GEOGRAPHICAL ANALYSIS

ORIGINAL ARTICLE

Assessment of Vegetation Dynamics in the Western Ghats using Remote Sensing

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Abstract

The Western Ghats, one of the world's most significant biodiversity hotspots, play a vital role in maintaining ecological balance, carbon sequestration, hydrological regulation, and biodiversity conservation. However, increasing anthropogenic activities and climate variability have significantly influenced vegetation dynamics across the region, necessitating continuous monitoring of vegetation health. The present study evaluates the spatio-temporal dynamics of vegetation in the Karnataka segment of the Western Ghats during the period 2004–2024 using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data integrated with Geographic Information System (GIS) techniques. Three widely adopted vegetation indicators, namely Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), and Vegetation Health Index (VHI), were employed to assess vegetation canopy density, photosynthetic activity, biomass characteristics, and vegetation health. The analysis revealed that the Western Ghats maintained predominantly healthy vegetation conditions throughout the study period despite temporal fluctuations associated with climatic variability and anthropogenic disturbances. LAI values indicated moderate to high vegetation canopy density, with temporary declines during stress years followed by rapid recovery under favourable climatic conditions. Similarly, NDVI values demonstrated consistently high vegetation greenness and productivity, while VHI analysis confirmed that the region experienced generally low drought stress and sustained vegetation resilience over the two decades. Higher vegetation health was consistently observed within dense evergreen forest regions, whereas comparatively lower values occurred in disturbed and anthropogenically influenced landscapes. The integration of LAI, NDVI, and VHI provided a comprehensive assessment of vegetation dynamics and highlighted the ecological resilience of the Western Ghats. The findings demonstrate the effectiveness of remote sensing and GIS techniques for long-term vegetation monitoring and provide valuable scientific information to support sustainable forest management, biodiversity conservation, and environmental planning in this ecologically significant region.

Keywords: Leaf Area Index (LAI); Normalized Difference Vegetation Index (NDVI); Vegetation Health Index (VHI); Remote Sensing; Geographic Information System (GIS); Western Ghats

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1 Introduction

Vegetation forms the foundation of terrestrial ecosystems by regulating carbon sequestration, hydrological processes, nutrient cycling, and biodiversity conservation. Forest ecosystems, in particular, play a crucial role in maintaining ecological stability and mitigating the impacts of climate change. However, increasing anthropogenic disturbances, including deforestation, agricultural expansion, urbanization, and climate variability, have accelerated vegetation degradation across many parts of the world. Consequently, continuous assessment of vegetation health has become an essential component of ecosystem management and environmental conservation. Traditional field-based surveys provide valuable ecological information, but they are often constrained by limited spatial coverage, high cost, and time-consuming data collection. Remote sensing has therefore emerged as an efficient and reliable approach for monitoring vegetation dynamics over extensive geographical areas with high temporal consistency[6, 17].

The rapid advancement of satellite remote sensing has transformed vegetation monitoring by enabling continuous observation of land surface characteristics at regional, national, and global scales. Multi-temporal satellite datasets allow researchers to detect changes in vegetation cover, quantify ecosystem productivity, and evaluate the effects of both natural and anthropogenic disturbances. Because satellite observations provide repetitive and objective measurements, they have become indispensable for environmental monitoring, forest management, and climate-related studies[6, 14]. Furthermore, advances in geographic information systems (GIS) and digital image processing have significantly improved the extraction and interpretation of vegetation information from remotely sensed imagery, supporting evidence-based environmental decision-making.

Among the various remote sensing techniques, vegetation indices have become one of the most widely accepted approaches for evaluating vegetation condition and ecosystem productivity. The Normalized Difference Vegetation Index (NDVI), first introduced by Tucker [17], utilizes the contrast between red and near-infrared reflectance to quantify vegetation greenness and photosynthetic activity. Although NDVI has demonstrated excellent capability in monitoring vegetation, it is susceptible to soil background effects in sparsely vegetated regions. To overcome this limitation, Huete proposed the Soil Adjusted Vegetation Index (SAVI), which minimizes soil reflectance influences and improves vegetation discrimination. Subsequently, the development of the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation products further enhanced the capability of satellite-based vegetation monitoring by providing standardized and globally consistent vegetation indices with improved radiometric performance[5].

