. This temporal pattern demonstrates the sensitivity of NDWI to seasonal water availability and highlights the dominant role of climatic aridity in controlling soil moisture status in the study area.

4.3. CMR

CMR ranged from 1.06 to 1.10, signifying moderate clay mineral content across the region. Values in this range typically indicate soils with medium textural composition and low to moderate weathering intensity. The slight increase in CMR during the late summer months may result from enhanced spectral reflectance of dry soils in the SWIR bands, which amplifies the signal associated with clay minerals. Therefore, the observed variation likely represents surface desiccation effects rather than significant mineralogical alteration. This stability in CMR also implies limited geomorphological change within the short observation period.

4.4. NDSI

The NDSI exhibited an upward trend from 0.034 in June to 0.050 in September, suggesting a gradual increase in surface salinity as the dry season progressed. This pattern is consistent with intensified evaporation and capillary rise of dissolved salts toward the soil surface under prolonged arid conditions. The inverse relationship between NDSI and NDWI emphasizes that decreasing moisture availability directly promotes salinization processes. The results highlight that areas with high NDSI values during late summer are likely to experience salt accumulation, making them unsuitable for sensitive

crops without proper management or irrigation interventions.

4.5. FMR

The FMR index ranged between 1.07 and 1.11, indicating weak to moderate presence of iron-bearing minerals. Minimal temporal fluctuations suggest that the mineralogical composition of the soil and bedrock is stable, and observed spectral variations mainly result from surface moisture and reflectance effects rather than chemical transformation. The relatively steady FMR values reinforce the interpretation that geochemical changes are minor compared to physical processes such as evaporation and surface crust formation during the dry season.

4.6. Integrated Interpretation and Environmental Implications

The combined analysis of NDVI, NDWI, CMR, NDSI, and FMR reveals a coherent environmental pattern characterized by declining moisture, increasing salinity, and stable mineralogical composition during the summer months. As surface moisture decreases (negative NDWI), NDVI remains low while NDSI rises. This interaction underscores the coupled dynamics of water stress and salt accumulation in arid soils. Consequently, land management strategies in such environments should prioritize moisture retention, soil salinity monitoring, and selection of salt-tolerant species for sustainable land use and reclamation planning.

4.7. Temporal and Spatial Analysis of Chlorophyll-Related Indices

The quantitative analysis of chlorophyll-related spectral indices (CIrededge, CIgreen, GNDVI, and RE NDVI) across ten sampling polygons (G1–G10) and three observation periods (26 June, 25 August, and 21 September 2025) provides valuable insights into vegetation performance and canopy health under semi-arid conditions. As shown in Figure 6, the indices exhibited distinct temporal variations in

