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Temporal Dynamics of Vegetation in Hyderabad, Sindh: An NDVI-Based Analysis

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semi-arid environment

ABSTRACT

Rapid urbanization and climate-related environmental stress have intensified pressure on vegetation resources in semi-arid cities, yet long-term city-scale vegetation assessments remain limited for Hyderabad, Sindh, Pakistan. This study analyses the temporal dynamics of vegetation in Hyderabad over a 20-year period using Landsat-derived Normalized Difference Vegetation Index (NDVI) for 2004, 2014, and 2024. Satellite images from Landsat 7 ETM+ and Landsat 8 OLI were processed to calculate NDVI and classify the study area into four major classes: water bodies, urban/barren land, shrubs/low vegetation, and healthy vegetation. Random Forest classification and accuracy assessment were applied to improve land cover discrimination, achieving an overall accuracy of approximately 85%. The results show a substantial decline in healthy vegetation from 48.33% in 2004 to 21.96% in 2014 and 16.26% in 2024, representing an overall reduction of 32.07 percentage points. In contrast, urban/barren land increased from 19.50% in 2004 to 47.85% in 2014 and 49.20% in 2024, showing an overall increase of 29.70 percentage points. Shrubs/low vegetation showed minor variation, decreasing slightly from 30.79% to 30.04%, while water bodies increased from 1.36% to 4.48% during the study period. The findings indicate a clear transition from vegetation-dominated surfaces toward urban/barren land, particularly in rapidly expanding areas such as Latifabad and Qasimabad. This study highlights the effectiveness of NDVI-based monitoring for detecting vegetation loss and provides evidence to support sustainable urban planning, green infrastructure development, and environmental management in Hyderabad.

1. Introduction

Land use and land cover change is one of the most important indicators of environmental transformation, especially in regions facing rapid population growth, urban expansion, agricultural intensification, and climate variability [1]. Land is a vital component of the natural environment because it supports biodiversity, ecosystem services, agriculture, water resources, and human settlements [2]. However, increasing pressure from population growth and development has accelerated the conversion of natural and semi-natural landscapes into built-up, barren, and degraded surfaces, creating serious challenges for sustainable land management [3]. Climate change has further intensified these challenges by influencing vegetation distribution, ecosystem productivity, water availability, and land surface conditions [4].

Recent studies have emphasized that land surface changes are strongly connected with both human activities and climate-related stresses. For example, land surface changes in the highland environment of Gilgit-Baltistan, Pakistan, have been studied to support sustainable management of fragile mountainous landscapes [5]. Similarly, hydroclimatic research has shown that changes in evapotranspiration, temperature, humidity, wind speed, and precipitation patterns can directly influence vegetation condition, agricultural water demand, and land surface processes [6]. Recent studies on Pakistan's monsoonal precipitation have also highlighted shifting rainfall patterns, which can affect

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water availability, vegetation growth, and regional environmental stability [7]. Hydrological studies have further demonstrated that climate variability and human activities can alter streamflow and water resources, which are closely linked with land cover and vegetation dynamics [8].

Remote sensing has emerged as a powerful tool for detecting and quantifying changes in land cover, vegetation health, and ecosystem dynamics over large spatial and temporal scales [9]. Multi-temporal satellite imagery makes it possible to monitor land surface changes, classify different land cover types, and assess biophysical parameters in a consistent and cost-effective manner [10]. Multispectral remote sensing is particularly useful because it captures spectral differences among vegetation, water bodies, barren land, and built-up areas, allowing researchers to evaluate spatial patterns and temporal changes in the landscape [11].

The Normalized Difference Vegetation Index is one of the most widely used satellite-derived indices for vegetation monitoring because it uses the contrast between red and near-infrared reflectance to indicate vegetation greenness, density, and vigor [12]. Higher values generally represent healthy and dense vegetation, while lower values indicate sparse vegetation, built-up surfaces, barren land, or water bodies [13]. Previous studies have applied vegetation indices for vegetation monitoring, crop condition assessment, drought evaluation, and land cover analysis at local, regional, and global scales [14]. Therefore, this index provides a reliable basis for evaluating vegetation dynamics in semi-arid and rapidly urbanizing regions [15].

Hyderabad, Sindh, is an important urban center in the lower Indus Basin and is in a semi-arid climatic zone where vegetation and water resources are highly sensitive to land use change and climate variability. The city has experienced rapid expansion in recent decades, particularly in areas such as Latifabad, Qasimabad, and the central urban zone. This urban growth has increased pressure on agricultural land, shrubland, water bodies, and natural vegetation. In such environments, vegetation loss can intensify urban heat, reduce ecological stability, affect local biodiversity, and increase stress on already limited water resources [16].

