



Desertification Assessment in the Hodna Basin, Algeria using Desertification Degree Index and Geospatial Techniques

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Received: March 31, 2026 Accepted: August 03, 2026



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Citation

Mekentichi, S., Abdesselam, S. and Sahnouni, R. 2026. Desertification assessment in the Hodna Basin, Algeria using desertification degree index and geospatial techniques. *Annals of Arid Zone* 65(3): 157-171

<https://doi.org/10.56093/aaz.v65i3.177561>

<https://epubs.icar.org.in/index.php/AZ/article/view/177561>

Abstract: This study assesses desertification in the Hodna Basin, Algeria, using remote sensing and Geographic Information Systems (GIS) through the development of a Desertification Degree Index (DDI) based on feature-space analysis. Landsat 9 imagery was used to derive four spectral indices: the Normalized Difference Vegetation Index (NDVI), surface albedo, the Modified Soil-Adjusted Vegetation Index (MSAVI), and the Topsoil Grain Size Index (TGSI). Five feature-space combinations were evaluated, with the Albedo-NDVI and TGSI-NDVI models exhibiting the strongest statistically significant negative correlations. These two models were subsequently used for DDI generation and comparison. The Albedo-NDVI model achieved the highest performance, with an Overall Accuracy of 91.9% and a Kappa coefficient of 0.89, substantially outperforming the TGSI-NDVI model. The resulting desertification map indicates that approximately 65% of the Hodna Basin is affected by high to severe desertification, particularly in the central and southern regions, where prolonged aridity and intensive human activities have accelerated land degradation. In contrast, the northern part of the basin exhibits relatively low desertification levels owing to denser vegetation cover and more favorable environmental conditions. These findings demonstrate the robustness of the Albedo-NDVI feature-space model for desertification assessment in arid and semi-arid environments and highlight the value of integrating spectral indices with statistical feature-space analysis. The proposed approach provides a reliable and objective framework for large-scale desertification mapping and offers valuable decision support for soil conservation, ecosystem restoration, and sustainable land management in vulnerable dryland regions.

Key words: Desertification assessment, desertification degree index, geospatial techniques, Hodna Basin, Algeria.

Desertification is the degradation of land in arid, semi-arid, and dry sub-humid regions caused by the combined effects of climatic variability and human activities (UNCCD, 1994). It is one of the most critical environmental challenges affecting drylands, threatening ecosystem services, agricultural productivity, biodiversity, and human livelihoods. Globally, desertification affects nearly 40% of the Earth's land surface, impacts approximately 100 countries, and threatens the well-being of nearly two billion people living primarily in dryland regions (Cherlet *et al.*, 2018; Dregne *et al.*, 1991; Masson-Delmotte *et al.*, 2019) (Cherlet *et al.*, 2018; Masson-Delmotte *et al.*, 2019). Consequently, it has become a major concern for both the scientific community (Berdyayev *et al.*, 2025) and international organizations (Berry *et al.*, 2006; Cherlet *et al.*, 2018; UNCCD, 1994; Masson-Delmotte *et al.*, 2019; MEA, 2005). In Algeria, desertification poses a severe threat to the steppe ecosystem, which covers more than 20 m ha and represents one of the country's most vulnerable environments (MADR, 1974). Numerous studies have documented the increasing extent and severity of land degradation across these arid and semi-arid landscapes (Aïdoud *et al.*, 2006; Alliouche and Kouba, 2023; Arabi *et al.*, 2015; Belabbes and Tayeb, 2025; Belhadj *et al.*, 2023; Benslimane *et al.*, 2008; Bidi *et al.*, 2025; Hirche *et al.*, 2007; Nedjraoui and Slimane, 2008; Oussedik *et al.*, 2003; Kharchi *et al.*, 2024; Blissag *et al.*, 2024; Khadraoui *et al.*, 2025). Oussedik *et al.* (2003) produced the first desertification sensitivity map of northern Algeria using remote sensing and reported that more than half of the territory was classified as sensitive to very sensitive. Using MODIS imagery, Benslimane *et al.* (2008) estimated that approximately 75% of the steppe rangelands were already desertified or approaching the desertification threshold. More recently, Belabbes and Tayeb (2025) analysed 42 years of vegetation dynamics in Naâma using the Soil Adjusted Vegetation Index (SAVI), revealing pronounced fluctuations in vegetation cover ranging from 4.37% in 1977 to 0.20% in 1987, increasing to 8.80% in 1998, declining to 1.05% in 2008, and recovering slightly to 3.89% in 2019. These results highlight the high ecological vulnerability of Algeria's steppe ecosystems. The Hodna Basin, located in the centre of the Algerian steppe, exemplifies this

environmental vulnerability and has experienced extensive land degradation. Early investigations documented the expansion of agricultural land at the expense of natural rangelands and the progressive deterioration of soil resources (Abdesselam, 2013; Mimoune, 1995; Sebhi, 1987). Subsequent studies quantified desertification using different methodological approaches. Boudjemline and Semar (2018) applied the MEDALUS model and classified 61% of the basin as potentially sensitive to desertification. Sahnouni and Abdesselam (2018, 2023, 2024) analysed land cover dynamics between 1987 and 2016 and reported a 48.65% decline in rangelands, demonstrating that anthropogenic pressures, particularly overgrazing and population growth, contributed more strongly to degradation than climatic factors alone. Using logistic regression based on thirteen biophysical and socioeconomic variables, Kharchi *et al.* (2024) found that 45.4% of the basin exhibited high to very high susceptibility to desertification, with wind erosion and soil salinization identified as the dominant degradation processes. Blissag *et al.* (2024) employed a Cellular Automata-Artificial Neural Network (CA-ANN) model to simulate future land use and land cover dynamics through 2050, predicting continued expansion of bare land and a decline in agricultural areas. Khadraoui *et al.* (2025) assessed erosion sensitivity in the Soubella sub-watershed using the MEDALUS model integrated with GIS and showed that 56.4% of the area was highly sensitive to erosion. Similarly, Bidi *et al.* (2025) applied the MEDALUS approach in the Boussaada sub-basin, southwest of the Hodna Basin, and reported that 76% of the area was classified as sensitive to very sensitive to sand encroachment and desertification. Collectively, these studies demonstrate that the Hodna Basin is undergoing rapid degradation driven by the combined effects of climatic aridity and increasing human pressure. Despite these advances, important methodological limitations remain. The MEDALUS framework relies on expert-defined weighting schemes, whereas logistic regression provides a single statistical solution without evaluating alternative combinations of remotely sensed variables. Furthermore, many previous studies have relied primarily on conventional vegetation indices such as the Normalized Difference Vegetation Index (NDVI). Although NDVI