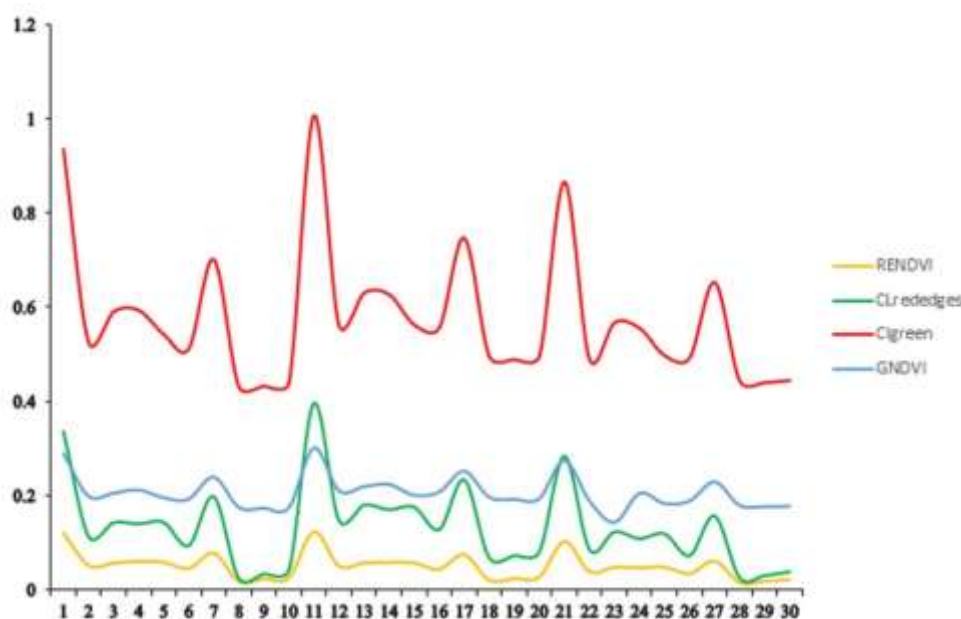


Figure 6. Temporal dynamics of key vegetation indices (GNDVI, CIgreen, CIrededge, RENDVI) across 30 spatial units in Gonabad during summer 2025. GNDVI showed the strongest chlorophyll signal, peaking in August, while CIgreen displayed high variability. CIrededge and RENDVI exhibited more stable, less seasonal trends, indicating differential sensitivity to environmental conditions across the landscape.

density during mid-summer. GNDVI values (0.17–0.30) followed a stable pattern, suggesting moderate but consistent vegetation vigor. RENDVI, ranging between 0.016 and 0.12, showed minimal variability, reflecting sparse vegetation or low red-edge reflectance sensitivity. These results confirmed that 25 August 2025 corresponded to the peak vegetation activity, where favorable soil moisture and temperature conditions likely enhanced chlorophyll synthesis and canopy expansion. The decline observed on 21 September 2025 reflected the onset of physiological stress and partial senescence due to water limitation and elevated evapotranspiration. The spatial behavior across polygons also revealed micro-environmental variability: polygons G1 and G7 consistently recorded the highest chlorophyll indices in all periods, suggesting localized areas of higher fertility or better moisture retention, possibly influenced by topographic position or soil composition. In contrast, polygons G8–G10 showed persistently low index values, indicating degraded or sparsely vegetated surfaces. Figure 6 illustrates the comparative trend of these indices across the study dates. The synchronized peaks of CIgreen and CIrededge emphasized their joint sensitivity to chlorophyll concentration and photosynthetic efficiency, while the subdued response of RENDVI underlined its limited applicability in low-biomass regions.

5. Conclusion and Recommendations

The temporal analysis of vegetation and soil-related indices indicates that the Gonabad region experiences persistently low vegetation cover, limited surface moisture, and increasing soil salinity throughout the dry season. The relatively low NDVI and NDWI values, coupled with a gradual rise in NDSI, reflect prevailing drought stress and surface salinization. However, the mid-summer increase observed in chlorophyll-sensitive indices (CIgreen, CIrededge, and GNDVI) suggests

localized vegetation recovery in areas such as polygons G1 and G7, likely due to temporary improvements in soil moisture or irrigation effects.

From an ecological and environmental standpoint, the region's main challenges are water scarcity and progressive salinization. Sustainable management strategies should therefore focus on improving water-use efficiency, restoring degraded soils, and maintaining ecological resilience. The integration of traditional qanat systems with modern subsurface or drip irrigation techniques can enhance groundwater recharge and minimize evaporation losses. Complementary measures, such as mulching, contour terracing, and soil salinity control, can further support long-term land stability and productivity.

In terms of agriculture, promoting drought- and salt-tolerant crops is essential. Crops such as saffron, pistachio, pomegranate, olive, and jujube are economically viable options, while native medicinal and aromatic plants including thyme, ferula, cumin, hyssop, and artemisia can be cultivated for ecological and economic diversification. In highly saline soils, the introduction of halophytic species such as *Salicornia* and *Tamarix* can serve as protective vegetation to mitigate land degradation.

From an urban and environmental planning perspective, establishing green belts using native xerophytic species, utilizing treated wastewater for irrigation, and restricting urban expansion in fertile or qanat-influenced areas are crucial for sustainable city development. Continuous monitoring of NDVI, NDWI, and NDSI should be adopted as an early-warning system to detect ecological stress and guide adaptive land-use planning.

Overall, the future development of Gonabad should adopt an integrated approach that combines indigenous water management traditions, advanced irrigation technology, and adaptive vegetation strategies to ensure

long-term ecological, agricultural, and urban sustainability in this semi-arid environment.

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