Although several studies have examined land surface change, hydroclimatic variability, evapotranspiration, precipitation shifts, and hydrological responses in Pakistan and other regions, limited attention has been given to long-term vegetation dynamics at the city scale in Hyderabad, Sindh [5] [6] [7] [8]. This represents an important research gap because Hyderabad is undergoing rapid urban development while also being exposed to semi-arid climatic conditions and water-resource limitations. A localized satellite-based vegetation assessment is therefore necessary to understand how vegetation cover has changed over time and how urban/barren land, shrubs, and water bodies have shifted during the last two decades.

The present study aims to analyze the temporal dynamics of vegetation in Hyderabad, Sindh, using Landsat satellite imagery for 2004, 2014, and 2024. The satellite-derived vegetation values were classified into water bodies, urban/barren land, shrubs/low vegetation, and healthy vegetation to quantify land surface changes over time. The specific objectives of this study are to assess spatial and temporal changes in vegetation cover, quantify the increase or decrease in major land cover classes, identify areas affected by urban expansion, and provide scientific evidence for sustainable urban planning, vegetation conservation, and environmental management in Hyderabad.

2. Materials and Methods

2.1 Study Area

The study was conducted in Hyderabad, Sindh, Pakistan, a rapidly urbanizing city located in the lower Indus Basin. The study area lies approximately between 25°10′–25°30′ N latitude and 68°20′–68°30′ E longitude (Fig. 1). Hyderabad is characterized by a semi-arid climate, limited annual rainfall, high summer temperatures, and strong dependence on surface and groundwater resources. The city includes a mixture of built-up land, agricultural fields, shrubland, open/barren surfaces, and water bodies associated with the Indus River system and irrigation channels.

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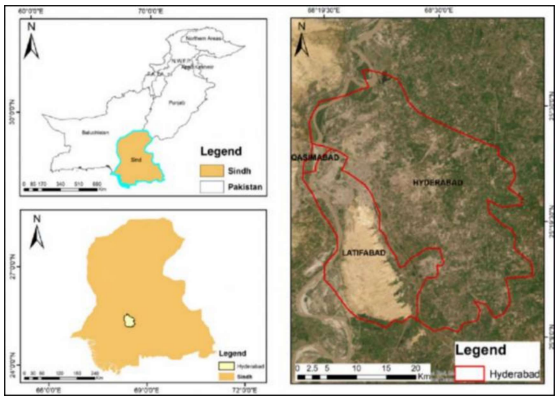

Fig. 1 Location map of the study area

2.2 Data Collection

Multi-temporal Landsat satellite images were used to assess vegetation dynamics in Hyderabad for the years 2004, 2014, and 2024. The satellite images were obtained from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov). Landsat imagery was selected because it provides long-term data availability, medium spatial resolution, and reliable spectral information for vegetation and land cover analysis.

For 2004, Landsat 7 Enhanced Thematic Mapper Plus imagery was used, while Landsat 8 Operational Land Imager/Thermal Infrared Sensor imagery was used for 2014 and 2024. Cloud-free or nearly cloud-free images were selected from the same season, preferably the post-monsoon period, to reduce seasonal differences in vegetation condition and ensure meaningful comparison across the selected years (Table 1).

Table 1: Details of satellite imagery used in the study

Year	Satellite/Sensor	Product level	Spatial resolution	Data source
2004	Landsat 7 ETM+	Collection 2 Level 2	30 m	USGS/GEE
2014	Landsat 8 OLI/TIRS	Collection 2 Level 2	30 m	USGS/GEE
2024	Landsat 8 OLI/TIRS	Collection 2 Level 2	30 m	USGS/GEE

2.3 Data Preprocessing

The satellite images were preprocessed before NDVI calculation and classification. The preprocessing steps included radiometric correction, atmospheric correction, band selection, layer stacking, mosaicking where required, and subsetting according to the boundary of the study area.

Landsat Collection 2 Level 2 surface reflectance products were used to minimize atmospheric effects and improve spectral reliability. The images were clipped to the study area using the Hyderabad boundary shapefile. Cloud-contaminated pixels, cloud shadows, and unwanted background areas were removed where necessary to improve classification accuracy.

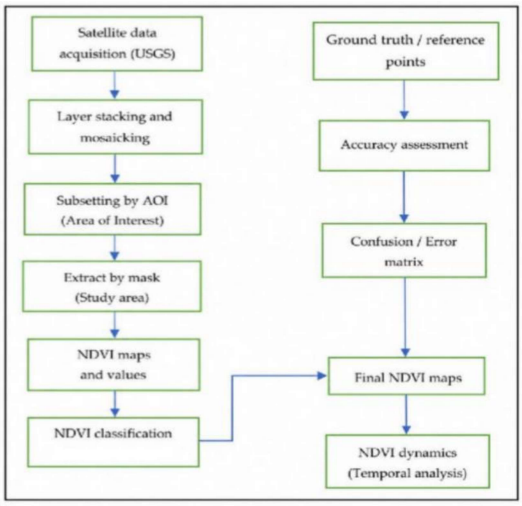

Fig. 2 Flow chart of methodology for current study.