performs well in densely vegetated environments, its sensitivity is substantially reduced in arid and steppe ecosystems because soil background reflectance strongly influences the spectral response, leading to systematic underestimation of sparse vegetation cover. The Modified Soil-Adjusted Vegetation Index (MSAVI) was specifically developed to reduce soil background effects and has demonstrated improved performance in sparsely vegetated environments; however, it has not yet been evaluated in the Hodna Basin using a feature-space framework. In addition, previous investigations generally analysed vegetation and surface characteristics separately rather than integrating their spectral relationships into a unified analytical framework. Feature-space models provide a promising alternative for addressing these limitations. These models examine the two-dimensional relationships between paired spectral indices and have demonstrated considerable potential for desertification assessment in arid environments. Ma *et al.* (2011) and Pan and Li (2013) introduced the Albedo-NDVI feature-space concept. Wei *et al.* (2018) subsequently demonstrated that the Albedo-TGSI model achieved the highest accuracy for identifying barren land on the Mongolian Plateau. Feyzolahpour *et al.* (2025) compared four feature-space combinations in the Qazvin Plain, Iran, using the Desertification Degree Index (DDI) and found that the Albedo-MSAVI model produced the strongest correlation ($r = -0.417$), while the proportion of land classified as very severely desertified increased from 2.4% in 2018 to 10.3% in 2023. Likewise, Lamqadem *et al.* (2018) and Salih *et al.* (2021) successfully applied the DDI approach in arid regions of Morocco and Saudi Arabia, respectively. To date, however, no study has applied or systematically compared feature-space models for desertification assessment in the Hodna Basin. Because the performance of these models is strongly influenced by local environmental conditions, including soil characteristics, vegetation cover, and climate, their applicability cannot be assumed without regional evaluation. Consequently, identifying the most appropriate feature-space model for this ecosystem remains an important research challenge. The novelty of the present study lies in the application of the Desertification Degree Index (DDI), a feature-space-based approach that integrates paired spectral indices through

linear regression analysis. Unlike previous studies, this approach provides four major advantages. First, it enables a systematic comparison of four complementary feature-space models (Albedo-NDVI, Albedo-MSAVI, Albedo-TGSI, and MSAVI-TGSI) to identify the most suitable model for the Hodna Basin. Second, the DDI is objective and fully reproducible because it relies exclusively on statistical relationships, including Pearson's correlation coefficient and the coefficient of determination (R^2), derived from satellite reflectance rather than subjective expert weighting. Third, it generates a continuous measure of desertification severity that can subsequently be classified into five levels ranging from very low to very severe, providing a more detailed characterization than conventional categorical land cover classifications. Finally, the use of high-resolution Landsat 9 imagery (30 m) combined with the feature-space approach enables improved detection of local spatial heterogeneity and ongoing degradation processes. Accordingly, this study aims to evaluate and compare four feature-space models (Albedo-NDVI, Albedo-MSAVI, Albedo-TGSI, and MSAVI-TGSI) derived from Landsat 9 spectral indices to determine the most effective approach for assessing desertification in the Hodna Basin, Algeria.

Materials and Methods

Study Area

The Hodna Basin is a large inland depression located in north-central Algeria, covering approximately 26,000 km² and surrounded by several mountain ranges that create a highly heterogeneous landscape (Fig. 1). The basin lies within a transitional climatic zone between Mediterranean and Saharan influences, resulting in a pronounced north-south gradient ranging from semi-arid to subhumid conditions in the northern mountains to arid and Saharan climates across the central plains and southern depression. High aridity, marked seasonal temperature fluctuations, and elevated evapotranspiration rates contribute to frequent droughts and accelerate land degradation.

Geomorphologically, the basin comprises dissected piedmonts crossed by numerous wadis, a gently sloping alluvial plain favorable for flood-based agriculture, and a central

saline depression where runoff accumulates and evaporates. Elevation gradually decreases from east to west. Although the central saline depression (Chott El Hodna) plays an important hydrological role, it was excluded from this study because its permanent saline surface is not representative of the desertification processes investigated.

The Hodna Basin was selected for this study for several reasons. First, it constitutes a major ecological transition zone between the humid Tell Atlas and the Sahara, serving as a natural buffer against desertification. Second, its endorheic character and soils dominated by sandy, calcareous, and gypsiferous materials make the region highly susceptible to wind erosion and soil salinization. Third, recurrent droughts, intense convective storms, and episodic flash floods further accelerate land degradation through water erosion. Fourth, increasing anthropogenic pressures—including overgrazing, population sedentarization, mechanical clearing for rainfed cereal cultivation, and the expansion of irrigated agriculture—have intensified ecosystem degradation (Boudjemline and Semar, 2018; Sahnouni and Abdesselam, 2023). In addition,

the basin encompasses a wide range of land-cover types, including forests, steppes, rangelands, agricultural lands, dune systems, and saline surfaces, providing an excellent natural laboratory for evaluating desertification under diverse environmental conditions. Finally, field surveys conducted in May 2022 confirmed the presence of active degradation processes, including sand encroachment, rangeland deterioration, and soil salinization, particularly in the central and southern parts of the basin. These characteristics make the Hodna Basin a representative case study for investigating desertification dynamics and evaluating feature-space models in Algeria's steppe ecosystems.

Data collection

Data collection was conducted in late May 2020 to maximize vegetation contrast, minimize cloud cover, and avoid spectral variability associated with the summer season. Four Level-1 Landsat 9 images covering the Hodna Basin were acquired from the USGS EarthExplorer platform. All images have a spatial resolution of 30 m and less than 10% cloud cover. The study area was delineated using a vector boundary of the Hodna Basin.

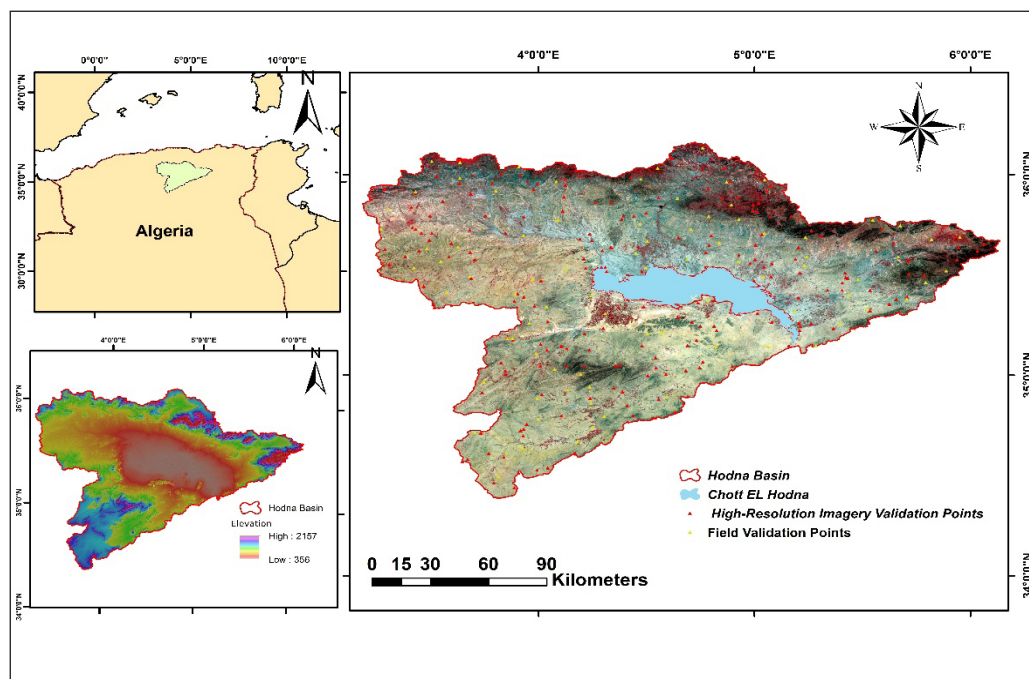


Fig. 1. Geographic location of the Hodna Basin, Algeria, showing the study area, the USGS Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) used to derive elevation values, and the Landsat 9 Operational Land Imager (OLI) RGB composite (bands 6-5-4) used as the background image to display the spatial distribution of the high-resolution imagery validation points and field validation points.

Table 1. Applied Remote Sensing Indices

Indices and Description	Equation
Normalized Difference Vegetation Index (NDVI) - Evaluates plant coverage. Positive values indicate vegetation and help distinguish healthy from degraded areas (Rouse <i>et al.</i> , 1974).	$NDVI = (NIR - R) / (NIR + R)$
Surface Albedo - Measures surface reflectivity to detect bare soils and land degradation; influenced by temperature, aridity, soil moisture, and vegetation cover (Liang <i>et al.</i> , 2003; Blok <i>et al.</i> , 2011; Guan <i>et al.</i> , 2009).	$Albedo = 0.356 \times B + 0.130 \times R + 0.373 \times NIR + 0.085 \times SWIR1 + 0.072 \times SWIR2 - 0.018$
Modified Soil-Adjusted Vegetation Index (MSAVI) - Adjusts NDVI for bare soil areas; useful for detecting sparse vegetation and desertification (Ren <i>et al.</i> , 2018; Qi <i>et al.</i> , 1994).	$MSAVI = [(2 \times NIR + 1) - \sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - R)}] / 2$
Topsoil Grain Size Index (TGSi) - Highlights exposed or minimally vegetated regions; high values indicate coarse, desertified soils (Xiao <i>et al.</i> , 2006).	$TGSi = (R - B) / (R + B + G)$

The accuracy assessment was based on 84 reference points collected during field surveys using a Global Positioning System (GPS) and complemented with high-resolution imagery available in Google Earth Pro.

Preprocessing of Satellite Images

Prior to spectral index calculation, all Level-1 Landsat 9 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) images underwent radiometric calibration to convert digital numbers (DNs) into top-of-atmosphere (TOA) reflectance. Atmospheric correction was subsequently performed using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm to derive surface reflectance. All preprocessing steps were carried out in ArcGIS 10.7.

The corrected images were then mosaicked and clipped using the Hodna Basin boundary while excluding the Chott El Hodna saline depression to produce the final study area used for subsequent analyses.

Derivation of Spectral Indices

Based on the pre-processed and clipped Landsat 9 OLI images, four spectral indices were derived to characterize land degradation and desertification in the Hodna Basin: the Normalized Difference Vegetation Index (NDVI), surface albedo, the Modified Soil-Adjusted Vegetation Index (MSAVI), and the Topsoil Grain Size Index (TGSi) (Table 1).

Data Normalization Processing

First, the minimum ($X_i, \min$) and maximum ($X_i, \max$) values for each index were determined across the entire study area. To facilitate direct comparison and combination in subsequent

analyses, these extrema were then used to normalize each indicator according to:

$$NDVI_{(Norm)} = ((NDVI - NDVI_{(min)}) / (NDVI_{(max)} - NDVI_{(min)})) \times 100$$

$$MSAVI_{(Norm)} = ((MSAVI - MSAVI_{(min)}) / (MSAVI_{(max)} - MSAVI_{(min)})) \times 100$$

$$Albedo_{(Norm)} = ((Albedo - Albedo_{(min)}) / (Albedo_{(max)} - Albedo_{(min)})) \times 100$$

$$TGSi_{(Norm)} = ((TGSi - TGSi_{(min)}) / (TGSi_{(max)} - TGSi_{(min)})) \times 100$$

Construction of Feature Spaces

To identify the optimal spectral index combination for desertification assessment, a systematic sampling grid consisting of 684 points spaced 6 km apart was generated in ArcMap across the Hodna Basin. The 6 km spacing was selected to provide homogeneous spatial coverage of the approximately 26,000 km² study area while ensuring a statistically robust sample size for correlation analysis.

For each sampling point, pixel values of the four normalized spectral indices (Albedo, NDVI, MSAVI, and TGSi) were extracted from the pre-processed Landsat 9 imagery. These data were used to construct five two-dimensional feature spaces representing the following index combinations: Albedo-NDVI, Albedo-MSAVI, Albedo-TGSi, TGSi-MSAVI, and TGSi-NDVI.

For each feature space, a linear regression model was fitted in Microsoft Excel, and Pearson's correlation coefficient (r) together with the coefficient of determination (R^2) were calculated to quantify the strength of the relationships between paired indices. The combination exhibiting the strongest statistical

relationship was selected for the calculation of the Desertification Degree Index (DDI). The 684 sampling points were used exclusively for feature-space analysis and model selection and were not included in the subsequent validation procedures.

