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Assessing Vegetation Recovery and Water Stress in Semi-Arid Grasslands Using Multi-Index Remote Sensing: A Case study of Tal Chhapar Sanctuary

Kajal Yadav
Research scholar Banasthali vidhyapeth (kjyadav786@gmail.com)
Dr.Chilka Sharma (Associate Professor, Earth Science Banasthali Vidhyapeth) Arun Kantiwal, MDS University

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Abstract

Rajasthan Tal Chhapar Sanctuary is a delicate semi-arid grassland region that struggle with issues like excess grazing, anthropogenic activity and insufficient rainfall. We find out the 2020-2024 trend analysis using Sentinal-2 satellite imagery to understand local vegetation changes , to evaluate soil condition, plant health, water accessibility and ecosystem resilience, we used variety of vegetation indices such, NDVI, EVI, SAVI, MSAVI,NDWI and VCI in combination with Inverse Distance Weighting (IDW) interpolation. The result of accuracy, which were validated using field data from 30 sites, was 82%.

Throughout four year period study, the vegetated area grew by 14.5%.the core and water adjacent area saw the most improvement, whereas the outside border close to village saw a decline in vegetation as result of intensive grazing and human activity improvement EVI,SAVI,MSAVI and VCI values indicate that vegetation has grown more and healthy, NDWI level decreased.

In summary, overall study demonstrates that monitoring delicate grassland may be accomplished successful by integrating spatial modeling satellite data. The result emphasizes the improved habitat restoration, managed grazing and water management to ensure sustainability for dry ecosystem.

Keywords: EVI, MSAVI, SAVI, VCI, Grassland, semi-arid

1.1

1.2 **Introduction -**

One of India's most delicate ecosystems is found in the semi-arid grassland of Rajasthan Thar Desert, which has been molded by centuries of human contact and severe weather. These grassland support herbivore population, preserve soil fertility and offer ecosystem services including carbon sequestration and microclimatic regulation, making them essential ecological buffers in arid region.

Their innate susceptibility to low and irregular, high temperature, overgrazing, encroachment and alien species, has led to a steady decline.

To guarantee the persistence of biodiversity and ecological sustainability in the desert landsca pe, such ecosystems must be monitored and conservedof these ecosystems, Churu district's T al Chhapar Sanctuary is particularly important for conservation and ecology.Located in the T har Desert's transitional zone at 27°47′ N latitude and 74°26′ E longitude, the sanctuary was c reated in 1962 and has an area of 8.90 km².It is most wellknown for supporting migratory bir ds, harriers, larks, and the blackbuck (Antilope cervicapra), a flagship species of Indian grassl ands. The climatic regime of the region is characterized by **low average annual rainfall (200–400 mm)** and **high thermal amplitude**, with summer maxima reaching ~48 °C and winter minima near 0 °C. Vegetation largely consists of **drought-tolerant grasses** including **Cenchrus ciliaris**, **Lasiurus sindicus**, and **Cynodondactylon**, complemented by sparse woody taxa such as **Prosopis cineraria** and **Acacia nilotica.** This unique vegetation mosaic underpins the sanctuary's ecological productivity but is highly sensitive to seasonal and interannual variations in rainfall.