For Landsat 7 ETM+, special attention was given to data quality because images acquired after 2003 may contain scan line corrector gaps. Where required, gap-filling or suitable cloud-free scenes were used to reduce the effect of missing data. All images were projected to a common coordinate system to ensure spatial consistency among the 2004, 2014, and 2024 datasets.

The preprocessing and mapping were carried out using ArcGIS 10.8. The final preprocessed images were then used for NDVI calculation, classification, accuracy assessment, and change detection (Fig. 2).

2.4 Normalized Difference Vegetation Index (NDVI)

The spectral features of vegetation, such as its ability to absorb visible light and photosynthetic energy, are considered in NDVI assessment. NDVI is a plant health assessment based on how the plant absorbs and reflects light at specific frequencies. The NDVI is an excellent indicator of vegetative growth conditions and vegetative cover degree. If a region is vegetated, its NDVI value is a positive number that increases as the vegetation cover improve [17].

Landsat data were obtained in HDF (Hierarchical Data Format). Subsequently, it was reprojected from the original sinusoidal projection to geographic projection (WGS84 datum). Then, stacking, mosaicking, and subsetting to AOI were performed in ArcMap 10.8. Likewise, NDVI matrices were calculated using an ArcMap spatial analysis tool (using a raster calculator) according to Equation (1). After processing all the data, maps for the years 2004, 2014, and 2024 were developed.

$$NDVI = \frac{NIR + RED}{NIR - RED} \quad (1)$$

Where NIR represents near-infrared band and RED represents red band. These indices have characteristic values between −1 and 1 [18]. NIR is reflected by leaves in plants, while chlorophyll absorbs it. If NDVI is high, it indicates that vegetation is abundant. Alternatively, if NDVI is low, there is little or no vegetation potential. Extremely low NDVI values (below 0.1) correlate to bare rock, sand, or snow regions. High levels imply temperate and tropical rainforests (0.2 to 0.3), whereas moderate values depict shrubs and grasslands (0.6 to 0.8).

For Landsat 7 ETM+, Band 4 was used as the NIR band and Band 3 as the red band. For Landsat 8 OLI, Band 5 was used as the NIR band and Band 4 as the red band. The resulting NDVI values ranged from negative values to positive values. Negative values generally represented water bodies, values close to zero represented built-up or barren surfaces, moderate values represented shrubs or sparse vegetation, and higher values represented healthy vegetation (Table 2).

The NDVI maps were classified into four major classes:

Table 2: NDVI classification scheme

NDVI range	Class	Description
NDVI < 0	Water bodies	Rivers, canals, ponds, or waterlogged areas
0 to 0.15	Urban/barren land	Built-up areas, bare soil, roads, and exposed land
0.15 to 0.30	Shrubs/low vegetation	Sparse vegetation, grassland, and low-density vegetation
NDVI ≥0.30	Healthy vegetation	Dense vegetation, cropland, and relatively healthy green cover

2.4 Data Classification

To improve the reliability of the classified outputs, Random Forest classification was applied using NDVI values and spectral information from Landsat imagery. Training and validation samples were selected for the four NDVI-based classes using visual interpretation of satellite imagery, false-color composites, natural-color composites, and reference/ground truth points. False-color composites helped in distinguishing vegetation, water bodies, and built-up surfaces, while natural-color composites supported the visual identification of urban areas, barren land, and surface water.

The Random Forest classifier was used because it is suitable for remote sensing classification and can handle spectral variability among different surface features. The classified NDVI outputs were further assessed using reference points. An accuracy assessment was performed through a confusion/error matrix to evaluate the reliability of the classification. The overall classification accuracy was approximately 85%, indicating that the classified NDVI maps were suitable for analyzing vegetation dynamics in the study area.

After classification, the area of each NDVI class was calculated for 2004, 2014, and 2024. Since Landsat imagery has a spatial resolution of 30 m, each pixel represents 900 m². The area of each class was calculated by multiplying the number of classified pixels by the pixel area. The area was then converted into hectares and percentages using the following equations:

$$\text{Area (ha)} = \frac{(\text{Counted Pixels}) \times (\text{Pixel size})^2}{10^4} \quad (2)$$

where the pixel size is 30 m for Landsat imagery.

$$\text{Area (\%)} = \frac{\text{Area of Class}}{\text{Total Area}} \times 100 \quad (3)$$

These area statistics were used to quantify temporal changes in vegetation and other NDVI-based classes. The resulting classified maps and area percentages were then compared across 2004, 2014, and 2024 to identify changes in water bodies, urban/barren land, shrubs/low vegetation, and healthy vegetation within Hyderabad, Sindh.