Extraction of the Degrees of Desertification Index (DDI)

The Desertification Degree Index (DDI) is a feature-space-based indicator widely used for mapping and assessing land degradation in arid and semi-arid environments (Becerril-Piña *et al.*, 2016; Hashem Geloogerdi *et al.*, 2021; Lamaamri *et al.*, 2023; Lamqadem *et al.*, 2018; Ma *et al.*, 2011; Pan and Li, 2013; Vendruscolo *et al.*, 2021; Wei *et al.*, 2020; Ahmadi and Kanani, 2025). In this study, the DDI was calculated from the optimal feature-space model using the following equation:

$$DDI = K \times \text{Index2} - \text{Index1}$$

where:

- DDI is the Desertification Degree Index;
- (K) is the slope of the orthogonal regression line fitted to the selected feature space;
- Index (1) and Index (2) represent the paired spectral indices defining the selected feature space.

The DDI was computed for each pixel across the Hodna Basin to generate a continuous desertification map. The resulting values were classified into five desertification levels: non-desertified, low, moderate, high, and severe desertification.

Classification thresholds were determined using the Jenks Natural Breaks algorithm (Jenks, 1963) implemented in ArcGIS 10.7. This method was selected because it minimizes within-class variance while maximizing between-class variance, making it particularly suitable for continuous environmental variables exhibiting natural groupings (Jenks, 1963; Wei *et al.*, 2018).

Accuracy Assessment

The accuracy of the desertification maps was evaluated using an independent validation dataset comprising 284 reference points. Of these, 84 ground-truth points were collected during field surveys conducted in May 2022. Sampling locations were selected to represent

the full range of desertification classes and land-cover conditions within the Hodna Basin. At each site, the degree of land degradation was assessed through direct field observations based on vegetation cover, soil exposure, sand encroachment, surface crusting, and visible signs of salinization. The geographic coordinates of all field observations were recorded using a handheld Global Positioning System (GPS) receiver.

To improve the spatial distribution of the validation dataset, an additional 200 reference points were generated through random sampling across the study area. These locations were independently interpreted using high-resolution Google Earth imagery acquired in May 2022 and verified against Landsat 9 true-color composites. The resulting dataset was used exclusively for the independent validation of the desertification maps generated from the different feature-space models.

Classification performance was evaluated using a confusion matrix from which Overall Accuracy (OA) and the Kappa coefficient (kappa) were calculated.

Overall Accuracy represents the proportion of correctly classified validation samples, whereas the Kappa coefficient measures the agreement between the classified and reference data after accounting for agreement expected by chance. Kappa values range from -1 to +1, with higher positive values indicating stronger classification agreement (Congalton and Green, 2019).

Results and Discussion

Characteristics of Desertification Indicators

The Hodna Basin encompasses a wide range of land-cover types, including forests, rangelands, steppes, bare soils, dune systems, agricultural lands, and sabkhas concentrated primarily in its central depression. To capture this environmental heterogeneity, four complementary spectral indices were selected to characterize the distinct biophysical properties of these landscapes. Figure 2 illustrates the spatial distribution of the Normalized Difference Vegetation Index (NDVI), Modified Soil-Adjusted Vegetation Index (MSAVI), surface albedo, and Topsoil Grain Size Index (TGSi), which were subsequently combined to derive the Desertification Degree Index (DDI).

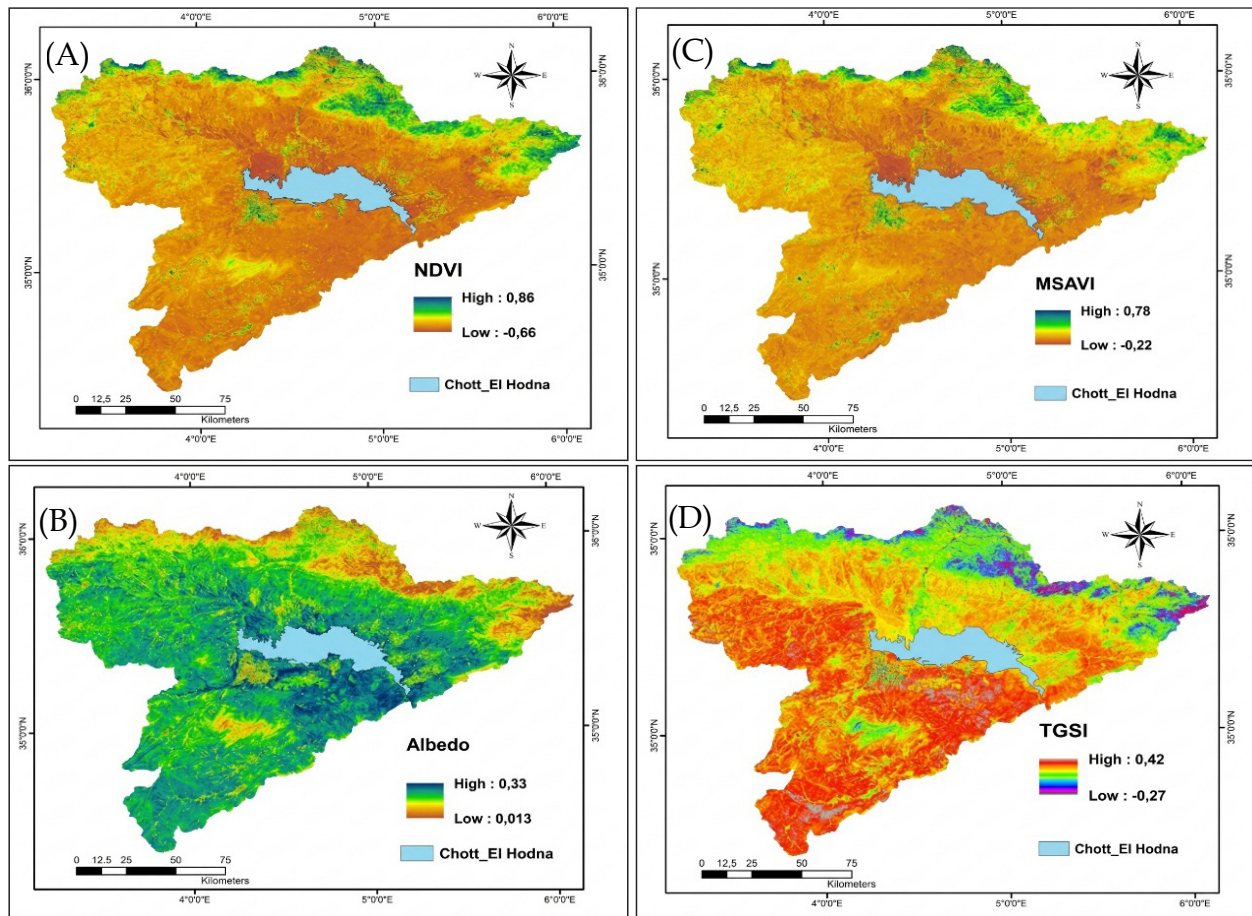


Fig. 2. Spatial distribution of spectral indices for desertification assessment in the Hodna Basin.

A) NDVI; B) MSAVI; C) ALBEDO; D) TGSI.

Vegetation-related indices (Fig. 2A and Fig. 2B) exhibited high values in densely vegetated areas, particularly the northern forests and irrigated agricultural lands distributed throughout the basin. NDVI ranged from -0.66 to 0.86 , while MSAVI varied from -0.22 to 0.78 . The highest values were associated with dense vegetation, whereas the lowest values occurred over dune fields, urban areas, and extensive bare soils located primarily in the central and southern portions of the basin. Surface albedo (Fig. 2C) ranged from 0.013 to 0.33 . Low albedo values characterized forests and irrigated croplands, whereas higher values were observed over sparsely vegetated or unvegetated surfaces, including steppes, sandy areas, and bare soils in the south-central basin. The spatial distribution of albedo showed a clear inverse pattern relative to the vegetation indices. The Topsoil Grain Size Index (TGSI) (Fig. 2D) ranged from -0.27 to 0.42 . High TGSI values, indicative of coarse-textured and highly reflective soils, were concentrated

in dune systems and other degraded surfaces. In contrast, low TGSI values were associated with forested and agricultural areas where vegetation cover was relatively dense.

Overall, the four spectral indices displayed consistent and complementary spatial patterns. Areas with dense vegetation were characterized by high NDVI and MSAVI values together with low albedo and TGSI values, whereas degraded landscapes dominated by bare soil and sand exhibited the opposite trend. These contrasting patterns demonstrate the complementary nature of the selected indices and support their combined use for detecting and mapping desertification across heterogeneous arid environments, consistent with previous studies (Becerril-Piña *et al.*, 2016; Ma *et al.*, 2011; Zeng *et al.*, 2006).

Feature Spaces and Linear Relationships Between Variables

Five feature-space models were constructed by combining the four spectral indices (NDVI,

MSAVI, Albedo, and TGSi) to improve the detection of desertified areas. The tested combinations included Albedo-TGSi, Albedo-NDVI, Albedo-MSAVI, TGSi-MSAVI, and TGSi-NDVI, with each pair selected to capture complementary land surface characteristics. Linear regression analysis was then performed to evaluate the strength of the relationships within each feature space and identify the most suitable model for desertification assessment. For each feature space, linear regression was applied to the 684 systematically distributed sampling points to determine the slope (K) and intercept of the relationship between the paired indices. The resulting regression equation was subsequently used to calculate the Desertification Degree Index (DDI) for each

pixel following the methodology of Pan and Li (2013).

The feature-space analysis revealed strong inverse relationships between the vegetation indices and the surface-related indicators. Significant negative correlations were observed for Albedo-NDVI ($r = -0.85$, $R^2 = 0.73$), TGSi-NDVI ($r = -0.80$, $R^2 = 0.64$), Albedo-MSAVI ($r = -0.70$, $R^2 = 0.49$), and TGSi-MSAVI ($r = -0.61$, $R^2 = 0.38$) (Fig. 3A-D). These relationships indicate that increasing Albedo or TGSi values are generally associated with decreasing NDVI and MSAVI values, reflecting reduced vegetation cover and greater land degradation. Conversely, low Albedo and TGSi values correspond to densely vegetated areas,

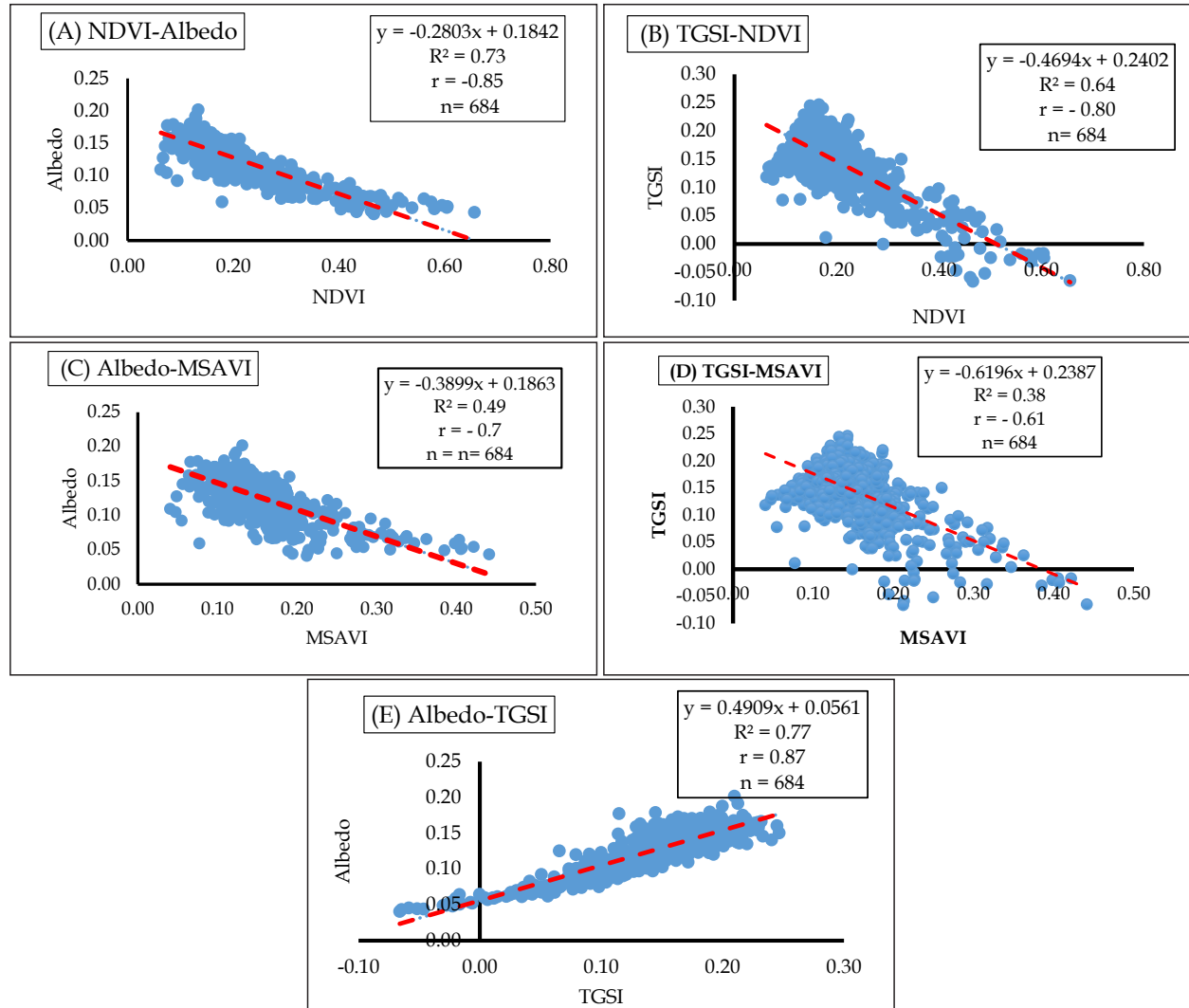


Fig. 3. Correlation analysis between spectral indices in constructed feature spaces (A) NDVI-Albedo, (B) TGSi-NDVI, (C) Albedo-MSAVI, (D) TGSi-MSAVI, (E) Albedo-TGSi.

indicating more stable and less degraded land conditions.

A strong positive correlation was observed between Albedo and TGSi (($r = 0.87$), ($R^2 = 0.77$)) (Fig. 3E), suggesting that both indices respond similarly to surface characteristics associated with land degradation, such as soil brightness, texture, and moisture conditions.

Among the evaluated feature-space models, Albedo-NDVI and TGSi-NDVI exhibited the strongest relationships, explaining 73% and 64% of the variance, respectively. The superior performance of the Albedo-NDVI model confirms its effectiveness in characterizing desertification patterns in the Hodna Basin, consistent with previous studies conducted in arid and semi-arid environments (Becerril-Piña *et al.*, 2016; Ma *et al.*, 2011; Zeng *et al.*, 2006). Accordingly, these two feature-space models were selected for the subsequent desertification mapping and assessment.

Desertification Degrees Assessment Based on NDVI-Albedo and NDVI-TGSi Feature Spaces

Areas classified as non-desertified are concentrated primarily in the northern and northeastern parts of the Hodna Basin, where forests and scattered agricultural lands predominate. Both the NDVI-Albedo and NDVI-TGSi models produced highly consistent spatial patterns for the non-desertified and low desertification classes, particularly along the northern foothills and the higher-elevation areas in the south.

Table 3. DDI Classification Ranges for Desertification Levels

Desertification class	NDVI-Albedo DDI range	NDVI-TGSi DDI range
Severe desertification	< 1.58	< 0.72
High desertification	1.49-1.67	0.27-0.56
Medium desertification	1.67-1.95	0.56-0.77
Low desertification	1.95-2.38	0.77-1.09
Non-desertification	2.38-3.50	1.09-1.99

Table 4. Desertification Area and Coverage Percentage

Class	Area (km ²) – NDVI-Albedo	Area (%)	Area (km ²) – NDVI-TGSi	Area (%)
Severe desertification	6,916.99	28.02%	0.67	0.003%
High desertification	9,134.16	37.00%	13,996.10	56.70%
Medium desertification	4,933.80	19.99%	6,907.92	27.98%
Low desertification	2,486.96	10.07%	2,619.27	10.61%
Non-desertification	1,212.58	4.91%	1,160.54	4.70%

Table 2. Coefficients (K) for Feature Space Models

Feature space model	K Value
NDVI-Albedo	3.75
NDVI-TGSi	2.13

Greater differences between the two models emerged in the moderate desertification class, mainly within the western and northeastern transitional zones. The NDVI-Albedo model classified 4,933.80 km² (19.99%) as moderately desertified, whereas the NDVI-TGSi model identified 6,907.92 km² (27.98%).

The discrepancies became more pronounced for the high desertification class. The NDVI-Albedo model mapped 9,134.16 km² (37.00%), primarily across the northern and western sectors of the basin, while the NDVI-TGSi model classified 13,996.10 km² (56.70%), extending over much of the eastern, central, and southeastern regions. The greatest contrast was observed for the severe desertification class. The NDVI-Albedo model identified 6,916.99 km² (28.02%), concentrated mainly in the central and southeastern portions of the basin. In comparison, the NDVI-TGSi model classified only 0.67 km² (0.003%) as severely desertified, highlighting a substantial difference in the spatial distribution predicted by the two models.

The regression slopes (K) obtained for each feature-space model are presented in Table 2, while the DDI classification thresholds derived using the Jenks Natural Breaks method are summarized in Table 3. The resulting desertification maps for 2022 are shown in

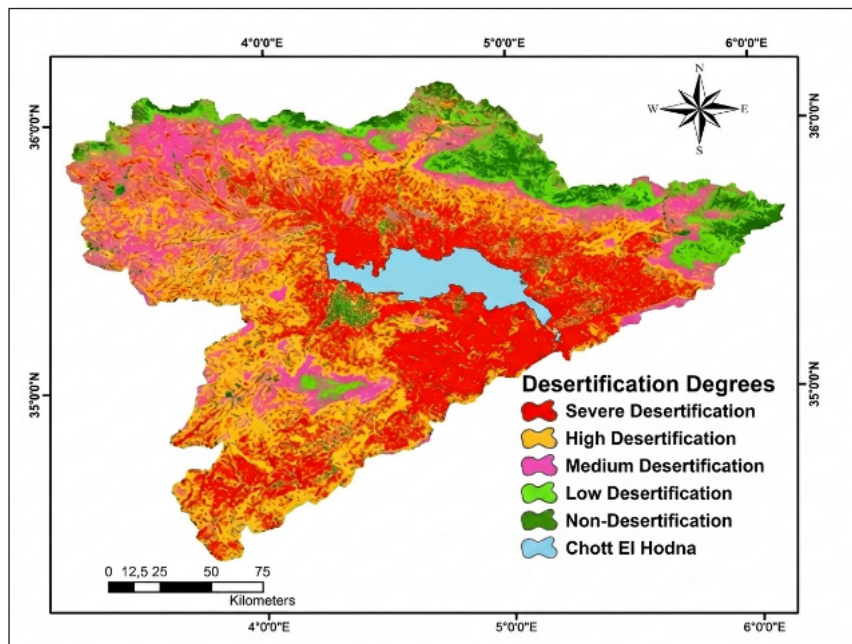


Fig. 4. Hodna Basin Desertification (2022) –Albedo and NDVI

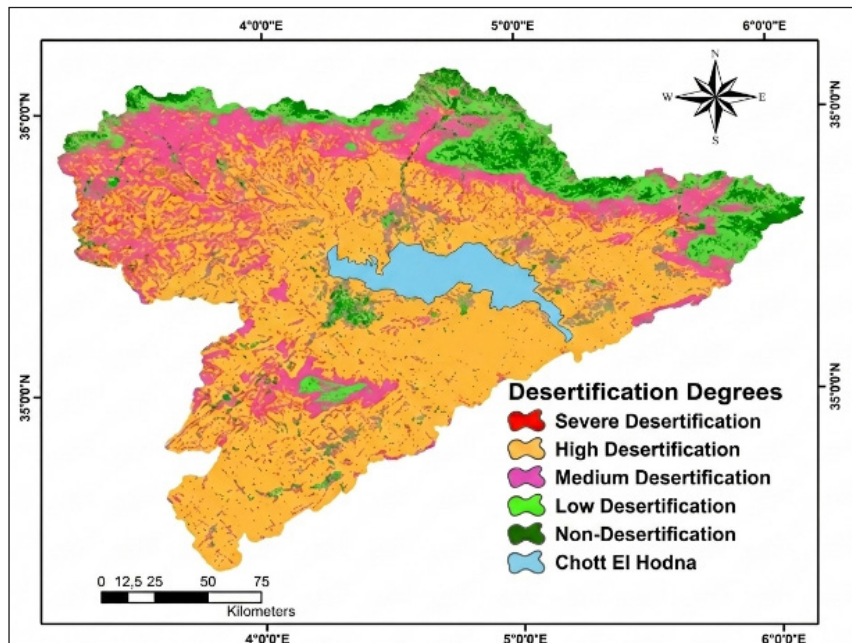


Fig. 5. Hodna Basin Desertification (2022) – NDVI and TGSI.

Fig. 4 and 5, and the spatial extent of each desertification class is reported in Table 4.

Accuracy Assessment

To assess the reliability of the classification, 284 ground truth points collected with GPS were compared against the classified outputs (Table 5).

The accuracy assessment demonstrated the clear superiority of the Albedo-NDVI

feature-space model over the TGSI-NDVI model across all desertification classes. The Albedo-NDVI model consistently achieved classification accuracies exceeding 85% and surpassed 90% for the moderate, high, and severe desertification classes.

In contrast, the TGSI-NDVI model exhibited substantially lower and more variable classification accuracies, particularly for the non-desertified and severe desertification classes,

Table 5. Comparative Summary of Classification Accuracy for NDVI-Albedo and NDVI-TGSI Models

Metric	NDVI-Albedo Model	NDVI-TGSI Model
Overall Accuracy (%)	91.90	46.83
Kappa Coefficient	0.89	0.24
Producer Accuracy – Severe Desertification (%)	92.75	0.00
Producer Accuracy – High Desertification (%)	93.94	68.42
Producer Accuracy – Medium Desertification (%)	93.62	67.24
Producer Accuracy – Low Desertification (%)	85.42	71.43
Producer Accuracy – Non-Desertification (%)	90.48	75.00
User Accuracy – Range (%)	79.17-95.52	40.00-46.71
Total Validation Samples	284	284

indicating limited capability to distinguish the full gradient of land degradation. Overall, the Albedo-NDVI model achieved an Overall Accuracy (OA) of 91.90% with a Kappa coefficient (kappa) of 0.89, demonstrating excellent agreement with the reference data. By comparison, the TGSI-NDVI model yielded an OA of only 46.83% and a Kappa coefficient of 0.24, indicating poor classification performance.

The near absence of pixels classified as severely desertified by the TGSI-NDVI model (0.003%) further highlights its limited sensitivity to extreme land degradation, consistent with its low Kappa coefficient. These results support the selection of the Albedo-NDVI feature space as the most reliable model for desertification mapping in the Hodna Basin. The superior performance of this approach is consistent with previous studies conducted in arid and semi-arid environments (Becerril-Piña *et al.*, 2016; Ma *et al.*, 2011; Zeng *et al.*, 2006).

Based on the Albedo-NDVI model, the Hodna Basin was classified into five desertification categories: non-desertified, low, moderate, high, and severe (Fig. 4). The resulting map revealed a pronounced spatial gradient in land degradation. Non-desertified areas are concentrated mainly in the northern part of the basin, where forests and intensive agricultural lands provide dense vegetation cover that mitigates desertification processes.

Areas classified as having low and moderate desertification account for 10.07% and 19.99% of the basin, respectively, and are distributed primarily across the Hodna and Belezma massifs and their foothills. These landscapes are characterized by moderate to dense vegetation cover, relatively favorable soil conditions, and less intensive human disturbance, including

controlled grazing, arboriculture, and seasonal agriculture.

In contrast, areas classified as having high and severe desertification occupy approximately 65% of the basin and are concentrated in the central and southern sectors, particularly around Chott El Hodna. These areas are characterized by sparse vegetation, extensive bare soils, and pronounced signs of land degradation. Compared with the MEDALUS-based assessment of Boudjemline and Semar (2018), which identified 61% of the basin as environmentally sensitive to desertification, the present results indicate a greater extent of severely degraded land, suggesting an intensification of desertification processes in recent years.

Drivers and Implications of Desertification in the Hodna Basin

Land degradation in the Hodna Basin results from the combined influence of climatic and anthropogenic drivers, including prolonged drought, increasing aridity, overgrazing, unsustainable agricultural practices, groundwater overexploitation, and the limited regeneration of natural vegetation (Abdesselam, 2013; Mimoune, 1995; Sahnouni, 2020; Sahnouni and Abdesselam, 2024; Sebhi, 1987). These interacting processes have progressively reduced vegetation cover, accelerated soil degradation, and increased the susceptibility of the basin to desertification.

The implementation of the National Agricultural Development Plan (PNDA) in 2000 further intensified these pressures by promoting agricultural expansion. Although the program contributed to agricultural production and rural development, it also accelerated the conversion of natural rangelands into cultivated

land, fragmented traditional grazing systems, and increased pressure on fragile soils and vegetation (Djeddaoui, 2018; The resulting decline in vegetation cover has favored sand encroachment and the expansion of degraded areas in some regions, as shown in Fig. 7, particularly in the southern part of the basin (Mimoune, 1995; Sahnouni and Abdesselam, 2018, 2024).

These findings are consistent with previous investigations conducted in the Hodna Basin. Boudjemline and Semar (2018), using the MEDALUS model, reported that a large proportion of the basin is environmentally sensitive to desertification. Likewise, Kharchi *et al.* (2024) identified extensive areas with high to very high desertification susceptibility using a logistic regression model based on thirteen environmental and socioeconomic variables. Similarly, Bidi *et al.* (2025) showed that 76% of the neighboring Boussaada sub-basin is sensitive to very sensitive to desertification and sand encroachment. At the national scale, several studies have reported comparable degradation trends across the Algerian steppe, highlighting the combined influence of climatic stress and increasing human pressure on rangeland ecosystems (Arabi *et al.*, 2015; Hirche *et al.*, 2011; Nedjraoui and Slimane, 2008; Djeddaoui, 2018).

Compared with these previous studies, the present work provides several methodological improvements. Earlier assessments were primarily based on expert-driven multicriteria approaches, such as MEDALUS, or statistical susceptibility models, such as logistic regression, which do not directly evaluate the spectral response of land degradation. In contrast,

this study employs an objective feature-space approach based exclusively on satellite-derived spectral indices. By systematically comparing four feature-space models using high-resolution Landsat 9 imagery, this research identifies the most suitable spectral combination for desertification assessment in the Hodna Basin while providing a continuous and spatially explicit characterization of degradation severity. This comparative framework reduces the subjectivity associated with weighting procedures and offers a reproducible methodology that can support future desertification monitoring in Algerian steppe ecosystems.

Conclusions

This study demonstrated the effectiveness of remote sensing-based feature-space models for assessing desertification in the Hodna Basin, one of Algeria's most environmentally vulnerable regions. By integrating spectral indices derived from Landsat 9 imagery, namely the Normalized Difference Vegetation Index (NDVI), surface albedo, and the Topsoil Grain Size Index (TGSi), two feature-space models were developed and evaluated. The results showed that the Albedo-NDVI model outperformed the TGSi-NDVI model, achieving higher classification accuracy, stronger agreement with the reference data, and greater ability to discriminate among different levels of land degradation. These findings demonstrate that the Albedo-NDVI feature space is particularly well suited for desertification assessment in arid and semi-arid environments characterized by sparse vegetation and strong soil background effects.

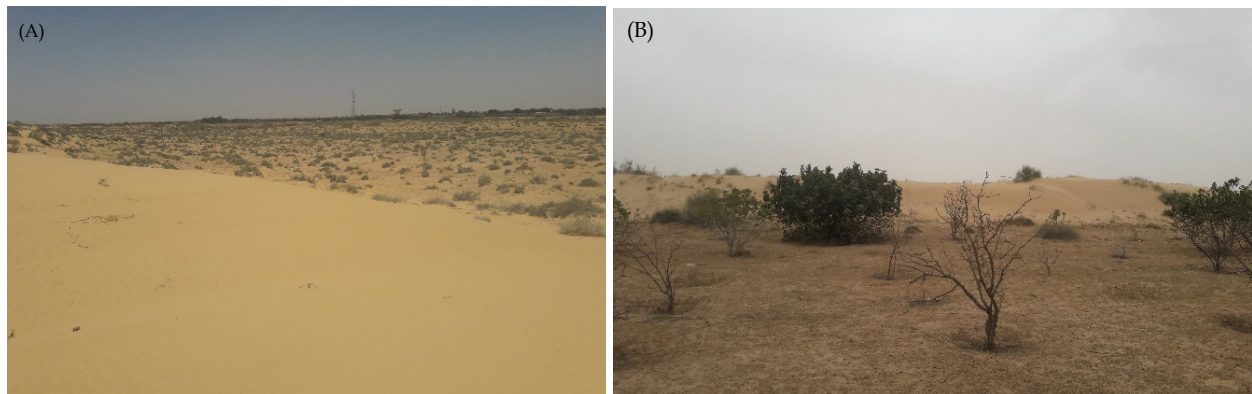


Fig. 7 (A) Vegetation degradation in agricultural and pastoral lands. (B) Sand encroachment and desertification in the central and southern parts of the Hodna Basin.

The resulting desertification map revealed that approximately 65% of the Hodna Basin is affected by high to severe desertification. The most degraded areas are concentrated in the central and southern parts of the basin, where prolonged aridity, reduced vegetation cover, overgrazing, and unsustainable land-use practices have intensified land degradation. In contrast, the northern mountainous regions exhibit lower desertification levels owing to denser vegetation cover, more favourable environmental conditions, and greater ecosystem resilience.

Beyond its regional application, this study demonstrates the value of feature-space analysis as a simple, objective, cost-effective, and operational approach for large-scale desertification mapping. The use of an independently validated reference dataset further strengthens the reliability of the results and highlights the potential of satellite remote sensing for environmental monitoring and sustainable land management.

The generated desertification map provides a valuable decision-support tool for policymakers, land managers, and environmental agencies. It enables the identification of priority intervention areas and can support ecological restoration, sustainable grazing management, vegetation rehabilitation, and long-term monitoring of land degradation. These applications are particularly important in the context of increasing climate variability and growing pressure on natural resources in dryland ecosystems.

Despite these encouraging results, several limitations should be acknowledged. First, the analysis was based on satellite imagery acquired during a single period, and the performance of spectral indices may vary with seasonal vegetation phenology and climatic conditions. Second, although the validation dataset was independent and robust, the spatial distribution of field observations was constrained by site accessibility, potentially limiting representation of some remote areas. Third, the proposed models rely primarily on spectral characteristics of vegetation and surface reflectance and do not explicitly incorporate other important drivers of desertification, including soil moisture, precipitation variability, groundwater availability, wind erosion intensity, and socioeconomic pressures.

Future research should incorporate multi-temporal satellite imagery to better capture the seasonal and interannual dynamics of desertification. Integrating additional climatic, edaphic, topographic, and anthropogenic variables would likely improve model robustness and predictive performance. Furthermore, combining feature-space analysis with advanced machine learning and artificial intelligence techniques offers promising opportunities for developing more accurate, dynamic, and transferable desertification monitoring systems. Such advances would improve understanding of land degradation processes and provide stronger scientific support for sustainable land management and desertification mitigation in the Hodna Basin and other dryland regions facing similar environmental challenges.

Declarations

The authors have no competing interests.

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