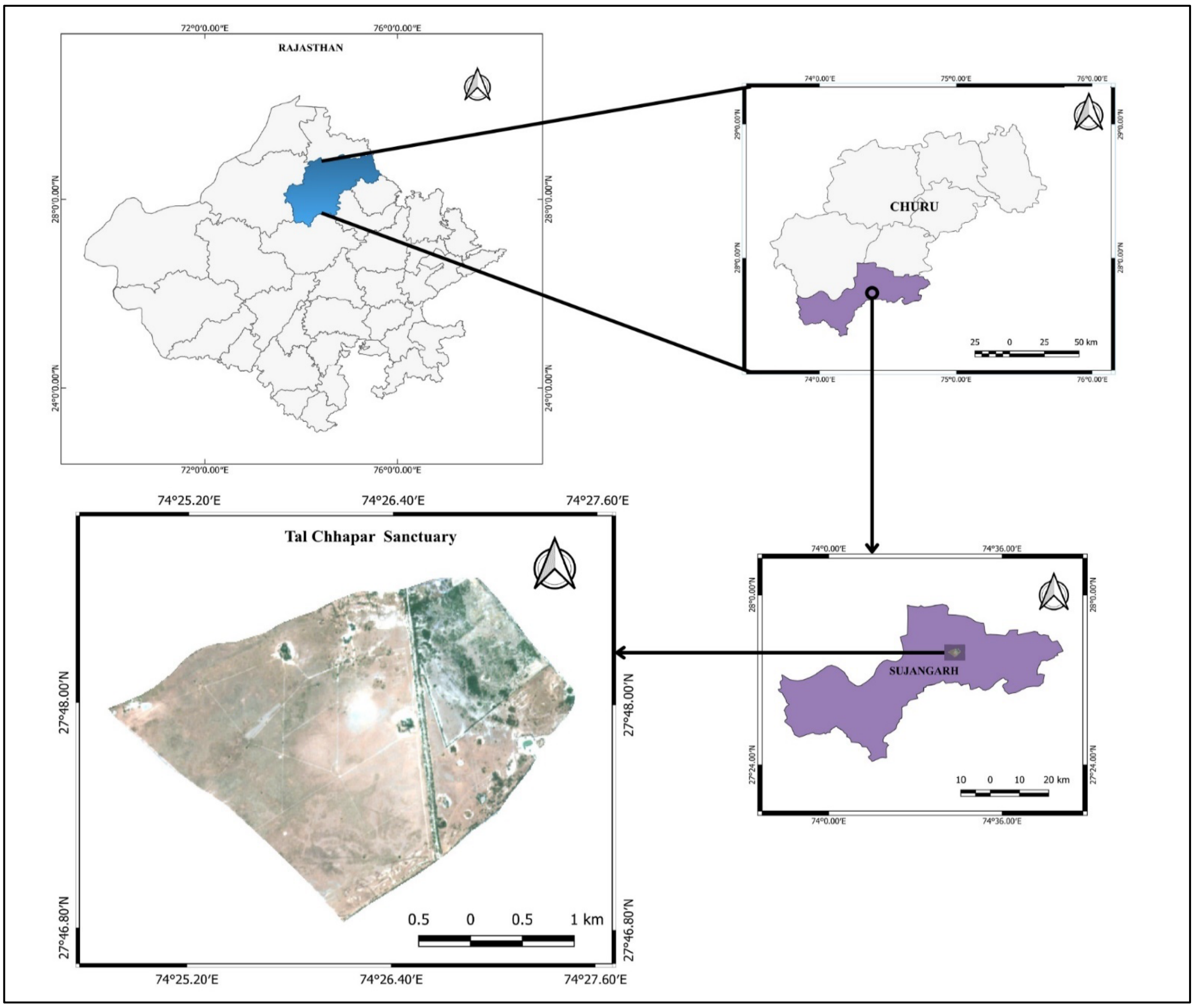
In such fragile ecosystems, **regular monitoring of vegetation health and dynamics** becomes essential for adaptive management. Traditional field-based vegetation surveys, though precise, are time-consuming, labor-intensive, and often limited in spatial coverage. **Remote sensing technologies** provide an effective alternative by enabling synoptic, repeatable, and spatially explicit monitoring of vegetation. The **Normalized Difference Vegetation Index (NDVI)** is one of the most widely used vegetation metrics in ecological research. Derived from the spectral contrast between red and near-infrared reflectance, NDVI correlates strongly with **photosynthetic activity, green biomass, and canopy cover**, thus serving as a proxy for vegetation vigor. Its applicability in arid and semi-arid ecosystems has been well-documented for detecting stress conditions, drought impacts, and land cover changes.

Despite its advantages, raw NDVI data are often available at discrete pixel points or limited ground-sampling locations, making it challenging to capture continuous patterns of vegetation variability. To address this, **spatial interpolation techniques** are employed to generate continuous surfaces from scattered data. Among these, **Inverse Distance Weighting (IDW)** is adeterministic method that estimates values for unsampled locations based on the principle of spatial autocorrelation—assigning greater influence to nearby observations and less to distant ones. IDW is computationally straightforward, widely applied in ecological and environmental studies, and particularly suitable where data density is moderate and the relationship between distance and influence is relatively uniform.Spatial Analyst extension were used to create presence/absence invasive plant distribution maps using IDW interpolation modeling techniques.An accuracy assessment of the field survey maps was conducted prior to testing the sampling and IDW interpolation techniques.The SAVI minimizes the impactof bare soil on the image of the study area. SAVI is used to reduce the influence of soil in vegetationobservation in regions with low vegetative cover and exposed soil surfaces.MSAVI minimizes the effect of bare soil on the Soil Adjusted Vegetation Index (SAVI). MSAVI is calculated as a ratio between the R and NIR values with an inductive L function applied to maximize reduction of soil effects on the vegetation signal.The Vegetation Condition Index (VCI)is expressed in and gives an idea where the observed value is positioned between the extreme values(minimum and maximum) in former times. Lower and advanced values indicate bad and good foliage state conditions, independently.VCI varies from 0 for extremely inimical conditions, to 100 for optimal. Lower and higher values indicate bad and good vegetation state conditions