2.5 Post-Classification Change Detection

This study used ArcGIS 10.8 and Google Earth Pro tools to analyze and classify satellite images from 2004 to 2024 based on satellite and actual geographical land utilization to detect NDVI changes. For this purpose, we conducted accuracy assessments to evaluate the classified images and NDVI changes.

2.6 Accuracy Assessment

The classification accuracy of satellite images can be assessed by calculating overall accuracy and Kappa Coefficient (K). The overall accuracy can be determined by estimating user and producer accuracy [67,70]. User accuracy is used to quantify the probability that a classified pixel matches the land cover class of its actual geographical position. The classification accuracy of actual land cover types is evaluated by producer accuracy, which is quantified by gap errors. About 50 random ground control points (GCPs) were created for each year, i.e., 2004, 2014, and 2024, and the minimum allowance distance set was 30 m for each class. The total accuracy of the classification of satellite images is determined by comparing how each pixel is classed against the actual land cover produced from their combined baseline data [19]. The coefficient K was utilized as an indicator of consistency between predicted results and actuality or to determine if the numbers included in an input dataset reflect a considerably best improvement.

The overall accuracy and coefficient K were found to be 88% and 85%, respectively. The calculation of accuracy assessment indices for the complete study period (2000–2021) is presented in the Results section.

3. Results and Discussion

3.1 Spatial Distribution of NDVI Classes in 2004

The NDVI-based classification for 2004 indicates that Hyderabad had a relatively higher proportion of healthy vegetation compared with the later study years. The classified map shows that healthy vegetation was mainly distributed in the northern, central, and peri-urban parts of the study area, while water bodies were concentrated along riverine and canal-associated zones. The spatial pattern suggests that, during 2004, agricultural fields, vegetated open spaces, and natural green cover were still dominant in several parts of Hyderabad.

The area statistics further confirm this pattern. In 2004, healthy vegetation covered 48.33% of the study area, making it the dominant NDVI class. Shrubs or low vegetation accounted for 30.79%, while urban/barren land occupied 19.50%. Water bodies represented the smallest class, covering only 1.36% of the total area. These values indicate that nearly half of the study area had relatively high vegetation density in 2004, while built-up and barren surfaces were comparatively limited (**Fig. 3** and **Fig. 4**).

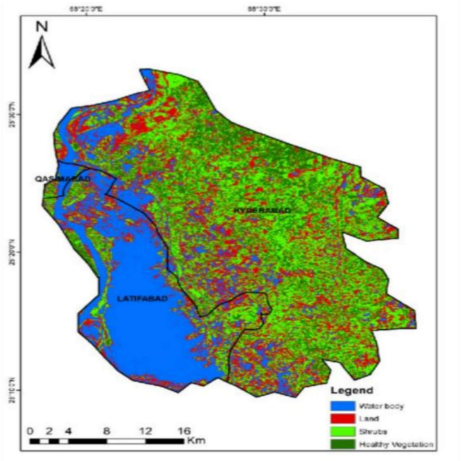

Fig. 3 NDVI map of 2004

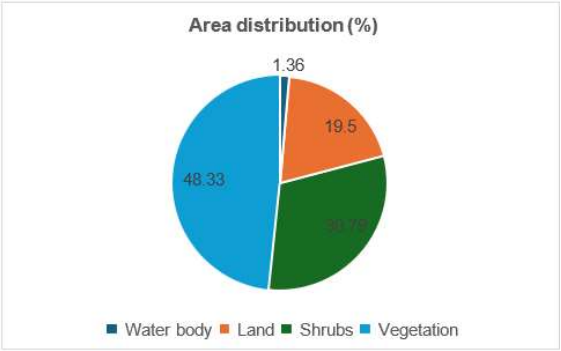

Fig. 4 Pie chart of NDVI map of 2004

3.2 Spatial Distribution of NDVI Classes in 2014

The NDVI classification for 2014 shows a clear shift in land surface conditions compared with 2004. The most prominent change is the expansion of the urban/barren land class, particularly in and around the rapidly developing areas of Latifabad, Qasimabad, and the central urban zone. This increase indicates that built-up surfaces, exposed soil, and non-vegetated land expanded considerably during the first decade of analysis.

In 2014, urban/barren land increased to 47.85%, showing a major rise from 19.50% in 2004. Healthy

vegetation decreased sharply from 48.33% in 2004 to 21.96% in 2014. This represents a decline of 26.37 percentage points within ten years. Shrubs or low vegetation decreased slightly from 30.79% to 28.27%, while water bodies increased marginally from 1.36% to 1.89%.

