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Assessment of Urban Green Space Dynamics towards Mitigating the Environmental Stress in Vijayawada City, Andhra Pradesh, India

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Abstract: Urban green spaces are recognized as essential elements of cities. They offer multiple benefits, including mitigating the urban heat island effect and its negative impact on public health. They also present opportunities for people to interact, recreate, and connect with nature. Rapid urbanization leads to a significant transformation of green spaces to impervious surfaces and urban infrastructures. A large number of cities throughout the world have experienced "urban heat island" (UHI) effects. UHI are characterized by a temperature difference between urban and rural regions. Urban green spaces can contribute to a broad range of ecosystem services, among which temperature mitigation is regarded as an important ecosystem regulating service. Understanding the influences of green space dynamics on the temperature variability is therefore of great interest for mitigating the UHI effect in cities. The UHI effect can be assessed by measuring surface air temperature and land surface temperature in the system. This study investigated green space dynamics and land surface temperature in the Vijayawada City, Andhra Pradesh, India. This research study addresses the pressing concern of environmental stress and green infrastructure (GI) deficiency, a rapidly urbanizing Tier-II study city. The central empirical concern is to assess spatial patterns of ecological degradation by integrating satellite-derived indices viz., Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), Urban Heat Island (UHI), Air Quality Index (AQI), and City Biodiversity Index (CBI). These indicators are employed to diagnose areas with inadequate green cover, extreme thermal exposure, and air quality, which often overlap with low-income and high-density urban zones.

The researchers have made systematic analysis and employed geospatial approach using multi-temporal Landsat imagery for quantification of NDVI and LST for the study region. UHI is computed by comparing urban LST with rural baselines. The biodiversity metrics are assessed using the Singapore Index Framework. Spatial overlays, zonal statistics, and descriptive ward-level synthesis are applied to integrate these indicators within ArcGIS 10.8. version. The result reveals 79% decrease in average NDVI during 1990 to 2024, with built-up areas increasing from 37% to more than 60%. LST values surpass 30°C in multiple wards, and UHI intensities reach up to 9°C, in thermally stressed zones like, Wards 2, 8, and 54. AQI values consistently exceed the permissible $PM_{2.5}$ limit, especially in industrial and commercial corridors. Biodiversity analysis yields a critically low CBI score of 32/92, reflecting habitat fragmentation and weak urban ecology governance in the system. These findings highlight the zones with cumulative environmental burdens, particularly in low-income wards, which are lacking access to GI. Based on the results, the study evolves a Green Infrastructural Planning Framework and to recommend strategies/guidelines for mitigation of Environmental Stress. Finally, the study concludes that spatially disaggregated, multi-indicator diagnostics are vital for prioritizing GI interventions in the system. The proposed framework can guide municipal administrators, urban planners, policy makers in allocating green resources equitably in cities might provide greater benefits for climate mitigation.

Keywords: Urban Green Space, Urban Heat Island, Environmental Stress, Biodiversity Index, Green Infrastructure Planning.

Introduction

Urbanization, the large-scale demographic and spatial shift from rural to urban settlements, has emerged as a defining feature of the 21st century. It encompasses not only population migration but also profound transformations in land use, infrastructure, and social organization. According to the [1], 56% of the world's population currently resides in urban areas, and this figure is projected to increase to 68% by 2050. This unprecedented growth is reshaping economies, driving technological advancements, and enhancing access to services and livelihoods. However, urbanization also exerts tremendous pressure on natural ecosystems, leading to land conversion, resource depletion, and heightened environmental stress. The world is urbanizing fast surpassing wars, public policies, and even natural disasters [2]. Today 54% of the global population is living in urban areas [3] and the urban population is expected to cover more than two-thirds of the world population by 2025 [4]. This rapid urbanization is causing congestion and pollution in the cities [5]. Many world cities have formulated sustainable urban development plans so that their urbanization process meets the requirements of urban sustainability [6]. Urban sustainability requires pollution reduction and useful feature addition such as trees so that our environment can be ameliorated [7]. Conservation along with the development of green spaces have been used for a long as an essential strategy to reduce the conflict between retaining the environmental quality and rapid urbanization. Green spaces provide numerous environmental services including noise reduction, air filtering, rainwater drainage, and microclimate regulation ([8], [9], [10], [11]).

The trajectory and impact of urbanization vary significantly across economic contexts:

- Developed nations, such as the United States, Germany, and Japan, have largely stabilized their urban growth. Their cities typically feature well-established infrastructure, robust governance frameworks, and carefully planned urban green spaces that mitigate environmental risks and improve liveability [12]
- Developing nations, including India, Brazil, and Indonesia, are experiencing rapid and often unplanned urban expansion. In these regions, weak enforcement of land-use regulations and high population density frequently result in the conversion of agricultural lands and wetlands into impervious surfaces. This accelerates the formation of urban heat islands (UHIs), exacerbates flood risks, and reduces biodiversity [13].
- Low-income nations, particularly in Sub-Saharan Africa and parts of South Asia, face the most acute challenges. Urbanization here is largely informal, with limited ecological planning, inadequate infrastructure, and insufficient green space allocation. These conditions contribute to critical environmental degradation, intensified heat stress, and increased vulnerability to climate hazards [14].

Amid such disparities, urban green spaces (UGS) play a vital role as ecological regulators and social equalizers in urban environments. These spaces, including public parks, community gardens, urban forests, wetlands, and roadside plantations, offer multiple ecosystem services critical to sustainable urban living:

I. Temperature regulation: Vegetation cools urban areas through evapotranspiration and shading, thereby reducing UHI effects [15].
II. Air quality improvement and public health: Urban trees capture particulate matter (PM2.5), nitrogen oxides (NOx), and carbon dioxide (CO_2), lowering the incidence of respiratory and cardiovascular illnesses [16].
III. Biodiversity support: Green corridors provide habitats and connectivity for urban flora and fauna, preserving ecological functions even in densely built-up areas [17].
IV. Social cohesion and well-being: Access to green space fosters recreational activities, mental wellness, and community interaction [18].

However, when green infrastructure is neglected, the consequences become apparent and severe. Cities begin to suffer from rising land surface temperatures, worsening air pollution, increased ecological fragmentation, and heightened vulnerability to climate-induced hazards such as floods and heatwaves. These challenges are especially pronounced in India's Tier-II cities, where urban growth often surpasses environmental planning. Vijayawada, a rapidly growing city in Andhra Pradesh, illustrates this condition vividly. Nestled along the Krishna River and surrounded by hillocks, the city has witnessed large-scale land-use change driven by real estate development, infrastructure projects, and a growing urban population. This expansion has resulted in the loss of wetlands, deforestation of hill ecosystems, and shrinking of vegetated patches, further compounding UHI intensity, degrading air quality, and diminishing biodiversity.

Vijayawada city is situated along the Krishna River and framed by hillocks, exemplifies this pattern. Rapid real-estate expansion and infrastructure build-out have accelerated land-use change, contributing to wetland loss, hill-ecosystem degradation, and shrinking vegetated patches; together, these shifts compound UHI intensity, undermine air quality, and erode biodiversity [19]. Recent India-focused research reinforces both the urgency and the opportunity of green-infrastructure planning. A spatio-temporal assessment by Ramamurthy, A. et.al., [20] in Bhopal links green-space depletion with thermal hotspot formation and ecological decline, underscoring the measurable cooling externalities of well-distributed parks and the need for operational guidance on sizing, spacing, and maintenance. Complementary evidence from Imphal shows that climate-responsive green infrastructure in peri-urban settings, where growth is often unregulated—can elevate quality of life when planned alongside core infrastructure and service delivery ([21]). Along India's vulnerable coasts, work integrating sea-level data with geospatial analyses in Kerala demonstrates why climate risks must be embedded in planning and regulatory instruments, strengthening the case for coastal buffers, setbacks, and nature-based solutions [22]. Broader Indian planning scholarship converges on the need for integrated, community-scale growth-management strategies that shape the amount, type, extent, rate, and quality of development to manage sprawl, protect environmental health, and advance sustainable community outcomes [23]; [24]

Drawing on these insights, the present research positions Vijayawada as a representative urban case for analysing the interplay among urbanization, environmental stress, and green-infrastructure planning. We employ a multi-indicator framework—comprising the Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), UHI intensity, Air Quality Index (AQI), and the City Biodiversity Index (CBI)—to conduct a ward-wise ecological vulnerability assessment that can inform spatial policy and investment priorities. The intent is twofold: (i) diagnose spatial disparities in environmental stress and access to green functions; and (ii) evolve a scalable urban green-infrastructure (UGI) framework for mid-sized Indian cities aligned with national sustainability and climate-resilience goals. In doing so, the study integrates global literature on UGS functions [15]; [16]; [17]; [18]; [12]; [13] with India-specific evidence on peri-urban governance, coastal risk management, and growth-management instruments [23]; [24]; [22]; [21]. This synthesis supplies both conceptual grounding and operational direction for Vijayawada's UGI strategy. Environmental stress refers to the cumulative pressures exerted on natural and built environments by physical, chemical, and biological factors that disrupt ecological balance and threaten human well-being. In urban contexts, these stressors often arise from rapid land-use changes, industrial emissions, vehicular pollution, heat accumulation, biodiversity loss, and inadequate green cover [14]; [13]. When these elements act together, they manifest as degraded air quality, elevated land surface temperatures, urban heat island (UHI) effects, reduced ecological resilience, and increased vulnerability to climate hazards such as floods and droughts. In cities experiencing accelerated and unplanned growth, environmental stress is intensified by high population densities, limited open spaces, and fragmented ecosystems. The consequences extend beyond environmental degradation to public health crises, economic losses, and diminished quality of life [16]; [17]. Addressing environmental stress requires an integrated approach that combines spatial planning, ecosystem restoration, climate adaptation, and equitable resource distribution. By recognizing environmental stress as both a cause and a symptom of unsustainable urbanization, policymakers can prioritize interventions, such as green infrastructure networks, biodiversity corridors, and air quality management, that restore ecological functions while safeguarding urban communities.

Urban Green Spaces and Their Implications In Urban System

Urban green spaces (UGS) provide important ecological, environmental, and cultural benefits, including biodiversity conservation and human wellbeing. However, a significant portion of urban green space is currently managed as highly manicured grassy lawns that provide limited ecosystem services. Managing urban green spaces as diverse meadows can have a multitude of ecosystem benefits such as biodiversity conservation, stormwater infiltration, and aesthetics. Relatively little is known about the range of ecosystem services or disservices in managing urban green spaces as lawns versus meadows. UGS are the ecological lungs of cities, delivering crucial ecosystem services that enhance environmental quality, human well-being, and climate resilience. They encompass public parks, urban forests, wetlands, open fields, community gardens, and roadside plantations, forming the foundation of urban green infrastructure (GI) [18] Climate regulation is a primary function of UGS. Vegetation mitigates urban heat island (UHI) effects through shading and evapotranspiration, lowering surface and ambient temperatures by 2–4°C in green corridors and shaded streets [25]. Storm water management is another critical function. Open green areas, wetlands, and vegetated swales increase infiltration, reduce surface runoff, and prevent urban flooding, providing a natural complement to traditional drainage systems [26].

UGS also enhance air quality and public health. Trees capture PM2.5, NOx, and CO_2, improving respiratory health and contributing to urban carbon sequestration [27]. In addition, UGS sustain urban biodiversity, offering habitat and connectivity for native flora and fauna. These ecological corridors reduce fragmentation and enhance long-term ecosystem resilience [17]. According to this study, based spatial analysis, Vijayawada has a per capita green space of approximately 3.5 m², which remains well below the WHO-recommended 9 m². Importantly, the distribution is highly uneven: while some peripheral wards approach 6–7 m² per capita, densely populated central wards fall below 2 m², amplifying heat stress, air pollution, and ecosystem fragmentation. This inequity underscores the urgent need for strategic GI planning to achieve environmental justice and climate resilience in the city.

Study Region Profile

Figure 1: Administrative Divisions of Vijayawada City

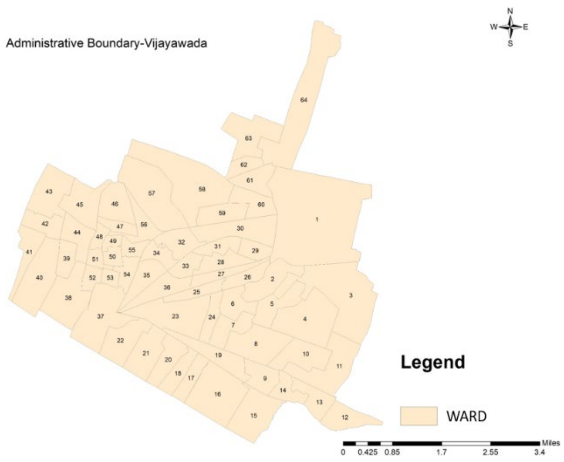
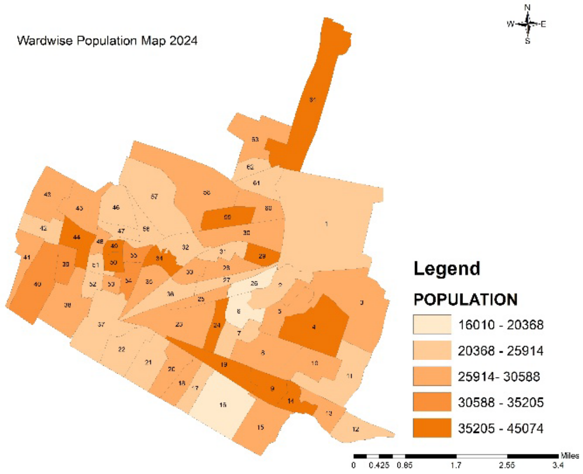


Figure 2: Ward-Wise Population 2024



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Vijayawada, a prominent Tier-II city in the Krishna district of Andhra Pradesh, India, is strategically located along the Krishna River floodplains at approximately 16.5° N latitude and 80.6° E longitude. The city spans 62.18 km² and is divided into 64 municipal wards under the Vijayawada Municipal Corporation (VMC). Its projected population in 2021 is approximately 1.2 million, resulting in an average population density exceeding 19,500 persons/km² in the central wards, with densities tapering towards the periphery. The topography is characterized by alluvial floodplains interspersed with isolated hillocks such as Indrakeeladri and Gunadala, which provide critical ecological niches and scenic landscapes. Historically, Vijayawada's land use was dominated by agricultural fields, riverine vegetation, and open lands, but rapid urbanization over the last three decades has led to substantial conversion of vegetated and open lands into residential, commercial, and transport infrastructure [19] This spatial analysis indicates that Vijayawada has an average per capita green space of approximately 3.5 m², which is well below the WHO-recommended 9 m² for healthy urban living. However, this average conceals pronounced spatial inequities. Peripheral and low-density wards offer up to 6–7 m² per capita, whereas central, high-density, and low-income wards have less than 2 m² per capita. These areas are also coincident with urban heat island (UHI) hotspots, high air pollution exposure, and fragmented biodiversity. In addition, the city's green infrastructure (GI) faces multiple challenges, including riverfront encroachments, unplanned urban expansion, hillock degradation, and fragmented open spaces. These conditions collectively contribute to heat stress, ecological vulnerability, and reduced urban liveability, reinforcing the urgency of strategic green infrastructure planning to achieve spatial equity and environmental resilience in Vijayawada.

Research Methodology

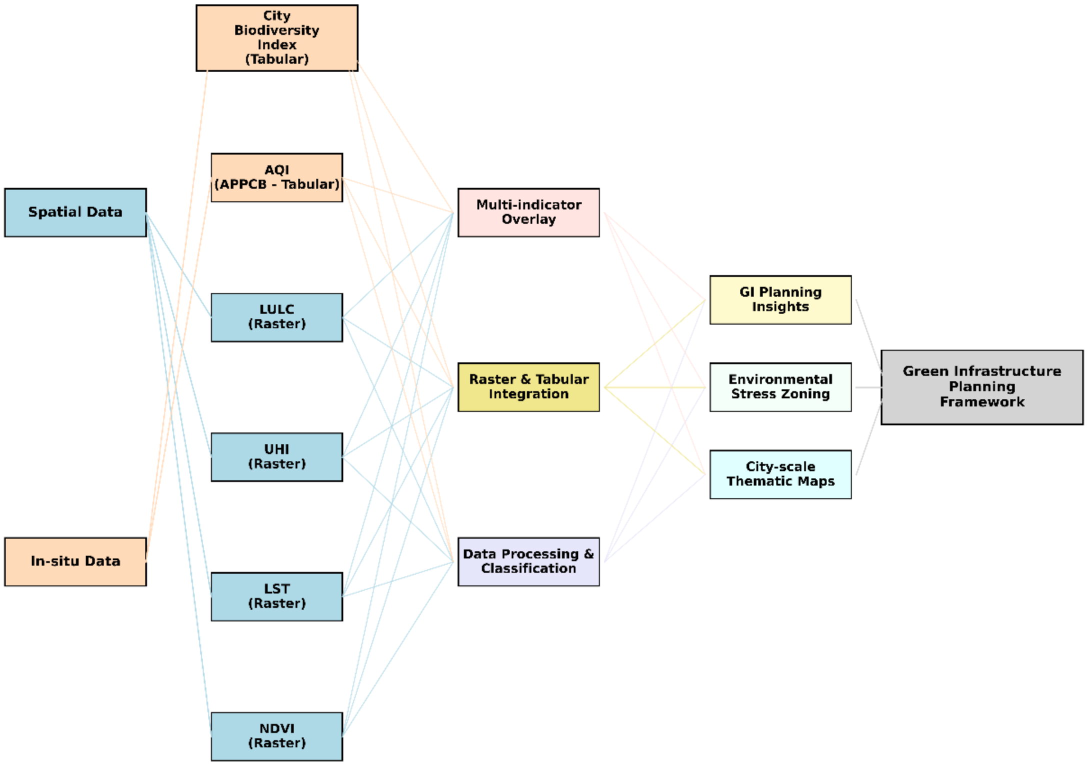
This study adopted a multi-indicator geospatial methodology to assess the spatial and ecological performance of Vijayawada's urban green infrastructure (UGI) and identify environmental stress hotspots. The methodology integrated remote sensing, environmental datasets, and field-based biodiversity assessments to ensure a holistic evaluation of the city's ecological condition.

Data Sources

- Satellite-Imagery: Multitemporal satellite data from Landsat 5 TM and Landsat 8/9 OLI-TIRS were used to generate land-use and vegetation indices for 1990, 2000, 2010, 2020, and 2024. The OLI bands supported NDVI and LULC analysis, while TIRS thermal bands facilitated LST and UHI extraction.

- Air Quality Data: Air Quality Index (AQI) data for 2018–2024 were obtained from the Central Pollution Control Board (CPCB) and Andhra Pradesh Pollution Control Board (APPCB). Parameters such as PM2.5, PM10, NOx, and SO_2 were used to assess ward-level health risks and environmental stress.
- Biodiversity: Assessment of field surveys and secondary ecological datasets were compiled into a City Biodiversity Index (CBI) using the Singapore Index framework. Parameters included native species richness, ecosystem connectivity, and habitat quality, reflecting the city's ecological resilience.

Figure 3: Conceptual Framework for Urban Green Infrastructure Planning



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Analytical Framework:

The analysis was conducted in six sequential stages, each providing critical insights into Vijayawada's environmental status:

- NDVI Analysis–Quantified temporal vegetation dynamics to measure green space loss and fragmentation.
- LULC Classification – Employed supervised classification to map changes in built-up, vegetation, waterbodies, and open land.
- LST & UHI Calculation – Derived land surface temperature using thermal bands and determined UHI intensity by comparing urban and rural reference points.
- AQI Assessment – Evaluated spatial air quality patterns and identified health risk zones.
- CBI Scoring – Assessed biodiversity performance, including species diversity and habitat continuity.
- Spatial Synthesis in ArcGIS 10.8 – Integrated all indicators (NDVI, LST, UHI, AQI, and CBI) to identify multi-stressor environmental hotspots.

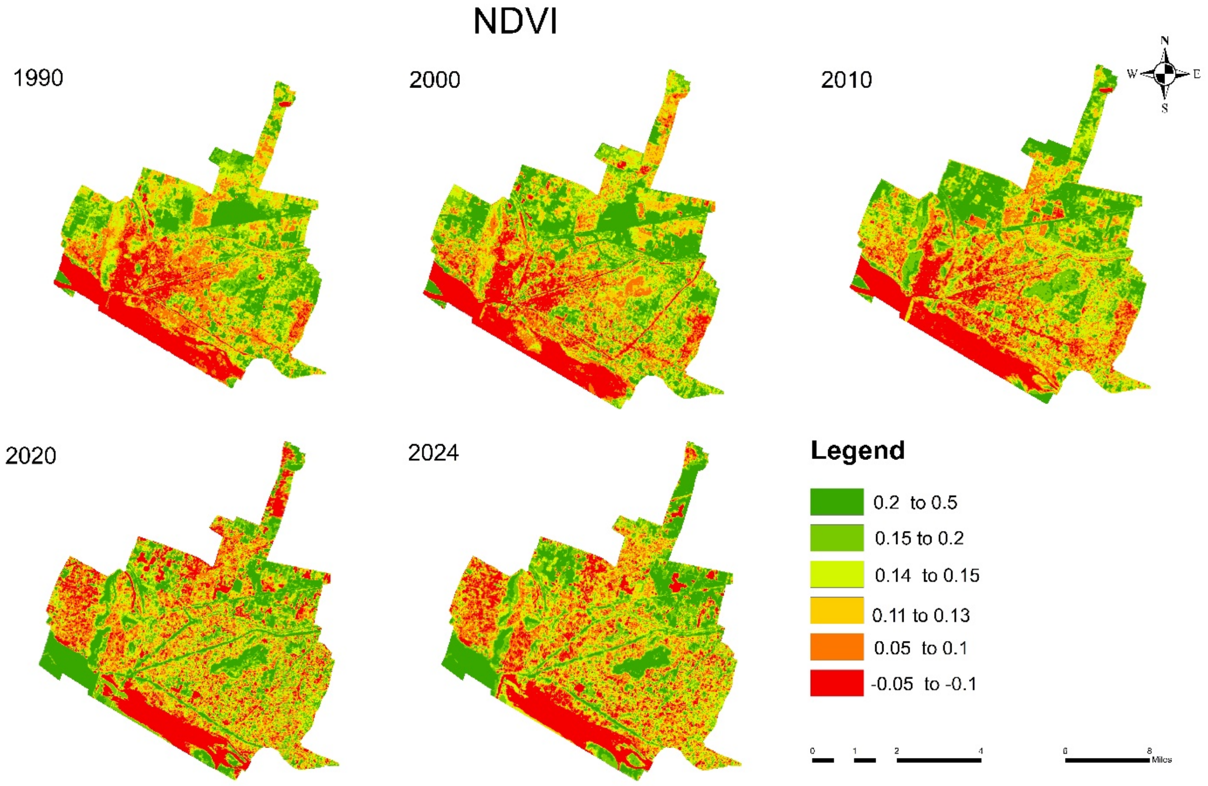
Urban Green Spaces and Data Analytics

The analysis of urban green spaces (UGS) in Vijayawada provides critical insights into the city's ecological dynamics and environmental stress. By integrating remote sensing indicators with air quality and biodiversity data, this study identifies both temporal trends and spatial disparities in green infrastructure (GI) distribution. The analysis focuses on Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), Urban Heat Island (UHI) intensity, Air Quality Index (AQI), and City Biodiversity Index (CBI) to holistically assess the city's environmental performance.

NDVI Analysis

NDVI serves as a primary indicator of vegetation health and distribution. Multi-temporal Landsat imagery (1990–2024) reveals a substantial decline in NDVI values across Vijayawada. In 1990, NDVI averaged 0.28, reflecting the presence of continuous riverine vegetation, open lands, and agricultural fields. By 2024, NDVI declined to 0.04, indicating a 79% reduction in healthy vegetation cover. This transformation aligns with extensive built-up expansion and fragmentation of green patches, especially in central and low-income wards.

Figure 4: 3 NDVI Trend Analysis for Vijayawada City for the years, 1990, 2000, 2010, 2020, & 2024



Source: Generated by authors, 2025

As mentioned in the section 4.1, the list of datasets used for NDVI generation, and the table below shows the statistical NDVI data derived.

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Table 1: Comparative Analysis of Vegetation Health of Vijayawada City over the years (1990, 2000, 2010, 2020 & 2024)

Satellite Name		Sensor / Instrument / Payload	Resolution	Path/Row	Year	Date / Julian Day	Bands used for NDVI	NDVI Range	Average NDVI	Vegetation Health
Landsat 5	LT05	TM Thematic Mapper	30m	142/49	1990	June 3 154	Band 4 NEAR INFRA-RED (0.76 - 0.90 µm) Band 3 RED (0.63 - 0.69 µm)	-0.0346 – 0.427	0.28	Dense & Continuous
Landsat 5	LT05	TM Thematic Mapper	30m	142/49	2000	April 28 118	Band 4 NEAR INFRA-RED (0.76 - 0.90 µm) Band 3 RED (0.63 - 0.69 µm)	-0.0347 – 0.393	0.22	Moderate Fragmentation
Landsat 5	LT05	TM Thematic Mapper	30m	142/49	2010	June 26 177	Band 4 NEAR INFRA-RED (0.76 - 0.90 µm) Band 3 RED (0.63 - 0.69 µm)	-0.0113 – 0.418	0.18	Severe Fragmentation
Landsat 8	LC08	OLI Operational Land Imager	30m	142/49	2020	Dec 31 365	Band 5 NEAR INFRA-RED (0.851 - 0.879 µm) Band 4 RED (0.636 - 0.673µm)	-0.0291 – 0.416	0.09	Sparse, Isolated Greens
Landsat 8	LC09	OLI Operational Land Imager	30m	142/49	2024	Nov 12 317	Band 5 NEAR INFRA-RED (0.76 - 0.90 µm) Band 4 RED (0.63 - 0.69 µm)	-0.076 – 0.482	0.04	Critically Low

Source: Generated by Authors,2025.

LST&UHI Analysis:

The analysis of 2024 land surface temperature patterns in Vijayawada reveals alarming heat stress concentrated in densely built-up commercial zones and major transport corridors. In these areas, surface temperatures consistently exceeded 30°C, largely due to the replacement

Figure 5: Land Surface Temperature 2024, Vijayawada

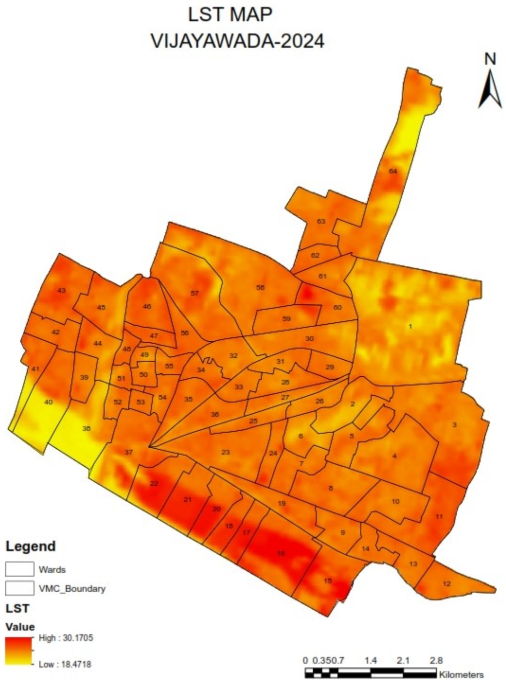
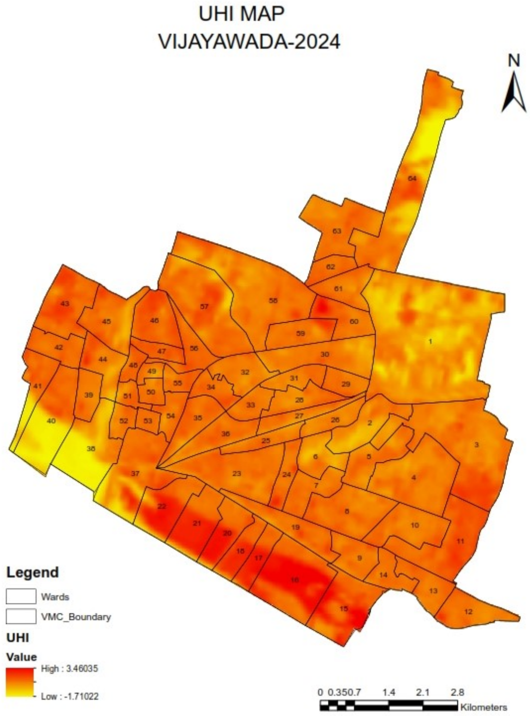


Figure 6: Urban Heat Island 2024, Vijayawada



Source: Generated by Authors,2025.

of vegetated land with impervious materials like concrete and asphalt. Zones registering NDVI values below 0.1 correspond closely with these thermal hotspots, indicating a critical loss of vegetative cover. The Urban Heat Island (UHI) effect is particularly intense here, with urban temperatures rising 7–9°C above adjacent green or peri-urban areas. This sharp thermal gradient exacerbates energy consumption for cooling, heightens health risks—especially for vulnerable populations—and magnifies the city's exposure to climate-related stressors. These findings highlight the pressing need to reintroduce vegetation in urban cores through targeted cooling interventions such as shaded streetscapes, vertical greening systems, and green rooftops, all of which are vital to restoring thermal comfort, public health, and urban resilience.

Spatial Analysis of Green Cover and LULC

Land Use and Land Cover (LULC) dynamics serve as vital indicators of urban growth, ecological balance, and planning efficiency. In rapidly urbanizing Indian cities like Vijayawada, monitoring LULC changes is essential to understand how natural landscapes are being altered by human activities. The transformation from vegetative and open land to built-up surfaces not only reflects demographic and infrastructural shifts but also signals mounting environmental pressures. Analysing these transitions over time provides critical insights into urban sprawl, ecosystem degradation, and the need for sustainable land management. This section explores the LULC evolution in Vijayawada from 1990 to 2024.

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Figure 6: Land Use Land Cover Over the Years (1990, 2000, 2010, 2020, & 2024)

WATERBODY	6.13%
BUILT-UP	37.11%
Light Vegetation	10.35%
Thick Vegetation	20.90%
Open Land	25.52%
Total	100%

WATERBODY	4.54%
BUILT-UP	41.17%
Light Vegetation	11.96%
Thick Vegetation	23.52%
Open Land	18.82%
Total	100%

WATER	3.28%
BUILT-UP	40.98%
Light Vegetation	18.03%
Thick Vegetation	16.39%
Open Land	21.31%
Total	100%

WATERBODY	4.92%
BUILT-UP AREA	49.18%
LIGHT VEGETATION	8.20%
THICK VEGETATION	18.03%
OPENLAND	19.67%

WATER	3.57%
BUILTUP AREA	60.43%
LIGHT VEGETATION	17.66%
THICK VEGETATION	14.19%
OPEN LAND	4.15%
TOTAL	100%

Source – generated by authors

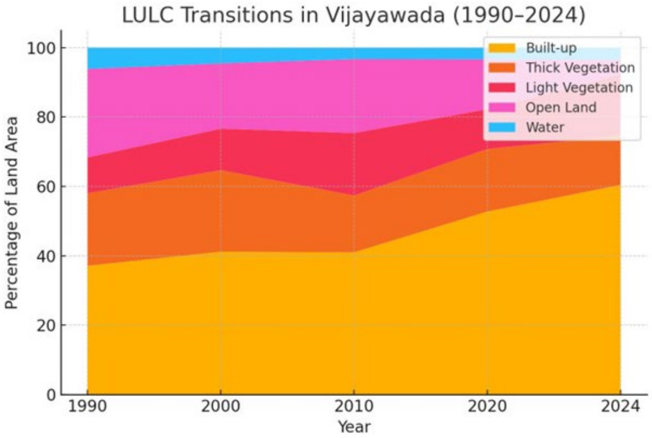
Land Use Land Cover (LULC) transitions from

1990 to 2024 reveal:

- Built-up area increased from 37.1% → 60.4%
- Open land decreased from 25.5% → 4.2%
- Thick vegetation reduced from 20.9% → 14.2%

These changes emphasize the rapid urbanization-driven transformation, wheregreen spaces are increasingly isolated, reducing their ecological function.

Figure 1:LULC Transitions in Vijayawada (1990-2024)



Source: generated by authors

Urban Health Risk and Air Quality of Vijayawada City

Air quality has emerged as a crucial determinant of public health in rapidly urbanizing cities. As urban populations grow, so do vehicular emissions, industrial pollutants, and construction-related particulates, significantly degrading ambient air quality. The Air Quality Index (AQI) serves as a standardized tool to measure and communicate these pollution levels and their direct implications on human health. In urban areas, prolonged exposure to poor AQI values is closely linked to respiratory disorders, cardiovascular stress, reduced cognitive functioning, and increased mortality, particularly among vulnerable populations such as children, the elderly, and individuals with pre-existing conditions. The World Health Organization and national environmental agencies have identified urban air pollution as one of the top environmental risks to health, emphasizing the need for continuous monitoring and mitigation. In this context, analysing AQI trends provides a valuable lens through which planners can identify high-risk zones and frame responsive green infrastructure and emission control strategies. Understanding AQI is thus not just an environmental concern—it is central to safeguarding the health and well-being of urban residents in a sustainable and equitable manner.

Air quality trends in Vijayawada between 2018 and 2024 reveal a dynamic pattern shaped by seasonal meteorological conditions and urban activities. The average AQI peaked at 89.7 in 2018 due to intensive traffic and construction but declined to 59.8 in 2020, likely due to reduced emissions during COVID-19 lockdowns. However, by 2022, AQI rebounded to 75.2, marking a return of pollution linked to resumed economic activity [28]. Seasonally, winter exhibits the highest AQI levels (often above 90), as cooler temperatures restrict pollutant dispersion. Pre-monsoon also records poor air quality due to dry weather and dust-laden winds. Conversely, monsoon months offer temporary relief through rainfall-induced pollutant washout, though moderate AQI levels persist. Post-monsoon conditions remain transitional, with AQI hovering around 84.3.

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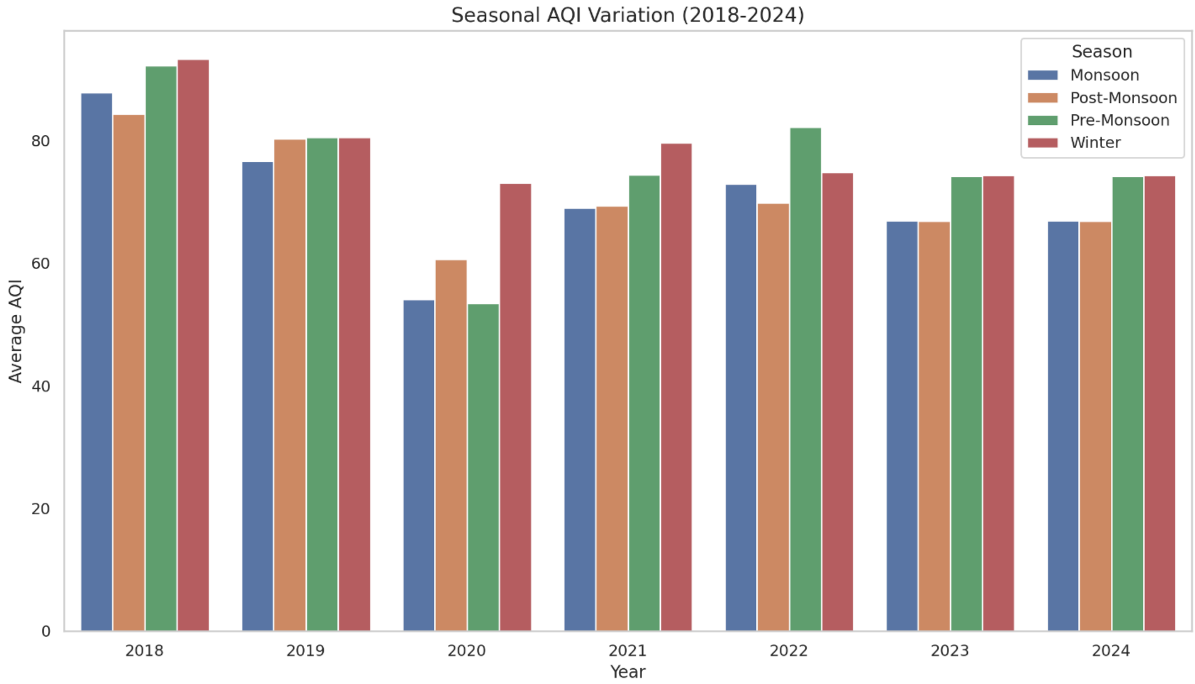
Figure 8: Seasonal Variation in Air Quality Index (2018- 2024)



Source: Generated by Authors,2025.

This pattern necessitates season-specific interventions. For instance, increased urban greening and roadside vegetation during winter and pre-monsoon could buffer pollution in congested zones. Long-term strategies like expanding green spaces, regulating vehicular emissions, and enhancing air quality monitoring are essential for sustainable urban health. Ultimately, AQI should be considered a key secondary indicator guiding green infrastructure planning in Vijayawada ([29]; [30]).

Nexus between City Biodiversity Index (CBI) and Urban Ecosystems:

Vijayawada, a rapidly urbanizing Tier-II city in Andhra Pradesh, is witnessing increasing pressure on its natural ecosystems due to expanding infrastructure, shrinking green cover, and land-use change. In this context, the City Biodiversity Index (CBI) serves as a critical tool to evaluate and monitor the health of urban biodiversity. It provides a structured framework to assess the city's performance in conserving native flora and fauna, integrating ecological assets into planning, and enhancing ecosystem services. By applying CBI, Vijayawada can identify ecological gaps, prioritize restoration zones, and promote nature-based solutions for a more resilient and sustainable urban future. The evaluation of Vijayawada's City Biodiversity Index (CBI) underscores the fragile state of its urban ecological systems. With a score of 32 out of 92, the city ranks low on biodiversity health and resilience. The data reveals significant ecological fragmentation and inadequate integration of biodiversity concerns into urban planning.

Notably, the presence of native species is restricted primarily to natural pockets such as the Krishna riverbanks and hillocks like Indrakeeladri, highlighting limited habitat continuity across the city. Ecological corridors are severely disrupted, limiting species movement and undermining climate resilience. Furthermore, public access to green spaces remains limited, particularly in densely built inner-city wards, contributing to rising socio-ecological vulnerabilities among urban residents ([31]; [32]). These findings suggest the urgent need to restore biodiversity linkages and enhance equitable green access. Strengthening ecological networks through nature-based solutions such as riparian buffers, green roofs, and community biodiversity gardens can improve the city's ecological health and contribute to the larger goals of urban resilience and sustainability.

Synthesis Of Spatial Planning And Associated Environmental Stress In Vijayawada City

When all five indicators—NDVI, LST, UHI, AQI, and CBI—are over laid, hotspot wards emerge with consistently poor environmental performance. These include Ramavarappadu, Bhavanipuram, Kothapeta, and Payakapuram. Here, multiple stressors coincide: NDVI < 0.1, UHI > 7°C, AQI > 85, and CBI scores below 40%.

Table 2: Integrated Environmental Vulnerability Matrix – Vijayawada City (2024)

Indicators	**Highly Vulnerable Wards (Severe ecological degradation)**	**Moderately Vulnerable Wards (Partial degradation, needs restoration)**	**Low Vulnerable Wards (Ecologically stable/resilient)**
NDVI (2024)	8, 12, 20, 32	9, 13, 22	58, 59, 60, 62
LST (2024)	8, 20, 32, 36	13, 9, 22	58, 59, 60
UHI Intensity	8, 12, 20, 32	9, 13, 22	58, 59, 60
AQI (avg. > 85)	18, 19, 33, 12	9, 13, 22	58, 59, 61
CBI (score < 35/92)	8, 12, 20, 32	13, 34, 36	58, 59, 60
Environmental Stress (Cumulative multi-indicator impact)	**Wards 8, 12, 20, 32, 18, 19, 33→ High heat, low NDVI, high AQI, weak biodiversity**	**Wards 9, 13, 22, 34, 36→ Mixed stress, some resilience**	**Wards 58, 59, 60, 61, 62→ Good vegetation, cooler LST, better biodiversity**

Source: Generated by Authors, 2025

A pattern of recurrent ecological stress is visible in Wards 8, 12, 20, and 32, which appear in the highly vulnerable category for most indicators—NDVI, LST, UHI, and CBI. These areas are likely located in the urban core with compact development, limited vegetation, and high exposure to anthropogenic heat and pollution. On the other hand, Wards 58, 59, 60, and 62 consistently rank as ecologically stable, indicating resilience and potential to serve as green lungs for Vijayawada. The integrated analysis of spatial and environmental indicators reveals a layered pattern of ecological vulnerability across Vijayawada. This synthesis—incorporating NDVI, LST, UHI intensity (from GIS), and AQI and CBI (from secondary datasets)—demonstrates that environmental stress is disproportionately concentrated in inner-city wards, particularly those with dense populations and inadequate green infrastructure. By integrating spatial and environmental indicators, this study highlights a data-driven foundation for equitable green infrastructure planning. The synthesis underscores that urban environmental management in Vijayawada must shift from reactive to anticipatory, embedding resilience into the city's developmental fabric. These findings are pivotal for aligning municipal interventions with SDGs, especially Goal 11 (Sustainable Cities) and Goal 13 (Climate Action). These findings provide evidence-based guidance for urban planners to prioritize green infrastructure interventions in environmentally critical wards. Establishing cooling corridors, pocket parks, and biodiversity linkages in these hotspots can substantially reduce multi-stressor impacts and improve urban liveability.

Comprehensive Framework Of Green Infrasructure Planning For Mitigation Of Environmental Stress

The environmental vulnerability matrix reveals consistent stress patterns across Wards 8, 12, 20, and 32—where all five indicators (NDVI, LST, UHI, AQI, CBI) align to signal a high degree of ecological degradation. Wards 9, 13, 22, and 36 emerge as transition zones, while Wards 58, 59, 60, and 61 are ecologically stable. Based on this stratification, the following framework has been designed to offer targeted, data-backed, and context-specific interventions.

Green Equity and Spatial Access: Wards 8, 12, 20, and 32 show repeated NDVI deficiency. Green cover in these zones is alarmingly low, with values below 0.1 and per capita green space under 2 m².

- Green Equity Zoning: Prioritize Wards 8, 12, 20, and 32 for green infrastructure investment. Develop ward-specific urban greening plans.
- Micro-Greenspace Development: Convert public margins, school yards, utility spaces, and road medians into functional greens in dense wards.

- Greening in Informal Settlements: Introduce community gardens and rooftop greens in low-income housing clusters. Enhancing green access in deprived wards promotes not only environmental balance but also social equity—improving mental health, urban cooling, and inclusivity.

  Urban Heat and Climate Resilience: LST exceeds 30°C and UHI intensity ranges from 7–9°C in Wards 8, 20, 32, and 36—directly aligned with NDVI loss.
- