

Assessment of agricultural soil sustainability using selected spectral indices: an applied study in Al-Saqi Farm – Western Desert of Karbala Governorate, Iraq

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Abstract

This study aimed to evaluate agricultural soil sustainability in arid environments using a set of advanced spectral indices, namely the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Optimized Soil-Adjusted Vegetation Index (OSAVI), based on Sentinel-2 satellite data processed within the Google Earth Engine platform. The study was conducted at Al-Saqi Farm located in the western desert of Karbala Governorate, using (50) field observation points. The results showed that NDVI values ranged from (-0.041 to 0.135), GNDVI values ranged from (-0.114 to 0.269), and OSAVI values ranged from (-0.036 to 0.113), reflecting the dominance of sparse vegetation cover and bare soil conditions. Spatial analysis revealed that bare lands constituted (63.95%) according to NDVI, (80.52%) under severe stress conditions according to GNDVI, and (83.50%) as barren lands based on OSAVI. Statistical analysis indicated a very strong correlation among the indices ($r = 0.86-0.89$, $p < 0.01$), demonstrating their integrative capability in characterizing environmental conditions. Furthermore, the composite sustainability index (SI) results showed that more than (80%) of the study area falls within the low sustainability category. The findings confirm that spectral indices represent an effective tool for assessing soil sustainability in arid environments and can be reliably utilized to support sustainable agricultural management decisions.

Keywords: agricultural sustainability, arid soils, remote sensing, spectral indices

Introduction

Agricultural sustainability represents one of the fundamental pillars for achieving food security and preserving natural resources, particularly in arid and semi-arid environments characterized by fragile ecosystems and high susceptibility to degradation. Recent literature indicates that soil degradation in such regions is closely associated with multiple factors, including water scarcity, high temperatures, increasing soil salinity, and unsustainable agricultural practices (Li et al., 2024).

In this context, remote sensing technologies have emerged as effective tools for assessing environmental changes and monitoring soil and vegetation health, as they provide accurate spatial and temporal data covering large areas with high efficiency (Xie et al., 2023). Spectral indices are among the most important outputs of these technologies, widely used to estimate biomass, chlorophyll content, and plant stress, serving as indirect

indicators reflecting soil condition and sustainability (Zhang et al., 2024). The NDVI is one of the most commonly used indices for vegetation assessment, relying on the difference between red and near-infrared reflectance, and has proven its efficiency in monitoring long-term vegetation changes (Tucker, 1979). However, its limited sensitivity in areas with sparse vegetation has led to the development of alternative indices such as GNDVI, which utilizes the green band and is more sensitive to chlorophyll content, making it effective for detecting early plant stress (Wu et al., 2023). On the other hand, the OSAVI index was developed to minimize soil background effects, especially in areas with low vegetation cover, by incorporating a correction factor that reduces soil reflectance influence (Rondeaux et al., 1996). Recent studies have demonstrated that integrating these indices provides a more accurate and comprehensive assessment of soil and vegetation conditions (Chen et

al., 2024). In Iraq, particularly in desert regions such as Karbala Governorate, soils face significant environmental challenges, including continuous degradation and declining agricultural productivity, which necessitate the adoption of modern tools for sustainability assessment and agricultural management planning (Zhao et al., 2024).

Materials and Methods

Study Area

Al-Saqi Farm is located within the western desert of Karbala Governorate in central Iraq, between longitudes (43.50°–43.56° E) and latitudes (32.37°–32.42° N). It lies within a transitional zone between agricultural and semi-arid environments (**Figure 1**). The area is characterized by relatively harsh climatic conditions, including high temperatures, low rainfall, and high evaporation rates. These climatic factors play a major role in influencing vegetation cover and soil properties in the region.

Al-Saqi Farm is situated on the outskirts of Karbala and is used for various agricultural purposes, relying primarily on artificial irrigation due to limited natural water resources. The area represents a suitable model for studying environmental degradation and agricultural sustainability using remote sensing techniques (Hussein & Munkhi, 2021).

Satellite Data

Sentinel-2 satellite imagery, provided by the European Space Agency (ESA), was utilized in this study. The satellite is equipped with the Multispectral Instrument (MSI), offering multispectral data with spatial resolution up to 10 meters. The selected image was acquired on December 11, 2025, and processed using the Google Earth Engine platform, which provides appropriate spatial and temporal resolution for spectral index analysis. These data were selected due to their high accuracy and reliability in assessing vegetation cover and environmental changes. The following spectral bands were used: Red, Green, and Near-Infrared (NIR), to derive the spectral indices (NDVI, GNDVI, OSAVI), which are standard indicators for vegetation assessment.

Image Processing

Digital image processing was performed using Geographic Information Systems (GIS) software and remote sensing tools such as ArcGIS and ENVI. The processing steps included:

- Radiometric and atmospheric correction
- Definition of the Area of Interest (AOI)
- Extraction of spectral indices
- Reclassification of indices into thematic classes

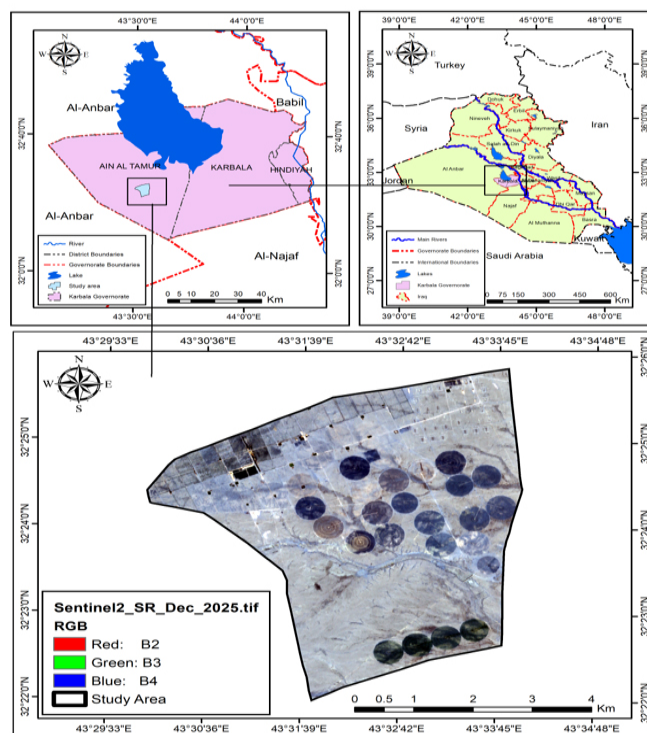


Figure 1. Location of the Study Area

The indices were classified using statistical approaches based on thresholding techniques, dividing the data into environmental categories representing different levels of vegetation cover and stress.

Spectral Indices Calculation

The spectral indices were calculated according to the following equations:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1) \text{ (Tucker, 1979)}$$

$$GNDVI = \frac{NIR - Green}{NIR + Green} \quad (2) \text{ (Gitelson et al., 1996)}$$

$$OSAVI = \frac{NIR + Red}{NIR + Red + 0.16} \quad (3) \text{ (Rondeaux et al., 1996)}$$

These indices are used to assess: vegetation cover density, plant health, and soil influence. Huete (1988) and Rouse et al. (1974) emphasized the importance of these indices in vegetation analysis.

Normalization

The normalization process was applied to the spectral indices to standardize their values within the range (0–1) using the following equation:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4)$$

This step ensures the compatibility of different indices for integration into a single composite index.

Weight Determination Using AHP

The Analytic Hierarchy Process (AHP) was employed to determine the relative weights of the spectral indices through pairwise comparisons and evaluation of their relative importance. Previous studies have shown that AHP is one of the most accurate and reliable methods for weight determination in environmental modeling (Saaty, 1980).

Agricultural Sustainability Index Calculation

The agricultural sustainability index was calculated using the following equation:

$$SI = 0.539 \times NDVI_{norm} + 0.297 \times GNDVI_{norm} + 0.164 \times OSAVI_{norm} \quad (5)$$

where the weights were determined based on the AHP matrix.

Statistical Analysis

Statistical analysis was conducted to examine:

- Correlation relationships among the indices
- Spatial variability
- The relationship between sustainability and environmental factors

Pearson correlation coefficients were used to determine the strength of the relationships among the spectral indices.

Mapping

Maps were produced using ArcGIS Pro, where the following steps were carried out:

- Representation of the spatial distribution of indices
- Classification of areas based on sustainability levels
- Calculation of area for each class

The results were visually represented to facilitate spatial interpretation of the phenomena.

Results and Discussion

Spatial Variability of Spectral Indices

The results of satellite image analysis revealed a clear spatial variability in the values of the spectral indices (NDVI, GNDVI, OSAVI) across the study locations, as shown in **Table 1**, which includes the numerical values for each observation point.

This variability indicates heterogeneity in the environmental characteristics of soil and vegetation within Al-Saqi Farm. The values ranged from low positive

Table 1. Spectral Index Values for the Study Locations

Site N°	NDVI	GNDVI	OSAVI	Site N°	NDVI	GNDVI	OSAVI
P1	0.1358	0.2698	0.1140	16	0.0630	0.1811	0.0544
P2	0.0697	0.1983	0.0580	17	0.0582	0.1696	0.0499
P3	0.0793	0.2210	0.0659	18	0.0723	0.1984	0.0611
P4	0.0656	0.1775	0.0547	19	0.0627	0.1777	0.0533
P5	0.0755	0.1931	0.0636	20	0.0680	0.1871	0.0583
P6	0.0759	0.2017	0.0647	21	0.0713	0.2102	0.0618
P7	0.0643	0.1791	0.0552	22	0.0635	0.1733	0.0541
P8	0.0685	0.2075	0.0592	23	0.0620	0.1786	0.0534
P9	0.0623	0.1818	0.0537	24	0.0597	0.1744	0.0515
P10	0.0614	0.1802	0.0527	25	0.0643	0.1741	0.0548
1	0.0582	0.1802	0.0505	26	0.0604	0.1830	0.0518
2	0.0726	0.2269	0.0616	27	0.0635	0.2219	0.0542
3	0.0577	0.1771	0.0495	28	0.0570	0.1972	0.0490
4	0.0728	0.2044	0.0624	29	0.0655	0.2055	0.0568
5	0.0607	0.1813	0.0522	30	0.0644	0.1958	0.0553
6	0.0738	0.1963	0.0632	31	-0.0142	-0.1141	-0.0093
7	0.0675	0.1821	0.0579	32	-0.0388	-0.0486	-0.0341
8	0.0678	0.1874	0.0579	33	-0.0030	0.0737	-0.0022
9	0.0755	0.1968	0.0645	34	-0.0411	-0.0540	-0.0361
10	0.0610	0.1952	0.0527	35	0.0561	0.1771	0.0477
11	0.0611	0.1667	0.0525	36	0.0784	0.1981	0.0652
12	0.0626	0.1720	0.0528	37	0.0786	0.2193	0.0671
13	0.0583	0.1972	0.0503	38	0.0804	0.2278	0.0653
14	0.0647	0.2057	0.0554	39	-0.0385	-0.0393	-0.0336
15	0.0491	0.1744	0.0421	40	0.0835	0.2253	0.0675

to negative in some locations, reflecting differences in vegetation cover, moisture content, and degree of soil degradation. Recent studies confirm that such spatial variability represents a direct indicator of heterogeneity in soil physical and chemical properties, particularly in arid environments characterized by environmental instability (Li et al., 2024; Zhang et al., 2024).

The spectral maps (Figures 2, 3, and 4) show that areas with high values are very limited and scattered, whereas low values dominate most of the study area, indicating the prevalence of unfavorable environmental conditions for vegetation growth.

The areas associated with rainfall variability or agricultural management practices. In contrast, the moderate vegetation cover, which constitutes only (10.49%), reflects the limited extent of areas with acceptable vegetation productivity. This may indicate the presence of agricultural pockets or zones characterized by relatively better soil and water conditions. These areas are likely associated with the availability of irrigation water or a relatively higher organic matter content, which enhances the soil's capacity to support plant growth.

The results presented in **Figure 2** and **Table 2** indicate that higher values are concentrated only in limited areas, often associated with the presence of irrigation sources or better agricultural management practices, whereas low values dominate areas distant from these

Table 2. Vegetation Cover Classification Based on NDVI

Class	Range	Area (km²)	Percentage(%)
Bare land (no vegetation cover)	-0.07 – 0.06	17.26	63.95
Low-density vegetation cover	0.07 – 0.09	6.90	25.56
Moderate vegetation cover	0.10 – 0.66	2.83	10.49
Total	—	26.99	100

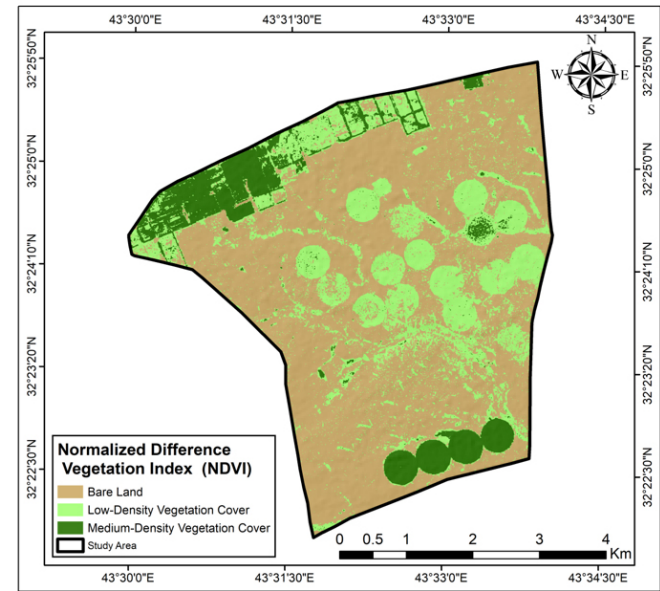


Figure 2. Spatial Distribution of the Normalized Difference Vegetation Index (NDVI)

factors. This distribution indicates clear environmental degradation, as the low proportion of healthy vegetation cover represents an indicator of declining ecosystem services, such as soil stabilization and erosion reduction. Furthermore, the dominance of bare lands increases the susceptibility of soils to both wind and water erosion, as confirmed by studies (Lal, 2020; FAO, 2021) regarding the relationship between vegetation cover and soil stability. Therefore, it can be concluded that the study area suffers from an imbalance in environmental equilibrium, which necessitates the implementation of sustainable management strategies, such as improving irrigation systems, rehabilitating vegetation cover, and adopting soil conservation agriculture techniques.

GNDVI Classification

The GNDVI values exhibited variability ranging from (-0.114 to 0.269). Table 3 and Figure 3 indicate that the severe stress class overwhelmingly dominates the study area, accounting for (80.52%), which suggests that most of the vegetation cover, if present, is experiencing high levels of stress, whether it is water stress or nutrient stress. The GNDVI is considered one of the most sensitive indices to plant chlorophyll content, and therefore it reflects the physiological condition of vegetation more

Table 3. GNDVI Classification

Class	Range	Area (km²)	Percentage (%)
Severe stress	0.20 – 0.29	21.73	80.52
Moderate stress	0.21 – 0.40	5.20	19.27
Low stress	0.41 – 0.59	0.06	0.21
Total	—	26.99	100

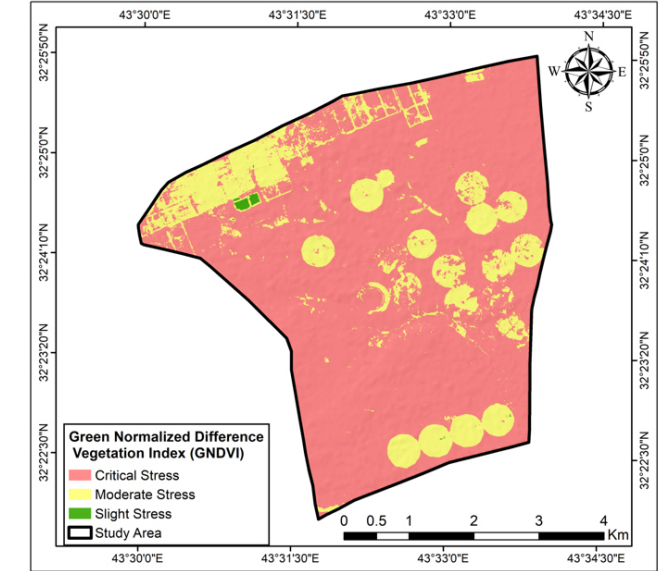


Figure 3. Spatial Distribution of the Green Normalized Difference Vegetation Index (GNDVI)

accurately compared to NDVI (Gitelson et al., 1996). The high proportion of severe stress can be attributed to several environmental factors, most notably water scarcity, high soil salinity, and poor availability of essential nutrients such as nitrogen. This is consistent with the findings of Rouse et al. (1974) and Gitelson et al. (2003), who reported that low GNDVI values are directly associated with reduced chlorophyll content, which is a clear indicator of weakened photosynthetic activity in plants. The moderate stress class (19.27%) represents areas with relatively less severe environmental conditions and may indicate better agricultural management or limited water availability. In contrast, the low stress class is nearly absent (0.21%), reflecting an almost complete lack of healthy or highly productive vegetation within the study area. These results highlight a condition of physiological degradation in vegetation, rather than merely a reduction in vegetation density, making GNDVI a crucial tool for assessing plant health. This has been confirmed by Delegido et al. (2011) and Croft et al. (2020), who emphasized that this index is among the most effective tools for evaluating vegetation stress in arid and semi-arid environments. The spatial distribution of stress indicates the presence of continuous environmental pressure, which may result from climate change or unsustainable land use

practices. Accordingly, the results highlight the need for agricultural and management interventions to improve plant health, such as optimizing water management and implementing balanced fertilization practices.

OSAVI Classification

The results presented in Table (1) indicate that OSAVI values ranged from (-0.036 to 0.113). The results shown in **Table 4** and **Figure 4** reveal the dominance of the bare land class, accounting for (83.50%), which is higher than that recorded for the NDVI classification. This can be attributed to the nature of the OSAVI, which minimizes the influence of soil reflectance in vegetation estimation, making it more accurate in environments with exposed soils (Rondeaux et al., 1996).

This high percentage of bare land confirms that most of the study area lacks effective vegetation cover, and that the higher NDVI values may be influenced by soil background effects. Therefore, OSAVI provides a more realistic representation of vegetation conditions, particularly in arid regions.

The low vegetation class (8.50%) and the good vegetation class (8.00%) represent very limited proportions, indicating that the actual vegetation cover, after correcting for soil influence, is lower than what is

suggested by other indices. This is consistent with Huete (1988) and Qi et al. (1994), who emphasized that the use of modified indices such as SAVI and OSAVI is essential in areas with low vegetation density.

These results confirm that soil plays a crucial role in interpreting spectral data, and that neglecting its influence may lead to an overestimation of vegetation cover. The low proportion of good vegetation reflects weak agricultural productivity, which may be associated with soil properties such as salinity or low organic matter content. Therefore, the use of OSAVI in this study represents an important methodological step to improve the accuracy of environmental assessment and enhances the reliability of the results compared to using a single index.

Analysis of Relationships Between Spectral Indices

The results presented in **Table 5** show the correlation matrix indicating very strong relationships among the three spectral indices. The correlation coefficient between NDVI and GNDVI reached (0.92), between GNDVI and OSAVI (0.94), and between NDVI and OSAVI (0.88). These high values indicate a strong consistency in the response of these indices to vegetation cover within the study area.

Table 4. OSAVI Classification

Vegetation Condition	From	To	Area (km²)	Percentage (%)
Bare Land	-0.06	0.06	22.54	83.50
Low Vegetation Cover	0.07	0.09	2.29	8.50
Good Vegetation Cover	0.10	0.55	2.16	8.00
Cover				
Total	—	—	26.99	100.00

Table 5. Correlation Matrix Between the Indices

Index	NDVI	GNDVI	OSAVI
NDVI	1	0.92	0.88
GNDVI	0.92	1	0.94
OSAVI	0.88	0.94	1

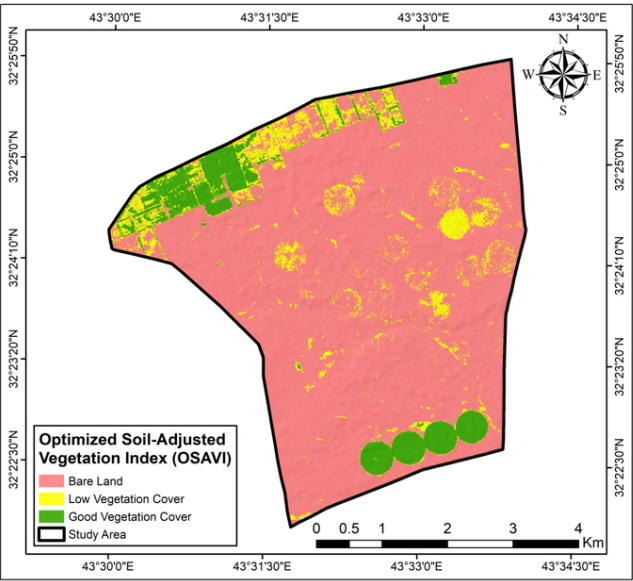


Figure 4. Spatial Distribution of the Optimized Soil-Adjusted Vegetation Index (OSAVI)

This strong correlation can be explained by the fact that all these indices primarily depend on reflectance in the red and near-infrared spectral bands, which are highly sensitive to vegetation characteristics. However, the slight differences among them reflect the influence of additional factors such as chlorophyll content in GNDVI and soil background effects in OSAVI. This is consistent with the findings of Glenn et al. (2008) and Su and Xue (2017), who emphasized that high correlations among indices do not necessarily imply they are identical, but rather that they measure different aspects of the same environmental phenomenon. For instance, GNDVI is more sensitive to physiological variations, whereas OSAVI provides greater accuracy in minimizing soil background effects. These results enhance the reliability of using the indices collectively within a composite model (Composite Index), as the high correlation ensures consistency, while the subtle differences provide additional complementary information. These relationships support the use of multiple

spectral indices in assessing vegetation conditions rather than relying on a single index, as recommended by several recent studies (Pettorelli et al., 2022; FAO, 2021).

Environmental Integration and Its Applied Implications

The integration of the results from the three indices (NDVI, GNDVI, and OSAVI) provides a comprehensive understanding of the environmental conditions in the study area. The results indicate the dominance of bare land, widespread vegetation stress, and weak effective vegetation cover. Collectively, these indicators reflect a state of environmental degradation that requires sustainable management interventions. The FAO (2021) emphasized that vegetation restoration and improved soil management are among the most important strategies to combat land degradation.

Improving soil fertility and increasing organic matter content can contribute to enhancing plant productivity and reducing environmental stress, as indicated by Lal (2020).

Agricultural Sustainability Assessment

Table 6 presents an integrated analytical framework for assessing agricultural sustainability in the study area. The indices NDVI, GNDVI, and OSAVI were combined to provide a comprehensive characterization of the environmental and vegetation conditions by linking vegetation density, plant physiological status, and soil properties. NDVI results indicate that the dominant class is bare land within the range (-0.07 – 0.06), covering an area of 17.26 km², representing 63.95%, which reflects the clear dominance of non-productive environments. The moderate vegetation class does not exceed 10.49%, indicating limited agricultural activity and a scarcity of favorable environmental conditions for plant growth.

GNDVI results showed that most of the study area falls within the severe stress class (0.20 – 0.29), accounting for a high percentage of 80.52% with an area of 21.73 km², while the low stress class is nearly negligible (0.21%). This indicates a severe decline in the physiological condition of vegetation and reduced photosynthetic efficiency, which is a direct indicator of environmental sustainability degradation.

Regarding OSAVI, the results confirmed the previous findings, where the bare land class recorded the highest percentage (83.50%) with an area of 22.54 km², which is higher than that recorded by NDVI. This demonstrates the effectiveness of OSAVI in reducing soil background effects and providing a more accurate representation of environmental reality. The good vegetation class did not exceed 8% of the total area,

indicating limited areas with acceptable agricultural sustainability.

When analyzing the three indices in an integrated manner, agricultural sustainability in the study area can be classified into three main categories:

- **Very Low Sustainability:** Represented by the dominant classes across all indices (bare lands, severe stress, and bare areas), covering more than 60–80% of the study area, reflecting a widespread state of environmental and agricultural degradation.

- **Low Sustainability:** Includes low vegetation and moderate stress classes, representing approximately 8–25% of the area. These areas are under environmental pressure but remain potentially improvable.

- **Good Sustainability:** Represented by moderate and good vegetation classes and low stress, but these do not exceed 8–10% of the total area, indicating the rarity of environmentally stable regions.

The strong agreement among the three indices enhances the reliability of the assessment, as NDVI reflects low vegetation density, GNDVI highlights vegetation physiological degradation, and OSAVI confirms soil influence and the dominance of non-cultivated lands. This integration, as emphasized by FAO (2021), indicates that the decline in agricultural sustainability in the region is not attributable to a single factor, but rather to a complex interaction of climatic factors (drought and high temperatures), soil properties (salinity and low organic matter), and human activities (poor water resource management and land exploitation).

The results confirm that the study area suffers from a very low level of agricultural sustainability, where non-productive environments dominate, accompanied by weak vegetation cover and high levels of plant stress. This necessitates the adoption of integrated management strategies to improve soil properties, enhance vegetation cover, and increase the efficiency of natural resource use, in agreement with the findings of Pettorelli et al. (2022).

Conclusions

The results of the study indicate that the study area suffers from a clear decline in vegetation cover efficiency and high levels of plant stress, which has directly contributed to the deterioration of agricultural sustainability. The spatial analysis revealed that the majority of the area falls within the low sustainability class, confirming the presence of environmental and agricultural degradation resulting from the interaction of climatic factors, soil characteristics, and unsustainable land management practices. The spectral indices used

in this study demonstrated their effectiveness in assessing environmental and agricultural conditions, as NDVI, GNDVI, and OSAVI provided different yet complementary dimensions of the ecosystem. The integration of these indices into a composite indicator contributed to delivering a more comprehensive assessment of agricultural sustainability.

The results indicate that improving agricultural sustainability in the study area requires integrated management of natural resources, with a focus on enhancing soil fertility, increasing water use efficiency, and strengthening vegetation cover, in order to achieve a balance between agricultural production and the conservation of environmental resources.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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