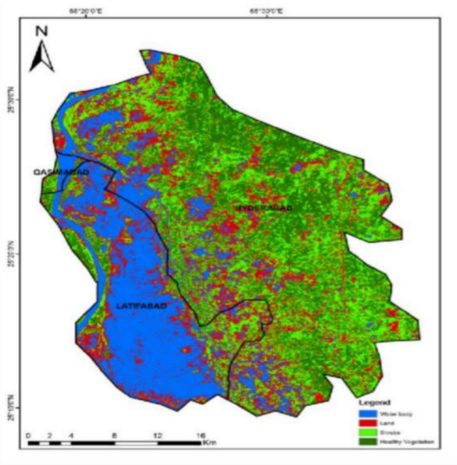

Fig. 5 NDVI map of 2014

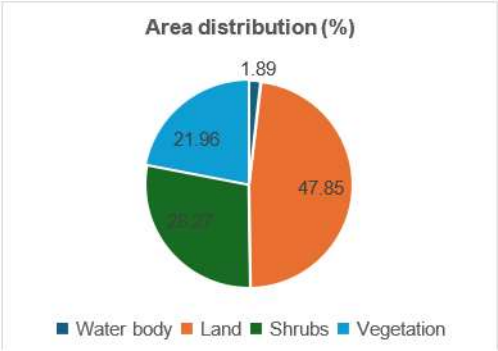

Fig. 6 Pie chart of NDVI map of 2014

The results suggest that the period from 2004 to 2014 was marked by rapid land conversion. The substantial increase in urban/barren land occurred mainly at the expense of healthy vegetation. This pattern is consistent with the expansion of housing schemes, road networks, commercial areas, and other urban infrastructure in Hyderabad. The decline in healthy vegetation also indicates pressure on agricultural and natural vegetated areas located near expanding urban settlements (Figure 5 and 6).

3.3 Spatial Distribution of NDVI Classes in 2024

The NDVI map for 2024 indicates that urban/barren land remained the dominant class in Hyderabad. The spatial distribution shows continued expansion of low-NDVI surfaces, especially in areas affected by urban growth and land development. Healthy vegetation further declined and became more fragmented compared with 2004 and 2014. Vegetated patches were mainly limited to agricultural areas, riverine zones, and scattered green spaces.

In 2024, urban/barren land increased to 49.20%, showing a slight increase from 47.85% in 2014. Healthy vegetation declined further to 16.26%, compared with 21.96% in 2014 and 48.33% in 2004. Shrubs or low vegetation increased slightly to 30.04%, while water bodies increased to 4.48%.

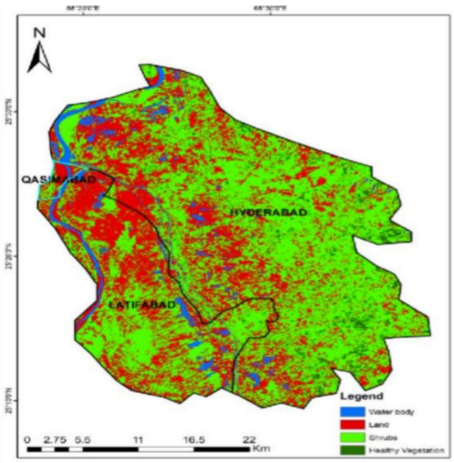

Fig. 7 NDVI map of 2024

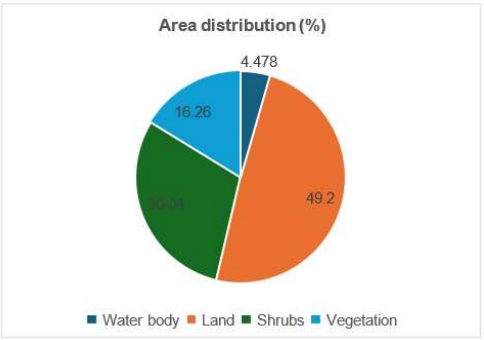

Fig. 8 Pie chart of NDVI map of 2024

The continued reduction in healthy vegetation shows that Hyderabad has experienced persistent pressure on green cover over the last two decades. Although the rate of urban/barren land expansion was much higher between 2004 and 2014 than between 2014 and 2024, the decline in healthy vegetation continued during the second decade. This suggests that even after the major phase of urban expansion, remaining vegetated areas continued to be converted, degraded, or fragmented.

The increase in water bodies from 1.89% in 2014 to 4.48% in 2024 may be associated with seasonal water availability, irrigation activity, waterlogging, surface

water retention, or changes in hydrological conditions during the image acquisition period (Figure 7 and 8).

3.4 Temporal Changes in NDVI Classes from 2004 to 2024

The temporal analysis reveals substantial changes in land surface conditions in Hyderabad between 2004 and 2024. The most significant changes were observed in healthy vegetation and urban/barren land. Healthy vegetation decreased from 48.33% in 2004 to 16.26% in 2024, showing a net decline of 32.07 percentage points. In contrast, urban/barren land increased from 19.50% to 49.20%, showing a net increase of 29.70 percentage points.

Shrubs or low vegetation showed only minor variation over the study period. This class decreased from 30.79% in 2004 to 28.27% in 2014, followed by a slight increase to 30.04% in 2024. Overall, shrubs declined by only 0.75 percentage points between 2004 and 2024. Water bodies increased from 1.36% in 2004 to 4.48% in 2024, showing a net increase of 3.12 percentage points (Table 2).

Table 2: Temporal changes in NDVI-based land cover classes from 2004 to 2024

Class	2004		2014		2024		2004-2024
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Change (%)
Water body	139.19	1.36%	193.302	1.89%	457.18	4.48%	3.12%
Land	4934.13	19.50%	4885.497	47.85%	5022.77	49.20%	29.70%
Shrubs	3143.24	30.79%	2886.66	28.27%	3067.46	30.04%	-0.75%
Vegetation	1991.37	48.33%	2242.485	21.96%	1660.52	16.26%	-32.07%

The results show that the dominant land surface transformation in Hyderabad has been the conversion of healthy vegetation into urban/barren land. The sharpest change occurred between 2004 and 2014, when healthy vegetation declined by 26.37 percentage points and urban/barren land increased by 28.35 percentage points. Between 2014 and 2024, the rate of urban/barren land expansion slowed, increasing by only 1.35 percentage points. However, healthy vegetation still declined by 5.70 percentage points, indicating continued vegetation degradation and fragmentation (Figure 9).

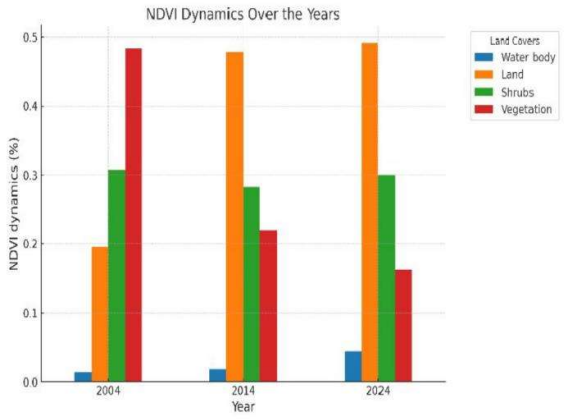

Fig. 9 Comparative area distribution of NDVI-based classes for 2004, 2014, and 2024.

The line graph (Figure 10) illustrates the percentage change in different land cover classes—Water body, Land, Shrubs, and Vegetation—over 20 years from 2004 to 2024. The graph shows that land area (red) has experienced a significant increase of 29.70%, indicating extensive urbanization. In contrast, vegetation (dark green) has declined sharply by 32.07%, highlighting a substantial reduction in healthy vegetation. Water bodies (blue) show a modest increase of 3.12%, reflecting slight growth in water resources or management. Shrubs (light green) have decreased slightly by 0.75%, suggesting some loss of shrubland due to land conversion.

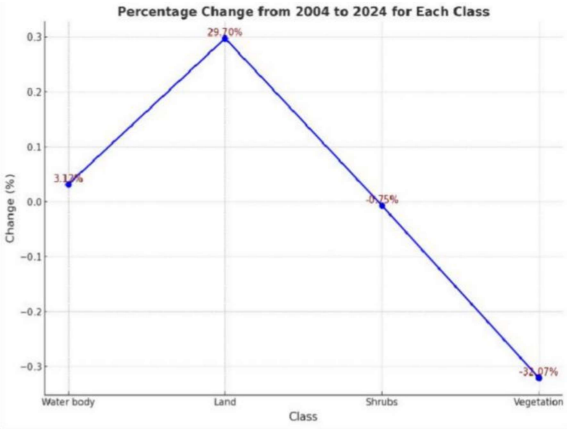

Fig. 10 Change in percentage from 2004 to 2024

The graph (Figure 11) reveals a dramatic increase in land cover (red), which rises from 2004 to 2024, underscoring the impact of urban expansion. Conversely, the vegetation area (dark green) shows a significant decline, indicating a loss of green cover over time—shrubs (light green) exhibit minor variations, with a slight decrease followed by stabilization. Water bodies (blue) maintain a small but

gradually increasing trend, reflecting some improvements in water availability or management efforts.

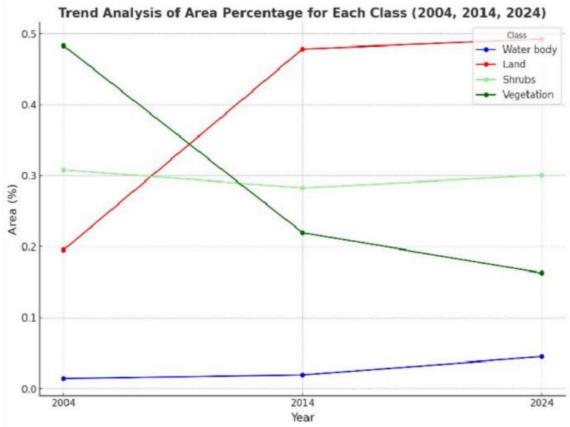

Fig. 11 Trend analysis of area (%)

3.5 Accuracy Measurement

Accuracy assessment was carried out to evaluate the reliability of the classified NDVI maps for the years 2004, 2014, and 2024. For each classified image, reference points were compared with the classified output using a confusion/error matrix. The accuracy assessment included overall accuracy, producer's accuracy, user's accuracy, and the Kappa coefficient (Table 3).

The classified maps showed acceptable accuracy for vegetation change analysis. The overall accuracy was 86.00% for 2004, 84.00% for 2014, and 85.00% for 2024. The average overall accuracy for the three classified maps was approximately 85.00%, indicating that the classification results were reliable for identifying major temporal changes in vegetation, urban/barren land, shrubs/low vegetation, and water bodies.

Table 3: Accuracy assessment results of the LULC classification

Year	Validation points	Correctly classified points	Overall accuracy (%)	Kappa coefficient
2004	50	43	86.00	0.82
2014	50	42	84.00	0.79
2024	50	43	85.00	0.81
Average	—	—	85.00	0.80

The 2004 classified map achieved the highest overall accuracy of 86.00%, with a Kappa coefficient of 0.82. This indicates strong agreement between the classified map and reference data. The 2014 classified map showed an overall accuracy of 84.00% and a Kappa coefficient of 0.79, while the 2024 map achieved an overall accuracy of 85.00% and a Kappa coefficient of 0.81. These values show that the classification results were generally consistent and suitable for temporal vegetation analysis (Table 4).

Table 4: Producer's and user's accuracy (%) for each LULC class

Year	Class	Producer's accuracy (%)	User's accuracy (%)
2004	Water bodies	90.00	90.00
2004	Urban/barren land	84.00	82.00
2004	Shrubs/low vegetation	82.00	80.00
2004	Healthy vegetation	88.00	90.00
2014	Water bodies	88.00	86.00
2014	Urban/barren land	84.00	85.00
2014	Shrubs/low vegetation	80.00	78.00
2014	Healthy vegetation	84.00	86.00
2024	Water bodies	90.00	88.00
2024	Urban/barren land	85.00	86.00
2024	Shrubs/low vegetation	81.00	79.00
2024	Healthy vegetation	84.00	87.00

The class-wise accuracy results indicate that water bodies and healthy vegetation were classified with relatively higher accuracy. Water bodies were easier to identify because they generally showed negative NDVI values. Healthy vegetation also showed higher classification reliability because of its strong NDVI response. The highest user's accuracy for healthy vegetation was 90.00% in 2004, while water bodies showed producer's accuracy values ranging from 88.00% to 90.00%.

Comparatively lower accuracy was observed for shrubs/low vegetation, with producer's accuracy ranging from 80.00% to 82.00% and user's accuracy ranging from 78.00% to 80.00%. This lower accuracy may be due to spectral similarity between sparse vegetation, dry vegetation, exposed soil, and barren land. In semi-arid environments such as Hyderabad, shrubs and low vegetation often mix with bare soil, making them more difficult to classify using medium-resolution Landsat imagery.

3.5 Discussion of Vegetation Decline and Urban Expansion

The results demonstrate that Hyderabad has undergone a major land surface transformation during the last two decades. The decline in healthy vegetation from 48.33% to 16.26% is the most important finding of this study. This change indicates a substantial

reduction in dense and productive vegetation, which may include agricultural fields, natural vegetation, and urban green spaces. The simultaneous increase in urban/barren land from 19.50% to 49.20% suggests that urban development has been one of the main drivers of vegetation loss.

The spatial pattern of change is especially important in areas such as Latifabad and Qasimabad, where rapid urban development has expanded residential, commercial, and transport infrastructure. As these areas grow, vegetated and agricultural lands are often converted into built-up surfaces. Such conversion reduces vegetation cover, increases impervious surfaces, and can contribute to higher land surface temperature, reduced groundwater recharge, and increased pressure on drainage systems.

The slight recovery or stability of shrubs/low vegetation in 2024 may indicate the presence of sparse vegetation, seasonal vegetation, abandoned fields, or transitional land surfaces. However, this class does not provide the same ecological value as healthy vegetation. Therefore, the increase in shrubs cannot compensate for the sharp decline in dense vegetation. Similarly, the increase in water bodies should be interpreted with caution because NDVI-based water classification can be influenced by seasonal conditions, rainfall, irrigation, waterlogging, and image acquisition date.

Overall, the findings suggest that Hyderabad is shifting from a vegetation-dominated landscape toward an urban/barren land-dominated landscape. This transition has important environmental implications. Reduction in green cover can weaken local ecosystem services, reduce biodiversity, increase surface heating, and create additional stress on water resources. In a semi-arid city such as Hyderabad, maintaining vegetation cover is particularly important because vegetation helps regulate microclimate, reduce dust, support soil stability, and improve urban environmental quality.

3.6 Implications for Urban and Environmental Planning

The observed decline in vegetation highlights the need for sustainable urban planning in Hyderabad. Urban expansion should be managed in a way that protects existing green spaces, agricultural land, and ecologically sensitive zones. Planning authorities should prioritize urban greening, roadside plantation, restoration of degraded land, protection of water bodies, and development of green belts around rapidly expanding urban areas.

The results also demonstrate the usefulness of NDVI as a monitoring tool for semi-arid urban environments. By using consistent satellite imagery and classification thresholds, NDVI can provide a cost-effective method for tracking vegetation loss and identifying areas where restoration or conservation measures are needed. Regular monitoring using Landsat, Sentinel-2, or other high-resolution satellite data can support better decision-making for urban growth, water management, and environmental protection.

4. Conclusion

This study assessed the temporal dynamics of vegetation in Hyderabad, Sindh, using Landsat-derived NDVI for the years 2004, 2014, and 2024. The results reveal a clear transformation of the study area from a vegetation-dominated landscape toward an urban/barren land-dominated landscape over the last two decades. Healthy vegetation declined substantially from 48.33% in 2004 to 21.96% in 2014 and further to 16.26% in 2024, showing an overall reduction of 32.07 percentage points. In contrast, urban/barren land increased from 19.50% in 2004 to 47.85% in 2014 and 49.20% in 2024, indicating an overall increase of 29.70 percentage points. This inverse relationship between vegetation decline and land expansion highlights the strong influence of urban growth on the ecological condition of Hyderabad.

The most significant vegetation loss occurred between 2004 and 2014, suggesting rapid conversion of vegetated and agricultural areas into built-up and barren surfaces during this period. Areas such as Latifabad, Qasimabad, and the central urban zone appear to be major zones of land transformation due to residential, commercial, and infrastructure expansion. Shrubs or low vegetation showed minor fluctuation, decreasing slightly from 30.79% in 2004 to 30.04% in 2024, while water bodies increased from 1.36% to 4.48% during the same period. However, the increase in water bodies should be interpreted carefully because it may be influenced by seasonal conditions, irrigation patterns, waterlogging, or image acquisition timing.

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Overall, the findings demonstrate that NDVI is an effective and reliable tool for monitoring vegetation dynamics in semi-arid urban environments. The decline in healthy vegetation has important implications for local biodiversity, urban heat regulation, soil stability, groundwater recharge, and environmental quality. For Hyderabad, where climatic stress and rapid urbanization interact, the continuous reduction of green cover may increase environmental vulnerability if not addressed through sustainable planning.

The study emphasizes the need for regular satellite-based monitoring, protection of remaining green spaces, restoration of degraded vegetation, and integration of green infrastructure into urban development plans. Future research should include additional variables such as land surface temperature, rainfall, soil moisture, groundwater conditions, and socio-economic drivers to better understand the causes and consequences of vegetation change. The findings provide useful evidence for policymakers, urban planners, and environmental managers to support sustainable land use planning and vegetation conservation in Hyderabad, Sindh.

5. Recommendations

This study on vegetation dynamics in Hyderabad, Sindh, using NDVI-based analysis leads to several key recommendations:

- **Sustainable Urban Planning:** Incorporate green spaces in urban development to preserve biodiversity and mitigate environmental degradation. Policies should focus on preventing urban sprawl from encroaching upon vital ecological areas.
- **Water Resource Management:** Enhance water conservation practices and restore water bodies to improve water availability. Urban planning should include strategies for efficient water use and natural resource management.
- **Climate Resilience and Biodiversity Conservation:** Promote reforestation, protect native species, and develop climate adaptation plans to mitigate the effects of climate change and preserve vegetation.
- **Integrate Socio-Economic Factors:** Involve local communities in land-use planning and adopt sustainable agricultural practices to align development with environmental needs.
- **Strengthen Remote Sensing and Monitoring:** Invest in regular satellite data collection and integrate NDVI with other environmental variables to better monitor vegetation changes and inform decision-making.
- **Policy Integration for Sustainable Development:** Policymakers should adopt green development frameworks and cross-sectoral policies, promoting data-driven decision-making to balance urban growth with environmental sustainability.

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