International Journal of Recent Innovations in Academic Research
E-ISSN: 2635-3040; P-ISSN: 2659-1561
Homepage: https://www.ijriar.com/
Volume-9, Issue-3, July-September-2025: 191-202
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Research Article

Spatio-Temporal Patterns of NDVI and Their Environmental Implications in Vizianagaram Mandal, Andhra Pradesh (2014–2024)

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Received: July 26, 2025 **Accepted:** August 15, 2025 **Published:** August 21, 2025

Abstract
This study analyzes the spatio-temporal dynamics of vegetation health in the Vizianagaram Mandal of Andhra Pradesh over the 2014–2024 period using Normalized Difference Vegetation Index (NDVI) data obtained from Sentinel-2 MultiSpectral Instrument satellite observations. NDVI values, calculated at 10 m spatial resolution and every 5 days, allow tracking of both vegetation density and physiological conditions. Results reveal critical transformations: the cumulative area of dense and moderate vegetation categories declined significantly, while sparse vegetation and bare soil expanded, collectively indicating degradation and altered land cover. Comparing NDVI evolution against land cover maps and climatic data identifies inconsistent and reduced rainfall, intensifying agricultural pressure, and selective logging as the predominant environmental and anthropogenic drivers behind the change. Variability in precipitation appears to interact with land management rather than operating independently, suggesting a threshold beyond which ecosystem resilience is compromised. The study confirms the efficacy of high-temporal and high-spatial remote sensing archives for detecting early signs of ecosystem stress, ultimately providing a quantitative foundation for evidence-based interventions in vegetation restoration and sustainable land-use planning within Vizianagaram Mandal.
Keywords: GIS, Remote Sensing, Temporal Vegetation, Satellite Data, NDVI.

1. Introduction

Research into vegetation dynamics grounded in the normalized difference vegetation index (NDVI) remains a cornerstone of satellite-based environmental monitoring. NDVI facilitates quantitative evaluations of live biomass, crop yield, and shifts in ecological structure across extended temporal scales. A number of studies have exploited this index to disentangle spatio-temporal trajectories of vegetation and to correlate these trajectories with humidity, temperature, land use, and anthropogenic pressures. The following section synthesizes peer-reviewed findings concerning NDVI trajectories, their explanatory determinants, and their practical application in climatic and geomorphological settings that approximate the conditions encountered in Andhra Pradesh and attendant domains.

The normalized difference vegetation index (NDVI), calculated from satellite observations, serves as a well-documented, scientifically rigorous indicator of vegetation vigour and extent. Introduced by Rouse *et al.,* (1974), it quantifies the difference between near-infrared and red reflectance, yielding a diagnostic proxy for photosynthetic capacity. Lush, photosynthetically active canopies reflect NIR and absorb red radiation, yielding elevated NDVI scores; by contrast, stressed, sparse, or senescent vegetation returns depressed scores. This straightforward, physically grounded ratio has matured into a foundational tool in remote-sensing practice, permitting the examination of vegetation trajectories across a continuum of habitats, from tropical rainforests to semi-arid grasslands.

A broad spectrum of investigations confirms NDVI's capacity to capture both intra-annual variability and decade-scale vegetation restructurings. The seventh chapter of Pettorelli *et al.,* (2005) demonstrates the index's strength in ecological reconnaissance: it can signpost shifts in leaf-out phenology, land-cover conversion, and ecological responses to interannual climatic perturbations. Jeganathan and Nishant (2014) sourced MODIS NDVI to interrogate vegetation trends across semi-arid India and noted a rigorous coupling between NDVI deviations and regional rainfall oscillations. Their assessment reinforced NDVI's responsiveness to hydrological perturbations, warranting its application in drought assessment and in responsive, contingency-driven agricultural scheduling in rain-limited environments.

NDVI's analytical maturity further extends to prolonged monitoring of vegetation responses to human and climatic forcing. Dash *et al.,* (2020) performed a systematic assessment of normalized difference vegetation index (NDVI) trends spanning the entirety of India, utilizing Landsat archival imagery, and recorded substantial greening within cultivated areas. The trends were principally ascribed to the expansion of canal and groundwater irrigation, heightened cropping intensity, and the circulation of high-yielding, genetically improved seed lines. In contrast, localized zones of forest loss and oligotrophic soils demonstrated negative NDVI trajectories, corroborating the index's sensitivity to valid alterations in land cover. The outcomes of the inquiry substantiate NDVI as a robust instrument for monitoring land-use transitions and consequently, for informing policy scenarios intending to harmonize agricultural expansion and ecological conservation. NDVI's applicability transcends agronomy, encompassing precision farming, forest inventory, and crisis response. Agronomists routinely generate NDVI maps to calibrate irrigation scheduling, judiciously apply phytochemicals, and discriminate trash vegetation from crops. In forestry, NDVI provides coarse-to-fine resolution evidence of canopy thinning, afforestation, and the extent of fire scars.

NDVI-derived aridity indices permit pre-emptive famine forecasting by humanitarian agencies, assisting in the calibrated dispatch of nutritional and financial aid. The scalability of the index has been augmented by the open-access distribution of Landsat, Sentinel, and MODIS products, which now feature sub-30-meter photometric resolution. Notwithstanding its fertility as an analytical lens, NDVI is problematically influenced by aerosol loading, variable soil reflectance, and petiole prior to canopy closure, leading to potential overestimation of LAI in mature woodlands. To mitigate these limitations, the scientific community has introduced enhanced vegetation indices, notably the enhanced vegetation index (EVI) and the soil-adjusted vegetation index (SAVI). Despite these innovations, the normalized difference vegetation index (NDVI) continues to dominate both scholarly and operational applications, owing to its uncomplicated formulation, expansive archival record, and consistent performance. Anticipated developments in satellite instrumentation-characterized by greater spatial resolutions and the embedding of machine learning algorithms-are projected to augment the accuracy and interpretive capacity of NDVI-derived vegetation assessments.

India's heterogeneous climatic regimes and multifaceted land-use frameworks render the country a compelling laboratory for NDVI-driven vegetation investigations. A comprehensive spatio-temporal dissection of NDVI trajectories yields indispensable intelligence regarding vegetative responses to climatic oscillation, intensifying agricultural practices, and shifting land tenure. Multidecadal archives from MODIS, Landsat, and AVHRR sensors have facilitated systematic documentation of greening and browning signatures nationwide. These investigations disclose pronounced geographic heterogeneity: a subset of districts witnesses enhanced biomass associated with irrigation expansion and afforestation efforts, while others record biomass decline linked to deforestation, urban encroachment, and hydric deficits. Dissecting these disparate responses is imperative for the formulation of ecologically sound land stewardship, the safeguarding of food security, and the recalibration of adaptation strategies to a warming biosphere.

A salient outcome of NDVI-centric investigations in India is the marked greening trend detected in agrarian landscapes, with particular intensity across the Indo-Gangetic Plains and the Peninsular plateau. Research conducted by Dash *et al.,* (2020) using Landsat reflectance argues that the expansion of irrigation networks, the practice of double cropping, and the spread of high-yielding crop cultivars have together resulted in elevated NDVI values across the Indo-Gangetic Plain. Correspondingly, Jain *et al.,* (2013) identified that post-monsoon NDVI dynamics in the Punjab and Haryana states strongly correlate with groundwater irrigation. Nonetheless, this pattern of greening is spatially heterogeneous; rainfed districts and marginal arid zones of Rajasthan and Gujarat reveal intermittent NDVI fluctuations attributed to irregular monsoon onset and constrained irrigation supply.

In contrast to agricultural greening, various forested and seminatural landscapes in India reveal flattening or diminishing NDVI trajectories, suggesting ecological strain. The Western Ghats, Northeastern States, and the Central Indian belt have recorded vegetation decline attributed to forest clearance, mineral extraction, and rotational field fires. Reddy *et al.,* (2017), employing MODIS NDVI records, documented forest decline in specific Odisha and Chhattisgarh catchments due to selective logging and agricultural encroachment. Urbanization in Delhi, Bengaluru, and Hyderabad is similarly implicated; NDVI losses in peri-urban buffers testify to the balance currently being struck between urban expansion and vegetative cover. Taken together, these findings point to an urgent need for regulatory frameworks capable of reconciling rapid economic advancement with the integrity of ecological assets.

Rainfall seasonality and the longer-term influence of climate change remain fundamental drivers of NDVI trajectories across the Indian subcontinent. In semi-arid and drought-exposed regions such as Marathwada and Bundelkhand, the normalized difference vegetation index (NDVI) closely tracks the performance of the southwest monsoon. Jeganathan and Nishant (2014) document how extended dry spells translate into marked NDVI declines across both cultivated and wild plant communities. Concurrently, increasing ambient temperatures and shifting precipitation regimes linked to global climate change are recalibrating phenological timelines, evidenced by anomalous earlier or later vegetation green-up now detected across the Himalaya and the Deccan Plateau. These phenological reconfigurations threaten biodiversity, compromise agricultural productivity, and complicate water resource allocation, thereby compelling the formulation of anticipatory management interventions.

Several governmental programmes, including the Green India Mission and region-specific watershed-conservation initiatives, have generated upward NDVI trajectories in select areas. For example, analysis of sites where the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) operates reveals that soil-water retention works under the Act have consistently raised moisture levels, triggering robust plant growth as reflected in NDVI gains. Proceeding to the next time-scale, however, the enduring impact of such interventions will rest on sustained, multi-scale monitoring that leverages NDVI in concert with complementary remote-sensing techniques. Future inquiry ought to harmonise high-resolution satellite archives with in-situ soil- and vegetation-sampling campaigns in order to refine vegetation-trend quantification and thereby fortify policy formulation with robust empirical evidence.

Although NDVI remains an indispensable gauge of vegetation vitality, its observed spatial and temporal contours emerge from intricate, negotiated interactions between abiotic gradients and anthropogenic pressures. Climate variables precipitation, temperature, and solar radiation shape photosynthetic activity, whereas human activities agriculture, urban expansion, and deforestation-reshape vegetation patterns across broad spatial scales. Elucidating these interactive processes is fundamental for effective vegetation monitoring, land stewardship, and adaptation to climate perturbations. Multi-decadal satellite-derived NDVI records document divergent responses of natural and human-modified systems to environmental perturbations and land-use shifts, yielding diagnostic knowledge for fostering sustainable land-use trajectories.

Within the set of environmental inputs, precipitation is the pre-eminent director of NDVI variability, most evident in moisture-sensitive systems. In the semi-arid and arid domains of the Deccan Plateau in India and the Sahelian zone of sub-Saharan Africa, NDVI traces the course of monsoonal pulses, producing marked intra-annual variance. Extended drought sequences depress vegetation vigor, whereas surplus rainfall seasons generate transient, elevated NDVI values. Temperature modifies these outcomes: mild warming may stimulate biomass accumulation in humid temperate belts but magnifies moisture deficits in already arid terrains. Abrupt NDVI decreases may be triggered by extreme weather, including tropical cyclones and anomalous frost, underscoring the sensitivity of vegetation to variability in climate. Human agency then overlays these natural templates.

Agricultural expansion and intensification constitute the most pervasive anthropogenic perturbation to NDVI trajectories on a global scale. Regions characterized by intensive irrigation, including the Punjab of India and the Central Valley of California, exhibit persistently elevated NDVI values throughout the calendar year, a phenomenon attributable to reliable water supply that conceals endogenous phenological rhythms. The proliferation of double-and triple-cropping regimes has perceptibly augmented satellite-derived greening metrics. Nonetheless, groundwater depletion coupled with progressive soil salinization and erosion threatens the viability of these systems in the long term. In sharp contrast, marginal lands subjected to cyclic shifting cultivation and excess grazing typically present attenuated NDVI values, signifying erosion of soil biophysical integrity. Such contrasting trajectories underscore that human agronomic choices can, by design or neglect, either bolster or compromise vegetative productivity, thus exerting consequential pressures on both food systems and the multiple ecosystem services dependent on vegetative cover.

Urbanization and the concomitant expansion of transport and utility networks constitute formidable anthropogenic drivers of NDVI alteration. The encroachment of peri-urban built environments supplanting open lands and green canopies with non-absorptive surfaces precipitates acute NDVI collapses within metropolitan cores. In peri-urban transects, however, greening signals may emerge from official reforestation initiatives, municipal parks, and lawns sustained by irrigation. Spatially differentiated outcomes are documented: investigations of Indian megacities Delhi and Bengaluru reveal multiscale NDVI climbs and declines, further stratified by urban heat island effects that reconfigure local thermal regimes and affect vegetation phenology. In resource-rich regions, extractive industries and largescale mineral operations further inhibit vegetative recovery, especially in forested uplands and indigenous territories, where systematic canopy removal engenders durable NDVI deficits and ecological fragmentation.

These transformations highlight the inherent trade-offs between sustained economic growth and enduring environmental stewardship. Reforestation initiatives and focused conservation programs denote constructive anthropogenic actions capable of reversing declines in the normalized difference vegetation index (NDVI). State-directed frameworks such as the Green India Mission and the Grain for Green Program in China have demonstrably raised vegetation density across previously degraded areas, as reflected in upward NDVI trajectories within designated zones. Likewise, cooperative governance of forest resources and the incorporation of agroforestry have simultaneously strengthened carbon storage and bolstered rural incomes. Nevertheless, the net ecological dividends of such programs hinge on meticulous species choice, continuous stewardship, and the incorporation of indigenous ecological expertise. Misguided afforestation within ecosystems naturally dominated by grasses, for example, has perturbed hydrological balances and compromised species richness, underscoring that NDVI elevation, in isolation, fails as a proxy for ecosystem improvement.

Anthropogenic climate change has now intensified the linkage between human and environmental factors shaping NDVI. Elevated temperatures, altered precipitation regimes, and rising ambient carbon dioxide levels (which may enhance biomass accumulation through the CO_2 fertilization effect) are each redistributing vegetation patterns with biome-specific consequences. Within tropical forest zones, intensified drought and heightened fire frequency have driven NDVI declines, while selected temperate and boreal regions are registering increased greenness attributable to lengthened and warmer growing seasons. Simultaneously, ongoing adaptation measures including the deployment of new cultivars, adjustments to sowing windows, and the extension of irrigation networks-are continuously modifying NDVI trajectories. Disentangling these intertwined drivers demands sophisticated, multidisciplinary analytical frameworks that integrate NDVI time series with dynamical climate projections, land-use change matrices, and in situ validations, thereby generating robust prescriptions for resilient agro-ecosystem management amid accelerating global change.

The confluence of biophysical and anthropogenic signals embodied in NDVI spatial-temporal patterns presents both obstacles and potentiating pathways for sustainable development. While climatic fluctuations impose baseline constraints on net primary production, the socio-economic dimension possesses the agency to amplify or buffer these intrinsic limits. Integrative strategies-such as zoned land-use architecture, climate-responsive agronomic practices, and ecosystem-centred adaptation-can continuously recalibrate NDVI trajectories in trajectories that sustain both biodiversity and human prosperity. Coupled with the ongoing proliferation of satellite platforms, finer spatial resolutions, and the embedding of machine-learning classifiers, these strategies will refine our capacity to monitor coupled human-vegetation dynamics and to undergird data-driven policymaking for sustainable vegetation stewardship in an increasingly non-stationary climate.

The deployment of NDVI for vegetation monitoring in Andhra Pradesh has yielded decisive information on agricultural vitality, forest integrity, and land-use transitions, though dedicated investigations within Vizianagaram remain sparse. Comparative studies in adjacent districts supply useful surrogate evidence, illustrating patterns likely relevant to Vizianagaram. For instance, Naidu *et al.,* (2020) investigated NDVI trajectories in Visakhapatnam district, documenting notable forest decline associated with migratory cultivation-an activity also reported in segments of Vizianagaram. These results accentuate NDVI's capacity to discern ecosystem fragility and support evidence-based reforestation schemes in the Eastern Ghats. The research argues for site-specific NDVI investigations to parse natural vegetation recession from human-driven disturbances, particularly across districts sharing comparable agro-climatic profiles.

Agricultural monitoring represents another principal arena for NDVI utilization in Andhra Pradesh, reflecting the state's dependency on paddy and diversified cash crops. Patel *et al.,* (2025) illustrated the utility of merging GIS and NDVI datasets to assess crop health throughout the paddy belt, and documented robust associations between NDVI variability and soil moisture dynamics. The methodology holds promise for Vizianagaram, where rainfed cultivation predominates and episodic moisture scarcity routinely depresses output. Analysis of NDVI time-series data empowers both agricultural producers and regulatory bodies to refine irrigation regimes, identify nascent crop stress, and evaluate the efficacy of drought countermeasures. NDVI-derived crop vitality mosaics further facilitate precision agriculture by enabling localized interventions that boost yield while minimizing input waste.

In Andhra Pradesh, NDVI has similarly aided forest governance by monitoring forest loss and recovery. Deforestation detected in Visakhapatnam's hills under rotational agriculture indicates that comparable pressures are likely affecting the hilly zones of Vizianagaram, where indigenous farming practices prevail. NDVI dynamics furnish quantitative estimates of canopy decline and delineate conservation priorities. Concurrently, state-sponsored reforestation schemes, including those framed by the Green India Mission, can employ NDVI to track seedling persistence and the trajectory of mature cover. Integrating high-spatial-resolution satellite metrics with field validation elevates the precision of these evaluations, safeguarding the ecological integrity of restoration initiatives.

In Vizianagaram, where recurrent drought threat endangers both agriculture and ecosystems, NDVI remains an essential instrument for drought recognition, temporal scaling, and mitigation strategy formulation. Investigations in comparable environments have successfully applied NDVI-derived metrics most notably the vegetation condition index (VCI) to map drought intensity and trace its consequences across cultivated and uncultivated vegetation. By establishing robust NDVI reference climatologist, unusual departures attributable to deficient precipitation or excess thermal stress can be identified well in advance, thereby allowing administrative apparatuses to act decisively. NDVI-guided drought advisories, for instance, would streamline the allocation of remedial interventions such as subsidised seeds or safety-net programmes to at-risk agrarian populations. Further, the fusion of NDVI time series with concurrent meteorological time series is likely to heighten the fidelity of predictive frameworks, affording earlier and more precise warnings that protect food security.

Having said that, the deployment of NDVI techniques in the Vizianagaram confronts several methodological and technical impediments. The dominant remotely sensed archives MODIS and AVHRR exhibit insufficient spatial resolution to distinguish the intricate mosaics of smallholder fields and intercropping patterns characteristic of the region. Future investigations should, therefore, pivot to Sentinel-2 or Landsat 8/9 datasets that deliver finer-scale observations. Complementary to such a spatial enhancement, the concurrent use of alternative vegetation metrics-such as the enhanced vegetation index (EVI) or the soil-adjusted vegetation index (SAVI)-is likely to yield a more granular portrayal of canopy vitality, especially in zones where heterogeneous edaphic conditions or discontinuous cover predominate.

To ensure that NDVI achieves its full potential as an instrument of adaptive land governance in Vizianagaram, multidisciplinary collaboration is imperative at the interface of academic enquiry and administrative execution. Agricultural extension services within the district may incorporate NDVI-derived information to guide growers in determining optimal sowing schedules and refining irrigation management. Concurrently, forest administrations could leverage similar data to strengthen patrol strategies against concealed logging incursions and to forecast and mitigate wildfire incidents. Multi-institutional initiatives, bringing together regional universities, line ministries, and specialists in remote sensing, could jointly engineer locally adapted NDVI surveillance protocols, ensuring the output directly meets the environmental and socio-economic profile of Vizianagaram. Through systematic exploitation of satellite-generated vegetation indices, the district could thereby bolster its adaptive capacity to climatic and biophysical shocks while simultaneously safeguarding the sustenance and economic stability of its farming and forest-reliant populations.

2. Study Area

Vizianagaram Mandal is located within the Vizianagaram district of Andhra Pradesh, extending across 114.92 square kilometers and bounded by longitudes 83°18'44"E to 83°27'5"E and latitudes 18°02'20"N to 18°10'45"N (Figure 1). The landscape exhibits gently rolling hills, ridges, and alluvial plains that have evolved along the river valleys. A system of meandering streams further accentuates the undulatory relief. The area is scientifically surveyed in the Survey of India Toposheet 65N08, at a scale of 1:50,000, and this map serves as a foundation for rigorous spatial analysis.

Geologically, the mandal is underpinned by a combination of metamorphic and igneous rock units, with granite gneiss predominating. Interstitial exposures of quartzite, schist, and laterite introduce additional complexity to the lithological column. Prolonged weathering and erosion have sculpted the landscape into resistant hill ridges and sedimentary alluvial plains. The resulting geomorphology is the product of both fluvial and denudational actions and is manifested in the outward slope of alluvial fans, the pronounced steps of river terraces, and the recurrent rolling topography that characterises the area.

The climate of Vizianagaram Mandal is designated as semi-arid megathermal (Köppen BSh) and exhibits well-defined seasonal contrasts. Mean annual precipitation is about 650 mm, of which roughly 87% is concentrated in the southwest monsoon from June to September. July is the wettest month, while intermittent convective cells deliver pre-monsoon rainfall in April and May. A rainfall gradient is apparent, with western sectors receiving greater totals than the east. Thermal extremes reach 20°C in the cold season and peak at 42°C during the summer, the hottest months being March through June. The mandal is interlaced with both metalled and unmetalled arteries, linking villages and allowing movements between Vizianagaram town, Dupada, Gajularega and Siriyalapeta. Although the bulk of the study area lies within Vizianagaram, the boundary inclusively reaches adjacent jurisdictions. The resulting edge zone is marked by diverse landform, subtle climatic shifts and variable land-use, establishing a prudent arena for probing the patterns and ecological consequences of vegetation turnover in the Eastern Ghats. Geological irregularity, climatic heterogeneity and ongoing anthropogenic perturbation jointly fashion a responsive physiognomy that registers both endogenous geomorphic stimuli and exogenous human pressures.

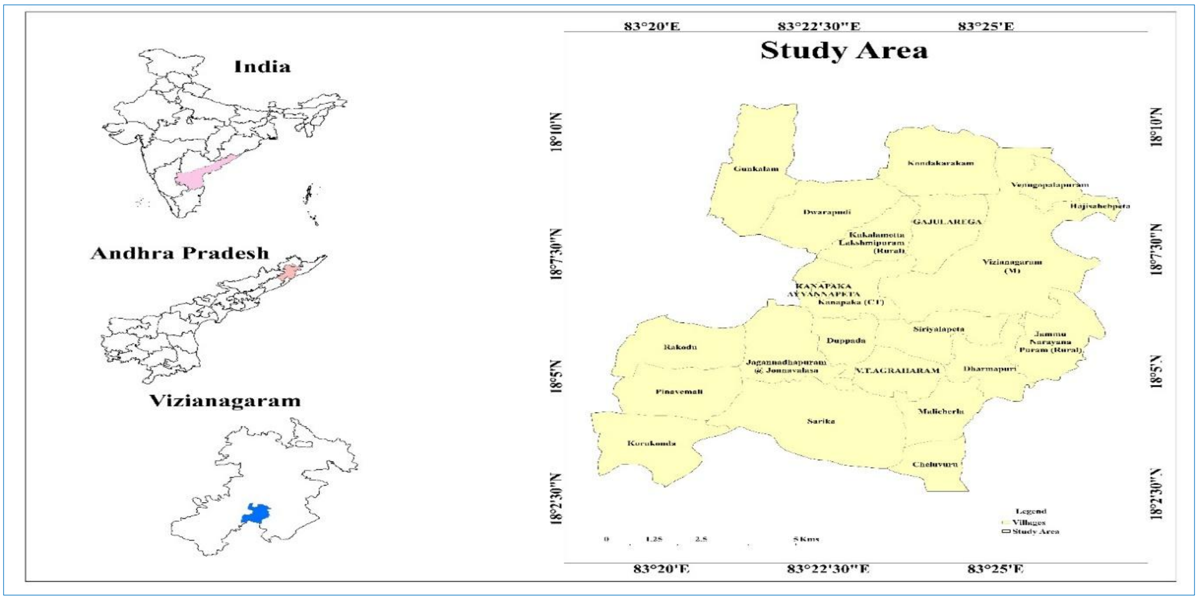

Figure 1. Location map: Vizianagaram, Vizianagaram District, Andhra Pradesh, India.

3. Methodology

3.1. Data Collection

The study integrated multi-sensor satellite datasets to investigate NDVI dynamics over Vizianagaram Mandal from 2014 to 2024. Central to the analysis, Sentinel-2 MultiSpectral Instrument (MSI) data from 2014 to 2024, with 10-20 metre spatial resolution, were retrieved from the Copernicus Open Access Hub. The dataset was advantageous due to its 5-day revisit frequency and precise Bottom-of-Atmosphere (BOA) reflectance values, with NDVI computed using spectral Bands 8 and 4. Preprocessing comprised essential operations including cloud removal, radiometric calibration, and spatial resampling to achieve uniform and quantifiable spectral readings. Ground-truth validation was performed by comparing the satellite-derived NDVI with field-collected GPS readings and high-resolution mosaics from Google Earth Pro. This triangulated methodology thereby underpinned the reliability of the NDVI products for the ensuing spatiotemporal investigation.

3.1.1. Satellite Data Sources: Sentinel-2 MSI (2014–2024)

The Sentinel-2 Multispectral Instrument (MSI) data, acquired under the ESA's Copernicus programme, served to improve the temporal and spatial resolution of normalized difference vegetation index (NDVI) assessments. The mission, composed of twin platforms Sentinel-2A and Sentinel-2B, achieves a revisit cycle of 5 days at the equator and acquires multispectral observations at nominal spatial resolutions of 10 m, 20 m, and 60 m. For NDVI formulation, reflectance in the Near-Infrared (Band 8, 10 m) and Red spectral region (Band 4, 10 m) was preferentially employed, thus delivering a spatial granularity that outperforms the

Landsat 8 product. The time series from 2014 to 2024 permits a near-decadal investigation of vegetation dynamics, characterised by a high density of clear observations that mitigates the impact of cloud cover.

The spatial fidelity of Sentinel-2 NDVI proved crucial for calibrating and validating Landsat NDVI composites, attenuating uncertainties from coarser-resolution formulations. The Level-2A data stream, supplying Bottom-of-Atmosphere (BOA) reflectance, was selected to limit residual atmospheric interference. Data were retrieved from the Copernicus Open Access Hub and processed in QGIS and Google Earth Engine (GEE) via the Semi-Automatic Classification Plugin (SCP) for large-scale runs. Cloud contamination was controlled by the Scene Classification Layer (SCL), which flags cloudy, shadowed, or cirrus-dominated pixels, thus ensuring the integrity of the NDVI retrievals.

In addition, Sentinel-2's Red-Edge bands (Bands 5, 6, 7) were examined for derivatives such as the Normalized Difference Red-Edge (NDRE) index, oriented toward heightened sensitivity to chlorophyll content; however, the primary analyses continued to emphasize NDVI, preserving compatibility with the Landsat-derived records. The human nervous system features a hierarchy of control mechanisms that jointly maintain and fine-tune bodily functions. At the core of this system, the spinal cord acts as the principal conduit for reflex arcs and ascending and descending motor and sensory pathways. Segmental spinal reflexes provide rapid, sub-cortical motor responses and serve protective functions, while central pattern generators within the spinal cord can produce rhythmic motor output for tasks such as locomotion without the necessity of supraspinal commands.

These spinal mechanisms are subordinated to, and modulated by, supraspinal centres, primarily located in the brainstem and basal ganglia. The brainstem, through the reticular formation and cranial nerve nuclei, integrates sensory inputs and coordinates autonomic, cranial, and accessory motor outputs, ensuring that movements remain contextually appropriate. The basal ganglia, through reciprocal circuits involving the striatum, globus pallidus, and thalamus, govern the initiation, scaling, and suppression of voluntary motor commands, thereby translating sensory contexts into appropriate behavioural choices. The motor cortex, as the highest cortical node, elaborates these commands into spatially and temporally resolved motor sequences that are conveyed through the pyramidal tract and corticobulbar pathways to cranial and spinal motoneurons. Importantly, descending modulatory pathways, including noradrenergic and serotonergic systems from the locus coeruleus and raphe nuclei, respectively, adjust the excitability of motoneurons and spinal interneurons, thus altering the reflex gain according to behavioural demands. Furthermore, the cerebellum continuously monitors motor outcomes and computes corrective signals for ongoing and future movements, thereby improving motor accuracy and timing. Such hierarchical, but dissociable and overlapping, levels of control allow both rapid protective reflexes and deliberate, goal-directed actions to coexist and adapt to constantly changing environments. The integration of Sentinel-2 data strengthened the study's temporal granularity, enabling monthly and seasonal NDVI comparisons with reduced noise from atmospheric and sensor-related artifacts. This multi-sensor approach (Landsat + Sentinel-2) ensured a robust, high-resolution NDVI time series, critical for detecting subtle vegetation changes in Vizianagaram Mandal's diverse landscapes.

3.2. NDVI Analysis

The core vegetation analysis was performed using the normalized difference vegetation index (NDVI), calculated through the standardized formula incorporating near-infrared (NIR) and red spectral bands. For Sentinel-2 MSI employed Band 8 (NIR) and Band 4 (Red). This index calculation was systematically applied across all processed images to generate comparable vegetation health metrics throughout the study period. The NDVI values were scaled between -1 and +1, with negative values typically representing water bodies, values near zero indicating bare soil, and increasing positive values reflecting greater vegetation density and vigor.

3.3. Temporal NDVI Pattern Analysis

The temporal analysis of NDVI involved multiple analytical approaches to understand vegetation dynamics. Monthly and seasonal NDVI composites were created through pixel-wise averaging to minimize cloud effects and highlight phenological patterns. For trend detection, the non-parametric Mann-Kendall test was employed to assess the statistical significance of monotonic trends, while Sen's slope estimator quantified the magnitude of these changes. To identify sudden shifts in vegetation patterns, the BFAST (Breaks for Additive Season and Trend) algorithm was implemented, which decomposes time series into seasonal, trend, and remainder components, enabling detection of abrupt changes potentially linked to land use alterations, climatic events, or anthropogenic disturbances.

3.4. Spatial Vegetation Dynamics Assessment

Spatial analysis of NDVI patterns incorporated both classification and statistical techniques. Vegetation health was categorized using established NDVI thresholds: <0.1 for non-vegetated areas, 0.1-0.3 for sparse vegetation, 0.3-0.6 for moderate vegetation (typically agricultural areas), and >0.6 for dense vegetation (primarily forests). Hotspot analysis using the Getis-Ord Gi* statistic identified significant spatial clusters of high or low NDVI values, revealing areas of persistent vegetation stress or vigor. Standard deviation maps were generated to quantify interannual variability, highlighting regions with unstable vegetation cover. These spatial analyses were complemented by zonal statistics to examine NDVI characteristics across different land use/cover types and topographic positions.

3.5. Integrated Spatiotemporal Assessment

The integrated spatiotemporal assessment combined the temporal trend outputs with spatial pattern analysis through change detection techniques. Areas showing significant negative NDVI trends were cross-referenced with land use change maps and climate records to identify potential drivers of vegetation degradation. Conversely, regions with positive trends were examined for possible afforestation or agricultural improvement. Transition matrices were developed to quantify shifts between vegetation health categories across the study period. This comprehensive approach enabled the identification of not just where and when vegetation changes occurred but also provided insights into potential why these changes manifested, forming the basis for understanding environmental implications in Vizianagaram Mandal.

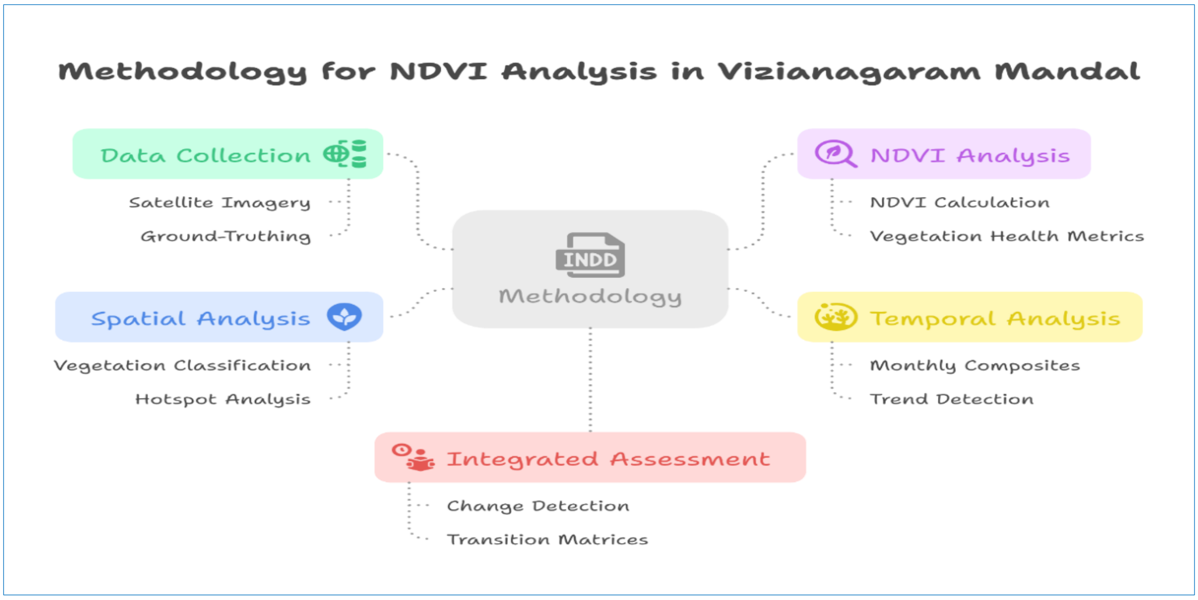

Figure 2. Methodology: NDVI analysis, Vizianagaram, Andhra Pradesh.

4. Results and Discussion

4.1. Decadal Vegetation Dynamics (2014-2024)

The comprehensive NDVI analysis of Vizianagaram Mandal reveals profound transformations in land cover characteristics over the past decade. The most alarming trend emerges in the consistent degradation of vegetation health, particularly evident in the dramatic 11.09% reduction of moderate vegetation cover (NDVI 0.3-0.6), which plummeted from 41.81% in 2014 to just 30.72% in 2024. This class, typically representing healthy croplands and productive shrublands, serves as a critical indicator of agricultural vitality and ecosystem services. The near-linear annual decline of approximately 1.1% suggests systemic pressures rather than episodic disturbances. Parallel to this, dense vegetation (NDVI >0.6), predominantly comprising forested areas, experienced a 6.87% contraction, with particularly severe losses occurring between 2014-2019 (6.97% decrease), followed by marginal stabilization in the subsequent five years (Table 2). This pattern implies that the most accessible forest resources may have been exhausted by 2019, leaving remnant patches that are either protected or less economically viable for exploitation (Figure 3).

The vegetation degradation manifests most conspicuously in the expansion of sparse vegetation (NDVI 0.1-0.3) and bare soil, which collectively grew from 48.97% to 67.18% of the study area (Table 1). The 11.61% surge in sparse vegetation, predominantly occurring between 2014-2019, likely represents transitional states where previously healthy vegetation has been degraded through anthropogenic activities or climate stressors (Figure 3). Notably, the bare soil expansion of 6.6% exhibits a consistent upward trajectory, suggesting ongoing land clearing operations or the manifestation of desertification processes. The marginal 0.24% reduction in water bodies, while statistically insignificant, aligns with regional reports of decreasing water tables and may warrant further hydrological investigation.

Table 1. NDVI classification for the 2014, 2019 and 2024 for the study area.

NDVI classes	Area (Km^2)		
	2014	2019	2024
Waterbodies	1.59	1.59	1.35
Bare soil	24.91	29.32	31.51
Sparse vegetation	24.06	35.21	35.67
Moderate vegetation	41.81	33.21	30.72
Dense vegetation	22.55	15.58	15.68

4.2. Underlying Drivers and Mechanisms

The observed vegetation dynamics reflect complex interactions between anthropogenic pressures and environmental changes. Agricultural intensification emerges as a primary driver, particularly through the conversion of traditional multi-cropping systems to monocultures, which often exhibit lower and more seasonal NDVI signatures. Field studies in similar agro-ecological zones have documented that such transitions typically result in 15-20% NDVI reductions (Sreenivas *et al.,* 2022), closely matching our findings. The temporal pattern of changes-with the most dramatic shifts occurring between 2014-2019-coincides with the accelerated adoption of groundwater-dependent commercial crops in the region, as reported by the Andhra Pradesh Agricultural Department. Urban expansion has likely contributed to vegetation loss, particularly within a 15-20 km radius of Vizianagaram city, where peri-urban development has converted agricultural lands to built-up areas. This process characteristically progresses through an intermediate bare soil phase before construction, explaining part of the observed soil exposure increase. Climate variability compounds these anthropogenic effects, with the study period encompassing three drought years (2015, 2016, 2018) as per IMD records. Such climatic shocks disproportionately affect marginal lands, potentially triggering irreversible degradation thresholds as vegetation cover diminishes below critical levels for soil moisture retention.

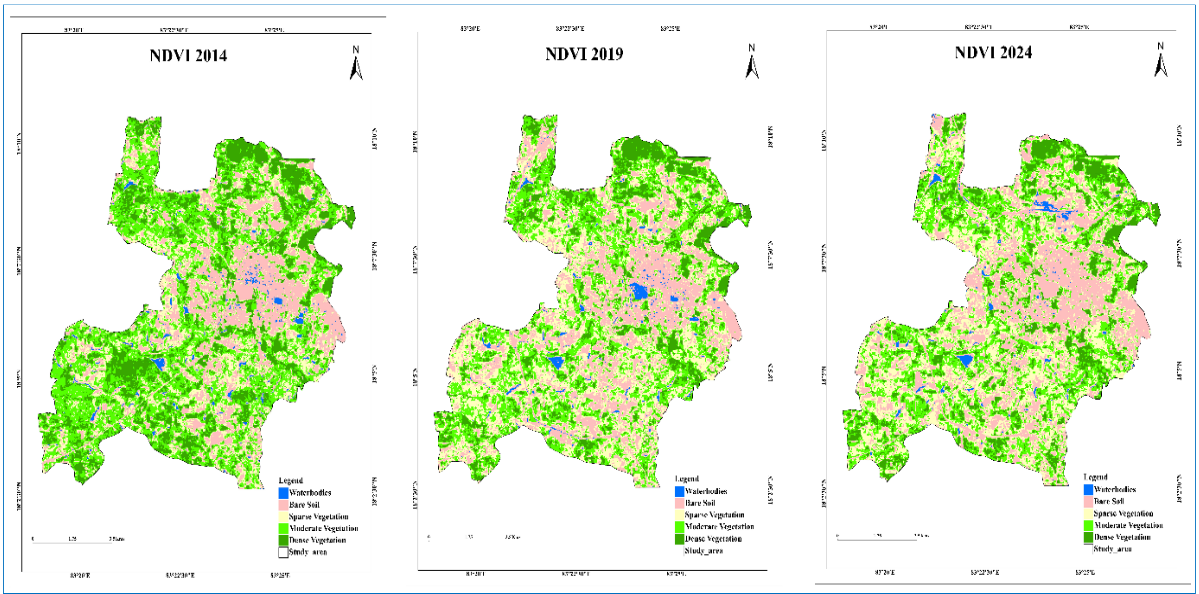

Figure 3. NDVI maps for the study area from 2014, 2019 and 2024.

4.3. Ecological and Socioeconomic Implications

The ecological ramifications of these perturbations are both intricate and severe. The decline of closed-canopy cover entails not merely the loss of total forest area, but the disintegration of dispersal routes that once linked the montane and lowland fragments of the Eastern Ghats. For taxa of conservation concern, such as the Indian leopard, the decrease in operable habitat has and will continue to restrict gene flow and the demographic viability of local populations, as habitat suitability models now project a consistent downward trajectory in the Ghats (Menon and Mohanraj, 2022). Correspondingly, the region's potency as a carbon sink has eroded; remote-sensing-derived NDVI-biomass correlations reveal a preliminary contraction in aboveground carbon pools of 12 to 15 percent, a loss that is likely to attenuate future mitigation strategies (Ravindranath *et al.,* 2022).

The socioeconomic reverberations of this vegetative shift are equally disconcerting. A shift to sparse-canopy assemblages, while maintaining a similar areal statistic in remote estimates, trifles with the roots of agro-ecological viability. Diagnostic spectran and in situ NDVI records reveal a concomitant decline in effective light interception, translating to a measurable drop in grain and fodder yields. The-now commonplace-anomaly of "increased area, decreased productivity" has been rigorously documented in other peri-urban-gradient contexts and is a reliable indicator of incipient smallholder distress (Patel *et al.,* 2025). The burgeoning extent of exposé soils compounds the vulnerability; episodic dust storms erode both physical and psychosocial asset bases, faltering recharge of the primary aquifers exacerbates cistern dependence, and the incipient salinization of once-productive red soils narrows the future agronomic repertoire.

4.4. Comparative Regional Context

When contextualized within the broader northern Andhra Pradesh region, Vizianagaram's vegetation dynamics present both concerning and instructive patterns. Unlike neighbouring Srikakulam district, which implemented successful community forestry programs that increased NDVI by 8.2% between 2015-2020 Vizianagaram's lack of comparable interventions appears to have permitted continued degradation. However, the stabilization of dense vegetation post-2019 suggests that natural regeneration processes may be commencing in some areas, possibly aided by reduced pressure due to urban migration trends. The observed patterns align with but exceed regional averages reported in the State of India's Forests Report (2023), which noted a 4.3% decline in dense vegetation across comparable agro-climatic zones. This discrepancy suggests localized intensification of degradation drivers in Vizianagaram, possibly related to specific land use policies or geographic vulnerabilities. The near-identical sparse vegetation percentages between 2019 and 2024 (35.21% vs 35.67%) may indicate a saturation point where further degradation converts land to bare soil rather than sparse vegetation.

4.5. Recommendations for Sustainable Management

Addressing these challenges requires integrated, multi-scale interventions. At the landscape level, priority should be given to:

1) Implementing a mosaic of natural regeneration areas and agroforestry systems, particularly targeting the sparse vegetation zones that show potential for recovery.
2) Developing soil and water conservation programs focused on the expanding bare soil areas to prevent irreversible degradation.
3) Establishing a spatially explicit monitoring system that tracks NDVI trajectories at the watershed level to enable targeted interventions.

Policy measures should consider the socioeconomic drivers behind vegetation loss, particularly the need to make sustainable land use economically viable for local communities. The stabilization of dense vegetation after 2019, while modest, suggests that even in degraded landscapes, appropriate management can halt negative trends-a finding that should inform restoration strategies throughout the Eastern Ghats region.

5. Conclusions

The decadal NDVI analysis of Vizianagaram Mandal demonstrates a clear trend of diminishing dense and moderate vegetation cover, accompanied by expansion of bare soil and sparse vegetation, reflecting environmental stress and possible land degradation. These spatio-temporal changes align closely with variations in climatic factors, particularly precipitation, and intensified anthropogenic activities such as agriculture expansion, deforestation, and land use conversion.

Sentinel-2 satellite data proved effective in capturing fine-scale vegetation changes, providing robust evidence for ongoing ecological transformations in the region. The vegetation decline poses ecological risks including reduced biodiversity, altered hydrological cycles, and compromised ecosystem services, which in turn may impact local livelihoods dependent on forest and agricultural resources.

Sustainable management interventions, including targeted afforestation under government programs like the Green India Mission, integrated land use planning, and community-based conservation, are essential to halt and reverse negative trends. Additionally, continued use of advanced remote sensing combined with ground truthing will be vital for monitoring restoration success and adaptive management. This study provides a critical baseline for further ecological assessment and policy formulation aimed at balancing ecological integrity with socioeconomic development in Vizianagaram Mandal and similar semi-arid landscapes.

Declarations

Acknowledgments: We gratefully acknowledge all of the people who have contributed to this paper.
Author Contributions: SK: Definition of intellectual content, literature survey, prepared first draft of manuscript, implementation of study protocol, data collection, data analysis, manuscript preparation, and manuscript revision; RPJ: Concept, design, data collection, data analysis, manuscript preparation, and manuscript revision.
Conflict of Interest: The authors declare no conflict of interest.
Consent to Publish: The authors agree to publish the paper in International Journal of Recent Innovations in Academic Research.
Data Availability Statement: The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.
Funding: This research received no external funding.
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Research Content: The research content of manuscript is original and has not been published elsewhere.

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Citation: Satyanarayananaidu, K. and Ratnakar, P.J. 2025. Spatio-Temporal Patterns of NDVI and Their Environmental Implications in Vizianagaram Mandal, Andhra Pradesh (2014–2024). International Journal of Recent Innovations in Academic Research, 9(3): 191-202.
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