Besides spectral vegetation indices, biophysical parameters such as the Leaf Area Index (LAI) have become fundamental indicators of vegetation canopy structure, biomass, and ecosystem productivity. LAI represents the total one-sided leaf area per unit ground surface area and is closely related to photosynthesis, evapotranspiration, and carbon exchange between vegetation and the atmosphere. Previous studies have demonstrated that remotely sensed LAI products provide reliable information for estimating forest productivity, monitoring vegetation dynamics, and assessing ecosystem responses to environmental change[4, 11]. Similarly, relationships between spectral reflectance and canopy characteristics have enabled accurate estimation of forest biophysical parameters across different vegetation types[2, 16].

Assessment of vegetation health has also benefited from the integration of vegetation and thermal information through the Vegetation Health Index (VHI). Developed by Kogan (1995)[8], VHI combines the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) to evaluate vegetation stress associated with drought and thermal anomalies. Unlike individual vegetation indices, VHI provides a comprehensive assessment of vegetation condition by integrating both moisture availability and temperature stress, making it particularly suitable for drought monitoring and long-term ecosystem assessment. Consequently, NDVI, LAI, and VHI together offer complementary information for understanding vegetation condition, biomass distribution, and environmental stress across heterogeneous landscapes.

The Western Ghats of India constitute one of the world's most significant biodiversity hotspots and are recognized for their exceptional levels of species richness and endemism. Extending parallel to the western coast of India, this mountain system supports diverse forest ecosystems that provide essential ecosystem services, including carbon storage, water resource regulation, and habitat conservation. The ecological integrity of the Western Ghats is increasingly threatened by deforestation, plantation expansion, infrastructure development, climate variability, and changing land-use practices. Such pressures have resulted in fragmentation of natural forests, alterations in vegetation composition, and changes in ecosystem functioning, emphasizing the need for systematic monitoring of vegetation health.

Several studies have investigated vegetation dynamics and climatic interactions within the Western Ghats using remote sensing techniques. Variations in MODIS-derived NDVI have been shown to be closely associated with southwest monsoon rainfall, indicating a strong dependence of vegetation growth on climatic variability[9]. Similarly, subsequent research demonstrated significant relationships between vegetation dynamics and monsoon behaviour, highlighting the sensitivity of Western Ghats ecosystems to interannual climatic fluctuations[15]. Despite these important contributions, most previous investigations have primarily focused on individual vegetation indices or short-term analyses. Comprehensive assessments integrating multiple vegetation indicators such as NDVI, LAI, and VHI over extended time periods remain comparatively limited.

Addressing this research gap, the present study evaluates the spatio-temporal dynamics of vegetation health across the Western Ghats during the period 2004–2024 using MODIS remote sensing data. By integrating NDVI, LAI, and VHI within a geospatial framework, the study examines vegetation canopy characteristics, biomass distribution, and vegetation health while identifying temporal trends associated with climatic variability and anthropogenic influences. The findings are expected to contribute to a better understanding of ecosystem resilience in the Western Ghats and provide scientific evidence to support sustainable forest management, biodiversity conservation, and long-term environmental planning.

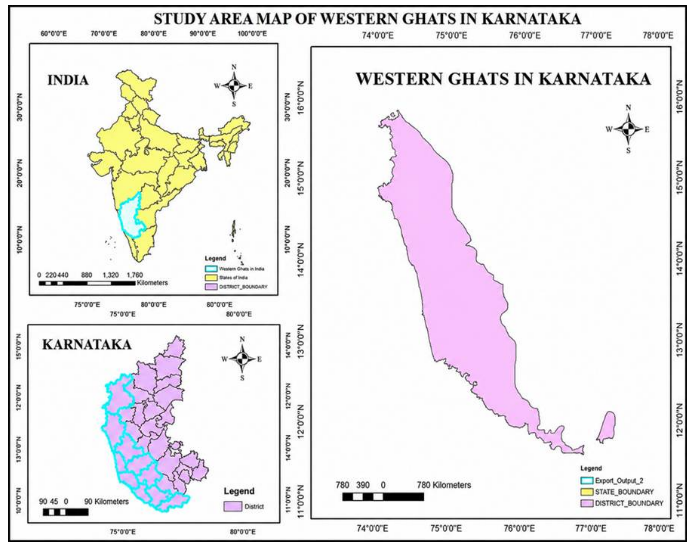
Objectives:

- To assess the spatio-temporal dynamics of vegetation in the Western Ghats using Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), and Vegetation Health Index (VHI) during the period 2004–2024.
- To evaluate vegetation canopy density, greenness, and health using MODIS satellite data integrated with Remote Sensing and Geographic Information System (GIS) techniques.

2 Study Area

The present study focuses on the Western Ghats, a continuous mountain range extending approximately 1,600 km along the western coast of India from the Tapti River in Gujarat to Kanyakumari in Tamil Nadu. Covering nearly 160,000 km², the Western Ghats traverse the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu. Owing to their exceptional biological richness, high species endemism, and ecological significance, the Western Ghats have been recognized as one of the world's 36 global biodiversity hotspots[10].

The study is confined to the Karnataka segment of the Western Ghats, encompassing the districts of Belagavi, Uttara Kannada, Shivamogga, Chikkamagaluru, Hassan, Kodagu, Udupi, Dakshina Kannada, and Chamarajanagar. The study area lies approximately between 11°30′ N and 15°30′ N latitude and 74°00′ E and 76°30′ E longitude. This region contains extensive tropical evergreen, semi-evergreen, moist deciduous, and montane forests, which support rich floral and faunal diversity and provide critical ecosystem services[1, 13].



Map 1: Western Ghats in Karnataka

The climate of the region is predominantly tropical monsoon, with distinct wet and dry seasons. The southwest monsoon, extending from June to September, contributes nearly 80–90% of the annual rainfall. Average annual rainfall varies considerably due to topographic influence, ranging from approximately 1,500 mm in the eastern rain-shadow regions to more than 7,000 mm along the windward western slopes. Mean annual temperatures generally range between 15°C and 32°C, with cooler conditions prevailing at higher elevations. These climatic gradients strongly influence vegetation distribution, forest productivity, and biodiversity patterns throughout the region[1].

Geologically, the Western Ghats are composed predominantly of Archaean crystalline rocks, including granites, gneisses, charnockites, and schists, representing some of the oldest geological formations in the Indian subcontinent. The terrain is characterized by rugged hills, steep escarpments, deeply incised valleys, and undulating plateaus. Elevation within the Karnataka portion generally ranges from about 300 m to over 1,900 m above mean sea level, creating significant variations in climate and vegetation along altitudinal gradients[12].

The dominant soil types include lateritic soils, red loamy soils, forest loam, and reddish-brown gravelly soils, which are generally acidic, well-drained, and rich in organic matter under dense forest cover. These soils, together with favourable climatic conditions and abundant rainfall, support luxuriant tropical vegetation and high primary productivity. However, increasing anthropogenic activities, including agricultural expansion, plantation development, urbanization, and infrastructure growth, have accelerated forest fragmentation and habitat degradation in several parts of the Western Ghats[7, 13]. Maintaining landscape connectivity and conserving native forest ecosystems are therefore essential for preserving the region's exceptional biodiversity and ecological integrity[1, 3].

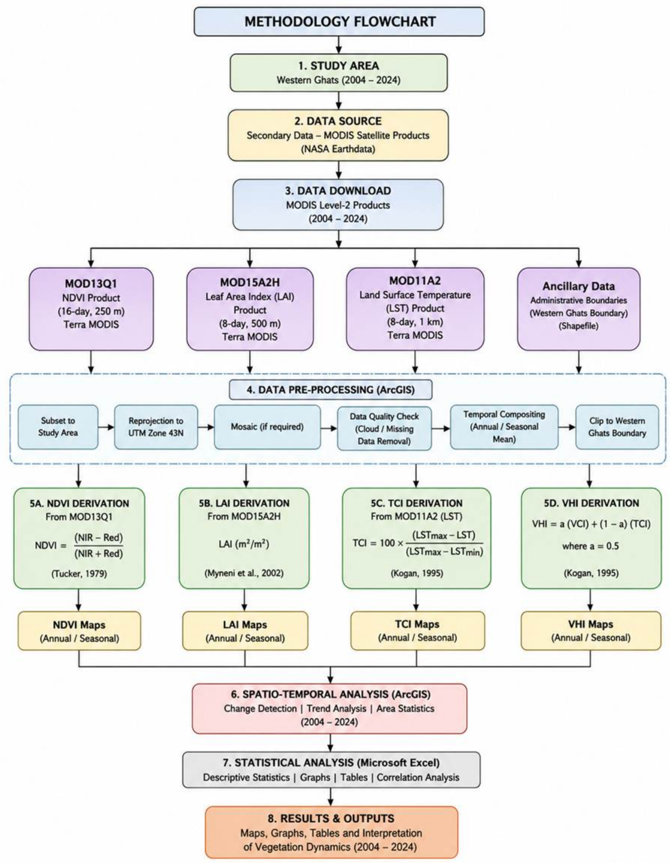
3 Data and Methodology

The Western Ghats were selected for the present study because they represent one of the world's most important biodiversity hotspots and play a significant role in maintaining ecological balance, hydrological processes, and carbon sequestration. The region supports diverse forest ecosystems ranging from tropical evergreen to moist deciduous forests, making it highly suitable for long-term vegetation monitoring using remote sensing techniques[10]. In recent decades, increasing anthropogenic activities such as deforestation, plantation expansion, agricultural encroachment, infrastructure development, and climate variability have considerably influenced vegetation dynamics across the region[1, 13].

The availability of long-term MODIS satellite observations from 2004 to 2024 provides a consistent and reliable dataset for analysing vegetation changes over time. Furthermore, the heterogeneous terrain, diverse climatic conditions, and ecological significance of the Western Ghats make it an ideal region for evaluating vegetation health using indices such as NDVI, LAI, TCI, and VHI. Therefore, the Western Ghats were selected as the study area to assess long-term spatio-temporal vegetation dynamics using remote sensing and GIS techniques.

- **Data Sources**

The present study is primarily based on secondary data obtained from satellite-derived remote sensing products.



Flow Chart

MODIS (Moderate Resolution Imaging Spectroradiometer) datasets were acquired from the National Aeronautics and Space Administration (NASA) Earth data archive. These datasets provide consistent temporal observations that are suitable for long-term vegetation monitoring and environmental assessment. All datasets used in the present study were Level-2 products, which are atmospherically corrected and suitable for vegetation index analysis.

- **Software and Tools**

The downloaded MODIS datasets were processed using ArcGIS software for image pre-processing, raster calculation, vegetation index generation, spatial analysis, and thematic map preparation. Statistical analysis, descriptive statistics, preparation of graphs, and tabulation of results were carried out using Microsoft Excel.

Table 1: Satellite Data Used

Satellite Sensor	Study Period	MODIS Product / Bands Used	Processing Level
Terra MODIS	2004–2024	MOD13Q1 (NDVI), Bands 1 & 2 (Red and NIR)	Level-2
Terra MODIS	2004–2024	MOD15A2H (Leaf Area Index - LAI)	Level-2
Terra MODIS	2004–2024	MOD11A2 (Land Surface Temperature for TCI)	Level-2
Terra MODIS	2004–2024	VHI generated using NDVI (VCI) and TCI	Level-2

- **Vegetation Indices Used**

1. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is one of the most widely used vegetation indices for evaluating vegetation greenness and photosynthetic activity[17].

$$\mathbf{NDVI} = \frac{\mathbf{NIR - Red}}{\mathbf{NIR + Red}}$$

2. Leaf Area Index (LAI)

Leaf Area Index (LAI) represents the ratio of total one-sided leaf area to the corresponding ground area and is widely used to estimate vegetation canopy density and biomass[11].

$$\mathbf{LAI} = \frac{\mathbf{Leaf\ Area}}{\mathbf{Ground\ Area}}$$

3. Temperature Condition Index (TCI)

The Temperature Condition Index (TCI) evaluates vegetation stress by utilizing land surface temperature observations derived from MODIS imagery[8].

$$\mathbf{TCI = 100\ x\ \frac{LSTmax - LST}{LSTmax - LSTmin}}$$

4. Vegetation Health Index (VHI)

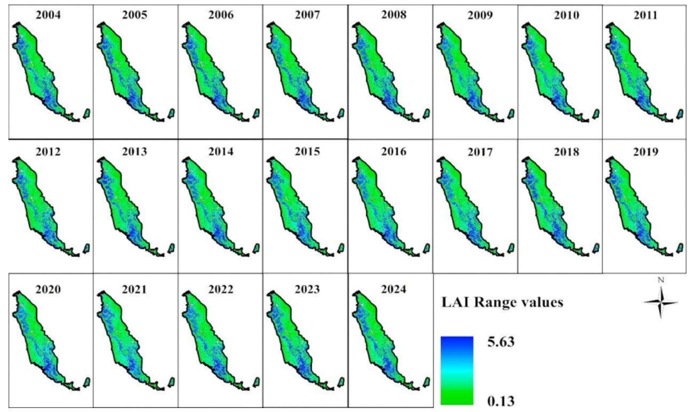
The Vegetation Health Index (VHI) combines the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) to provide an integrated assessment of vegetation health and drought conditions[8].

$$\mathbf{VHI = a(VCI) + (1 - a)(TCI)}$$

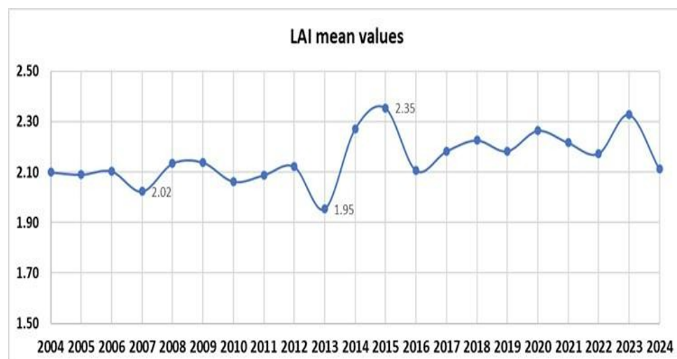
where a = 0.5.

4 Results and Discussion

- **Spatio-temporal Analysis of Leaf Area Index (LAI)**



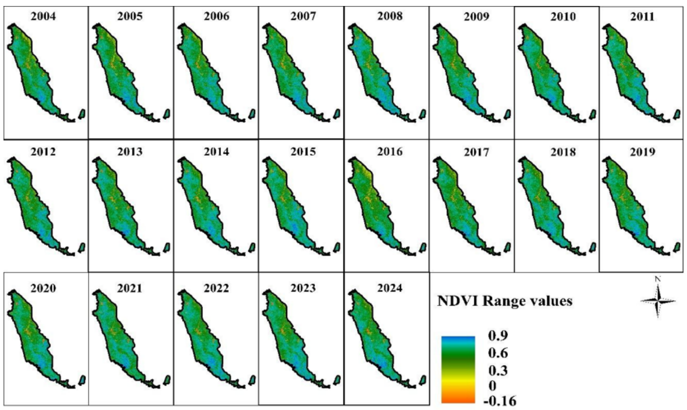
Map 2: Leaf Area Index of Western Ghats from 2004 to 2024



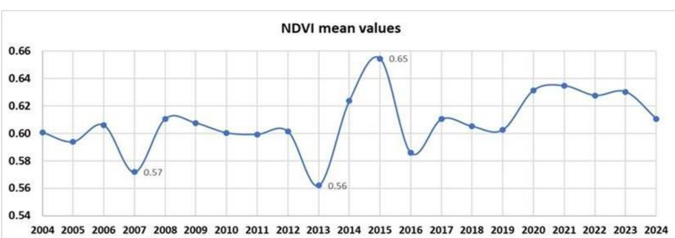
Graph 1: Leaf Area Index mean values of Western Ghats from 2004 to 2024

The Leaf Area Index (LAI) maps and mean LAI graph together reveal that the Western Ghats maintained predominantly moderate to high vegetation density throughout the study period (2004–2024), indicating generally healthy forest canopy conditions. Areas with higher LAI values were mainly concentrated in evergreen forest regions, reflecting dense vegetation cover and greater biomass, while lower values were observed in disturbed or sparsely vegetated zones. The mean LAI values fluctuated between 1.95 in 2013 and 2.35 in 2015, suggesting temporary reductions in canopy density during drought or stress periods followed by strong recovery under favorable climatic conditions. After 2015, LAI values remained relatively stable above 2.10, indicating sustained vegetation health despite climatic variability and anthropogenic pressures. The spatial and temporal patterns highlight the resilience of the Western Ghats ecosystem, while also demonstrating its sensitivity to rainfall variability, land-use changes, and human activities. Overall, the results confirm that the region continues to support a stable and productive vegetation canopy, particularly within protected forest landscapes.

- **Spatio-temporal Analysis of Normalized Difference Vegetation Index (NDVI)**



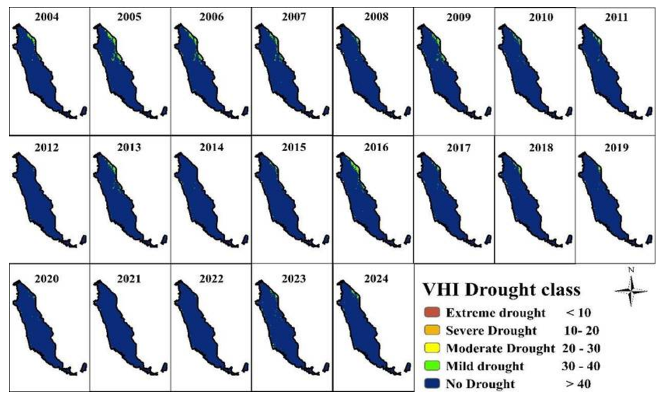
MAP 3: Normalized Difference Vegetation Index of western Ghats from 2004 to 2024



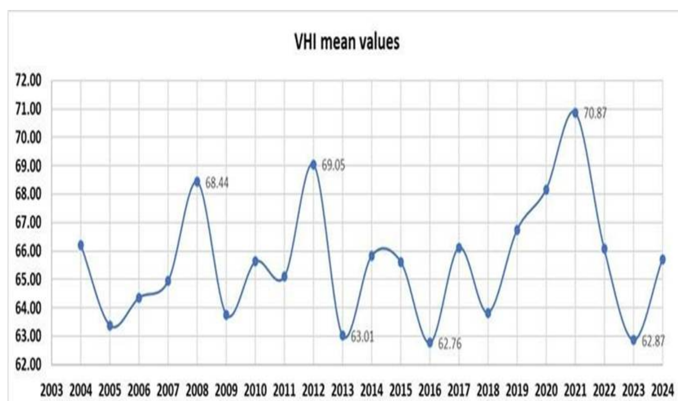
Graph 2: Mean Values of Normalized Difference Vegetation Index in western Ghats

The NDVI maps and mean NDVI graph together indicate that the Western Ghats maintained consistently healthy vegetation cover and strong photosynthetic activity throughout the study period (2004–2024). Spatially, higher NDVI values were concentrated in dense evergreen and semi-evergreen forest regions, while comparatively lower values occurred in sparsely vegetated and anthropogenically influenced areas. The mean NDVI values ranged from a minimum of 0.56 in 2013 to a maximum of 0.65 in 2015, reflecting moderate temporal fluctuations in vegetation condition. Following the decline observed during 2013, NDVI values recovered rapidly and remained relatively high, reaching approximately 0.63–0.64 during 2020–2023, indicating sustained vegetation vigor. The close correspondence between the spatial distribution and temporal trend of NDVI highlights the resilience of the Western Ghats ecosystem despite climatic variability and human-induced pressures. Overall, the results confirm the persistence of a productive and ecologically stable forest landscape across the region.

- **Evaluation of Vegetation Health Using Vegetation Health Index (VHI)**



MAP 4: Vegetation Health Index of western Ghats from 2004 to 2024



Graph 3: Mean Values of Vegetation Health Index in western Ghats

The VHI maps and mean VHI graph reveal notable spatial and temporal variations in vegetation health across the

Western Ghats during the study period. Areas with higher VHI values represent healthy vegetation experiencing minimal drought stress, whereas lower values indicate relatively stressed vegetation conditions associated with moisture deficiency. The mean VHI values varied from a minimum of 62.76 in 2016 to a maximum of 70.87 in 2021, demonstrating fluctuations in vegetation health in response to changing climatic conditions. Peaks in VHI correspond to periods of favourable moisture availability and improved ecosystem conditions, while lower values reflect episodes of increased vegetation stress. Spatially, the dense forested regions of the Western Ghats consistently exhibited higher vegetation health compared to more disturbed landscapes. Overall, the VHI results indicate that although vegetation health is influenced by climatic variability, the Western Ghats ecosystem has maintained a generally healthy and resilient condition over the study period

5 Conclusion

The present study assessed the spatio-temporal dynamics of vegetation in the Karnataka segment of the Western Ghats during 2004–2024 using MODIS-derived Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), and Vegetation Health Index (VHI) integrated with Remote Sensing and Geographic Information System (GIS) techniques. The results indicate that the Western Ghats have maintained generally healthy vegetation conditions throughout the study period despite periodic fluctuations caused by climatic variability and anthropogenic activities. Higher LAI and NDVI values observed across dense evergreen forests reflect stable vegetation canopy, high biomass, and sustained photosynthetic activity, while comparatively lower values in disturbed areas indicate the influence of land-use change and human interventions. The VHI analysis further revealed that the region experienced predominantly low drought stress, demonstrating the ecological resilience of the Western Ghats under varying climatic conditions. Although temporary declines in vegetation health were observed during certain years, rapid recovery highlights the adaptive capacity of the ecosystem. The integration of LAI, NDVI, and VHI provided a comprehensive understanding of vegetation condition by combining information on canopy structure, vegetation greenness, and moisture stress. Overall, the study demonstrates that satellite remote sensing and GIS are effective tools for long-term vegetation monitoring and can provide valuable scientific information for biodiversity conservation, sustainable forest management, climate change adaptation, and environmental planning in the Western Ghats.

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