In this research, IDW interpolation is applied to NDVI datasets for the years **2020 and 2024** to investigate **spatio-temporal vegetation dynamics** in Tal Chhapar Sanctuary. The analysis is further strengthened with **ground-truth validation**, ensuring reliability of remotely sensed outputs. By comparing vegetation cover changes across the two timeframes, this study seeks to identify patterns of degradation or recovery, assess the influence of rainfall changeability and climatic fluctuations, and highlight human-induced drivers such as grazing and land-use pressures. Tal Chhapar represents an ideal case to study vegetation dynamics in semi-arid grasslands, especially under climate variability and anthropogenic pressure. Understanding vegetation change patterns here can guide sustainable management measures and help maintain environment-friendly balance.The sanctuary's fragile ecosystem underscores broader challenges facing arid zone conservation throughout India. Ultimately, the study aims to contribute towards the **sustainable management of Tal Chhapar Sanctuary** by providing spatially explicit insights into vegetation health

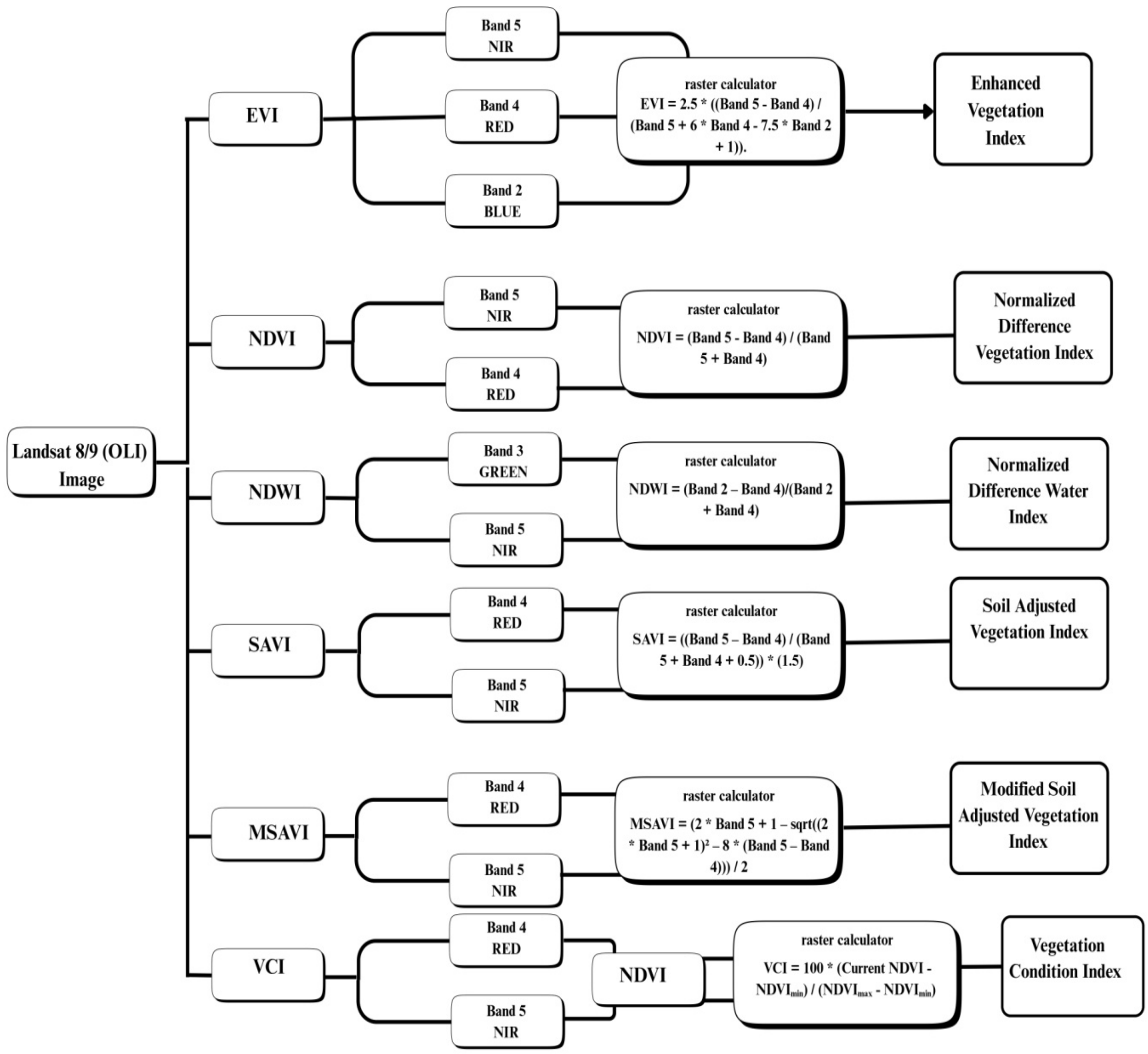
STUDY AREA –

Tal Chhapar Sanctuary is situated in Sujangarh Tehsil, Churu district, northeastern Rajasthan. It lies approximately at 27 47'N latitude and 74 26'E longitude .The sanctuary covers an area of roughly 8.90 sq Km., the sanctuary features flat salt plains and grassland savanna. It lies within Biogeographic Zone 3A—Thar Desert—and is surrounded by six villages (Chhapar, Charwas, Gopalpura, Dewani, Rampura, Soorwas). The region experiences a semi-arid climate influenced by the Aravalli rain shadow. Monsoon rains (July-September) account for



most precipitation; interannual variability is high, with 2024 receiving 536.3 mm (61% above the 334 mm long-term average) and 2020 receiving 401.9 mm (27% above the 315.5 mm normal for Churu)

Methodology -



NDVI Calculation

Inverse Distance Weighting Interpolation

Formula:= $$z_p = \frac{\sum_{i}^{N}\left(\frac{z_i}{d_i^{\,p}}\right)}{\sum_{i=}^{N}\left(\frac{1}{d_i^{\,p}}\right)}$$

Change Detection

Change detection employed NDVI differencing:

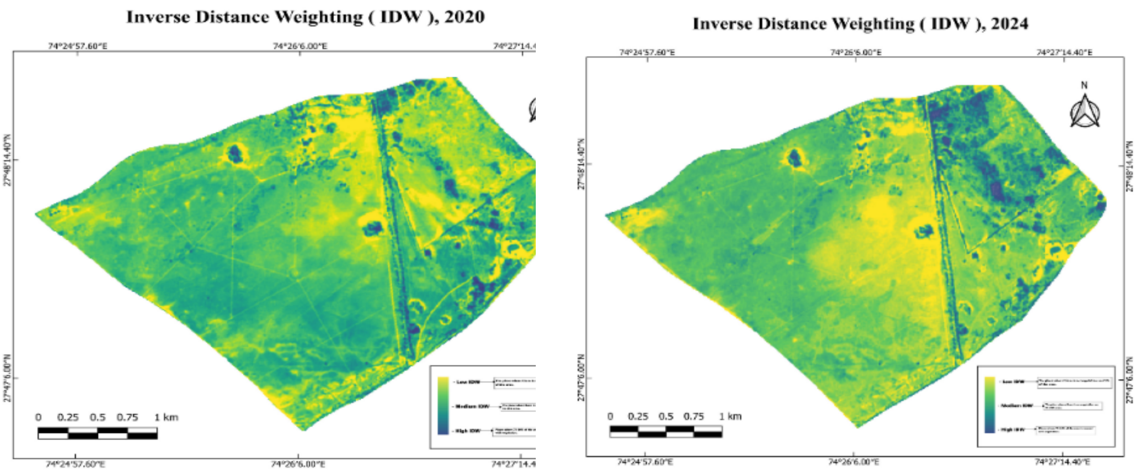
Formula:=ΔNDVI=NDVI2024−NDVI2020.ΔNDVI=NDVI2024−NDVI2020

Change thresholds were defined as ΔNDVI > 0.1 (significant increase), ΔNDVI < –0.1

(significant decrease), and –0.1 ≤ ΔNDVI ≤ 0.1 (no significant change).

IDW -

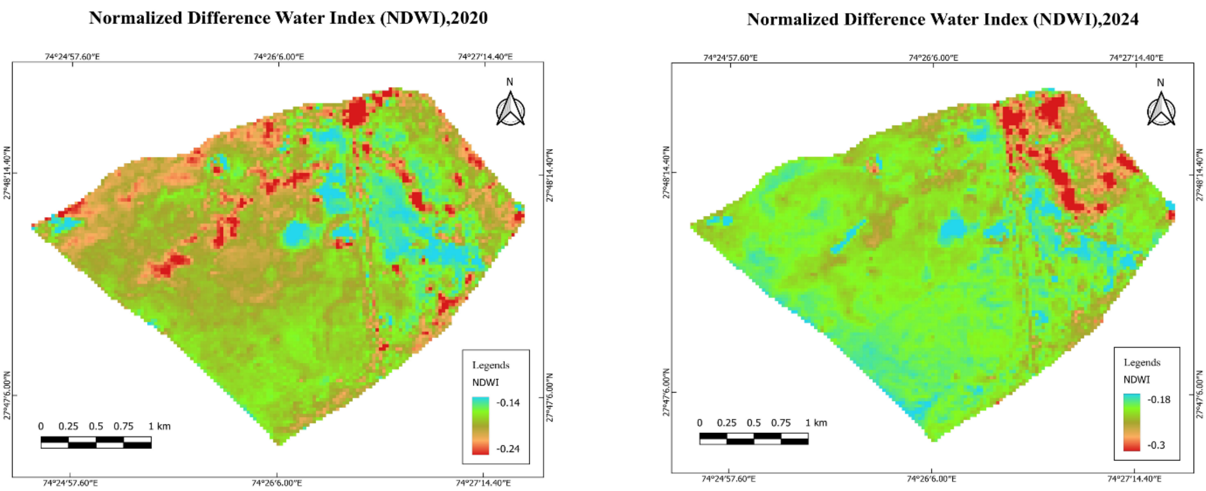
This map color variation show in vegetation weights in dark green color high weights and yellow color in low weights(Fig. 1, 2020 and 2, 2024). The accuracy levels for vegetation mapping are suitable for invasive plant manage.



(Fig. 1, 2020 & 2024)

NDWI - The Normalized Difference Water Index (NDWI) is another crucial vegetation index that focuses on the water content in vegetation and soil moisture. While NDVI primarily assesses overall plant health, NDWI is specifically designed to detect water stress and estimate vegetation water content .Higher positive values indicate higher vegetation water content. Lower or negative values suggest water stress or dry conditions.The Normalized Difference Water Index (NDWI) is a technique utilized in satellite imagery analysis to distinguish open water features by utilizing the near-infrared (NIR) and visible green (GREEN) spectral bands The calculation of NDWI is performed using the following fola .

NDWI values range from -1 to +1, where higher values indicate more water and lower values

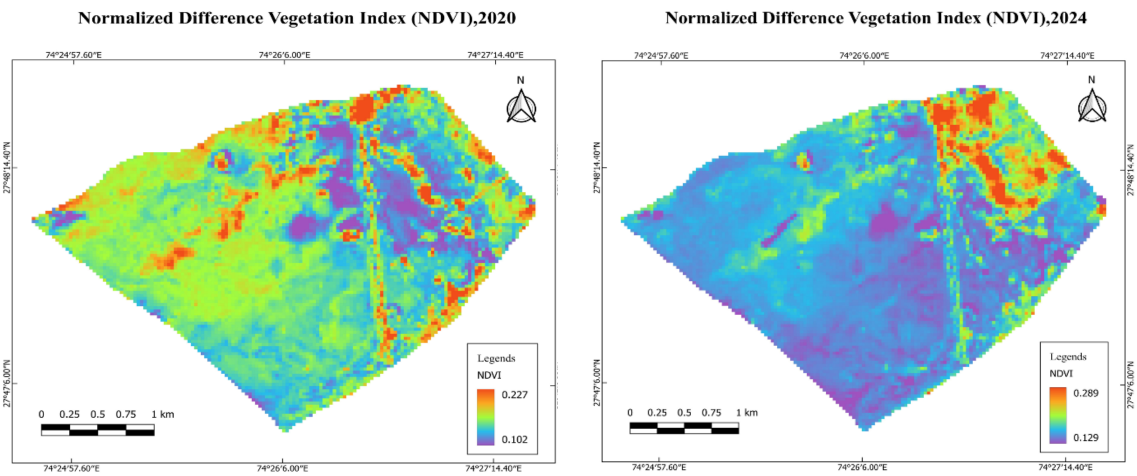


$$NDWI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$$

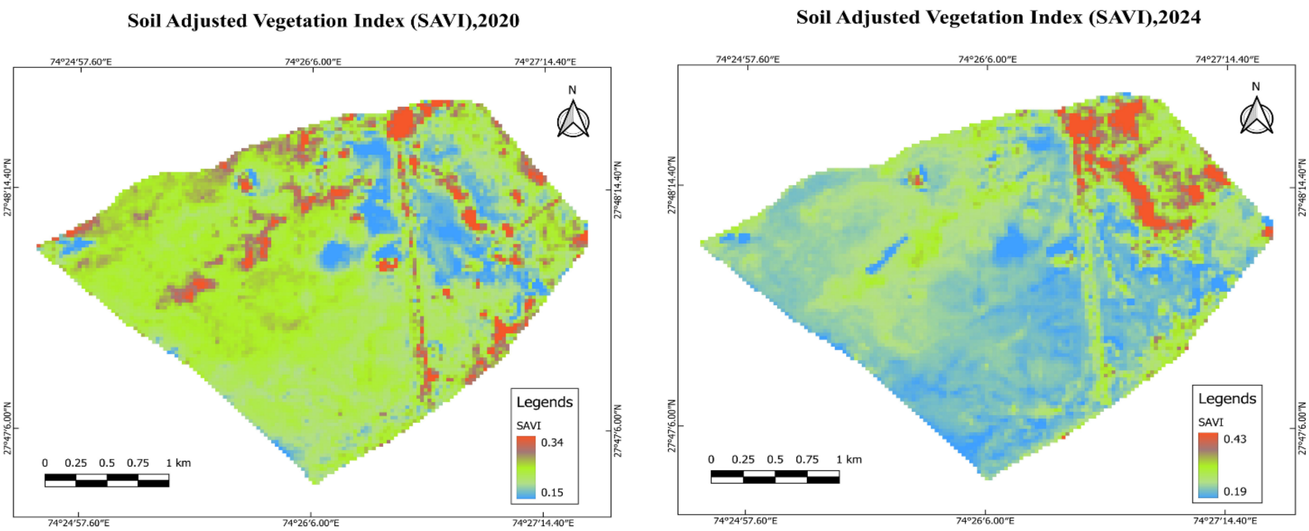
(Fig. 2 , 2020 & 2024)

NDVI - Normalized Difference Vegetation Index (NDVI) is a commonly used metric to quantify the density and health of vegetation. Its values range from -1 to 1, with negative values indicatingwater or bare soil, values near zero indicating sparse vegetation, and higher values indicating denser and healthier vegetation .The range of NDVI values in 2020 image from 0.102 to 0.227 and in 2024 image from 0.129 to 0.289 high. NDVI value indicates the high vegetation density while lower NDVI value shows the low density ofvegetation. The change of vegetation pattern is shown in the fig 3.

(Fig. 3, 2020 & 2024)



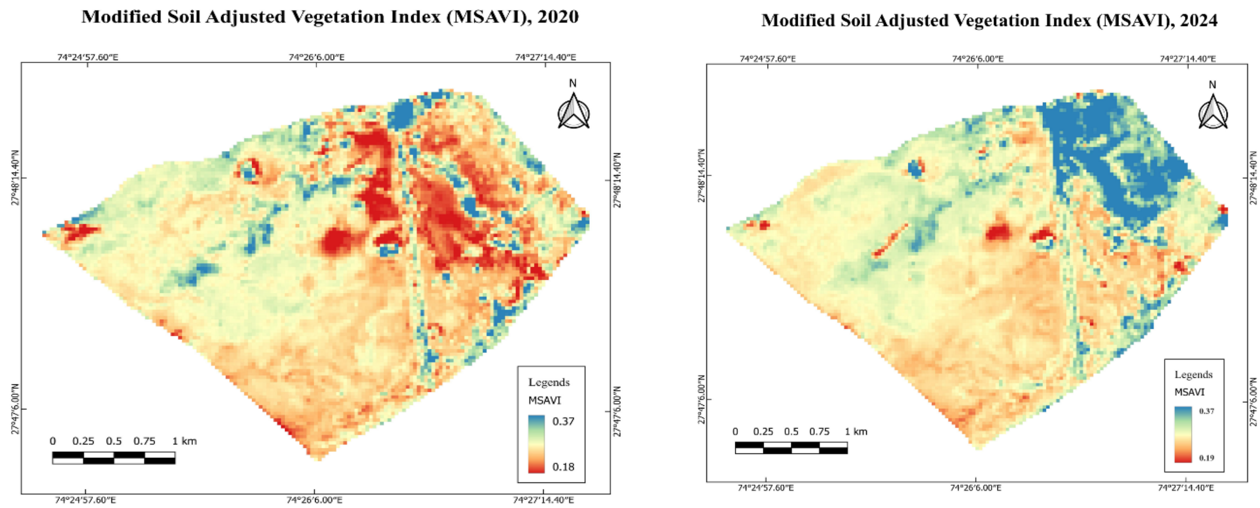
SAVI -SAVI values vary from -1.0to 1.5 when the L value 0.5 is used, with low values indicating a low coverage of vegetation. Fig. 4 below shows the spatial distribution of SAVI over the study area.Formula:= $SAVI = \frac{(NIR-RED)}{(NIR + RED+ L\,)} * (1 + L\,)$



(Fig. 4, 2020 & 2024)

MSAVI -A modified SAVI (MSAVI) was proposed to increase the dynamic range of the vegetation signal while further minimizing the soil background influences, resulting in greater vegetation sensitivity as defined by a vegetation signal to soil noise ratioSAVI values are easy to analyze. They range from -1 to 1, where:-1 to 0.2 indicate barren soil , 0.2 to 0.4 is the vegetation germination stage , 0.4 to 0.6 is the leaf development stage.(fig.5)Formula: $MSAVI = \frac{(1+L)*(NIR-RED)}{(NIR + RED + L)}$

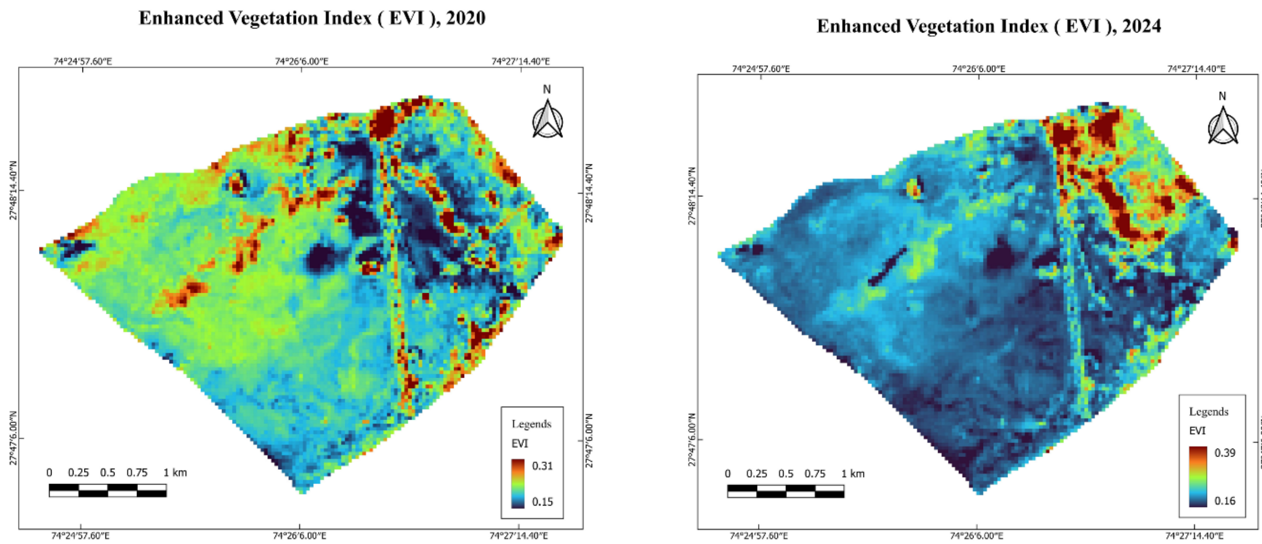
(Fig. 5, 2020 & 2024)



EVI - The Enhanced Vegetation Index (EVI) is an advanced vegetation index created with higher sensitivity to biomass, atmospheric background, and soil condition. It is regarded as the modified version of Normalized Difference Vegetation Index (NDVI) with a high potentiality of vegetation monitoring by correcting all the external noises.

EVI uses the blue, red, and NIR band. It incorporates an “ L ” value to acclimate for cover background, “ C ” values as portions for atmospheric resistance and values from the blue band(B). These advancements allow for indicator computation as a rate between the R and NIR values, while reducing the background noise, atmospheric noise, and achromatism in utmostcases.EVI Formula = $EVI = 2.5 * \frac{(NIR-RED)}{NIR+(2.5* \text{RED})+1}$

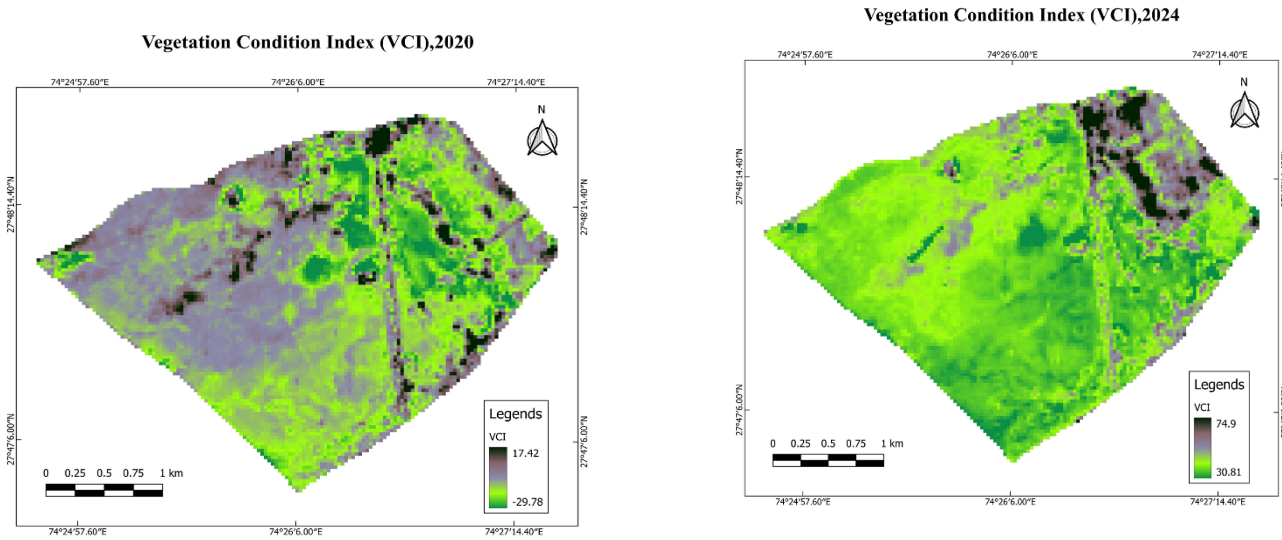
In areas of dense canopy cover, where leaf area index (LAI) is high, the blue wavelengths can



be used to improve the accuracy of NDVI, as it corrects for soil background signals and atmospheric influences.Values description: The range of values for EVI is -1 to 1, with healthy vegetation generally around 0.20 to 0.80 (fig.6)

(Fig. 6 , 2020 & 2024)

VCI -The Vegetation Condition Index (VCI) compares the current NDVI to the range of



values observed in the same period in previous years. The VCI is expressed in % and gives an idea where the observed value is situated between the extreme values (minimum and maximum) in the previous years(fig. 7) . Lower values indicate bad and higher values good vegetation conditions, respectively.Formula: = $VCI = \frac{(NDVIj - NDVImin)}{(NDVImax + NDVImin)} * 100$

(Fig. 7, 2020 & 2024)

Rainfall Variability –

Monsoon rainfall in 2020 (401.9 mm; +27% departure) and 2024 (536.3 mm; +61% departure) significantly exceeded long-term averages. Higher precipitation in 2024 corresponded with increased NDVI values across the sanctuary.

Vegetation Dynamics –

Mean NDVI increased from 0.34 ± 0.12 in 2020 to 0.41 ± 0.15 in 2024. Vegetated area (NDVI > 0.2) expanded from 6.2 km² (69.7% of sanctuary) to 7.1 km² (79.8%).

Spatial Patterns of Change –

Change Category	**Area (km²)**	**Sanctuary Percentage**
Increase (ΔNDVI > 0.1)	3.8	42.7%
Stable (–0.1 ≤ ΔNDVI ≤ 0.1)	3.2	36.0%
Decrease (ΔNDVI < –0.1)	1.9	21.3%

Vegetation gains predominated in central and core zones, particularly around artificial water bodies and areas of reduced grazing pressure. Declines occurred chiefly along peripheral zones adjacent to villages, where grazing intensity and soil compaction are higher.

Index	Formula	2020 Value Range	2024 Value Range	Observed Change	Ecological Interpretation
NDVI	$NDVI = \frac{(NIR - RED)}{(NIR + RED)} * (1 + L)$	Min: 0.102 Max: 0.227	Min: 0.129 Max: 0.289	Min +0.027, Max +0.062	Improved vegetation density and vigor
EVI	$EVI = 2.5 * \frac{(NIR - RED)}{NIR + (2.5 * \text{RED}) + 1}$	Min: -0.02 Max: 0.53	Min: 0.02 Max: 0.54	Slight increase	Enhanced canopy health, reduced atmospheric effects
SAVI	$SAVI = \frac{(NIR - RED)}{(NIR + RED + L)} * (1 + L)$	Min: 0.15 Max: 0.34	Min: 0.19 Max: 0.43	Min +0.04, Max +0.09	Improved vegetation cover, reduced soil influence
MSAVI	$MSAVI = \frac{(1 + L) * (NIR - RED)}{(NIR + RED + L)}$	Min: 0.18 Max: 0.37	Min: 0.19 Max: 0.37	Slight min increase	Better detection of sparse vegetation stages
NDWI	$NDWI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$	Min: -0.24 Max: -0.14	Min: -0.30 Max: -0.18	Decrease	Reduced water content, possible increased water stress
VCI	$VCI = \frac{(NDVIj - NDVImin)}{(NDVImax + NDVImin)} * 100$	Min: -29.31 Max: 17.42	Min: 30.81 Max: 74.9	Large increase	Strong vegetation recovery and resilience

NDVI & EVI: Higher NDVI and EVI in 2024 signal greater plant vigor, denser green cover, and improved photosynthetic capacity. This promotes carbon sequestration, soil conservation, and habitat stability—key features of sustainable landscapes.

SAVI & MSAVI: The increase in soil-adjusted indices reflects healthier vegetation cover even in areas affected by soil brightness or sparse growth. Sustainable management is indicated by the ability to maintain vegetation under suboptimal conditions, enhancing ecological resilience.

VCI: The jump in VCI confirms the recovery and resilience of the ecosystem to stress, which is a core marker of sustainability. Lands capable of restoring vigour after drought or disturbance help maintain biodiversity and ecological services.

NDWI: Although NDWI declined, signaling reduced water content, sustainable systems rely on efficient water use and adaptation to limited water. If vegetation thrives despite lower NDWI, it may reflect adaptive vegetation types or improved water management practices.

Conclusions

This study highlight that combining remote sensing indices, spatial mapping, and field validation is effective for monitoring vegetation changes in semi-arid ecosystems such as the Tal Chhapar Sanctuary. From 2020 to 2024, the sanctuary recorded 14.15% increase vegetated area (NDVI >0.2) indicating ecological recovery.

Most important vegetation improved mainly in center and adjacent area due to higher soil moisture and less anthropogenic activities. In contrast, adjacent zone area declining because of grazing, soil compaction due human activity. Rainfall variability was a key factor, with higher rainfall in 2020–2024 supporting recovery

Index based analysis result showed recovery, NDVI indicate healthier plant canopy density.EVI also slight rise. Indicating strong canopy vigor.SAVI and MSAVI value increased, suggesting better vegetation condition area with spare cover.VCI value improved sharply, shifting stress 2020 to 2024, highlight sanitary ecological under favorable condition. NDWI showed decline, indicate water stress. This highlight challenge is vegetation recovering but water availability remains limited. Managing and monitoring hydrological stress for sustainable grassland health in Tal Chappar sanctuary.

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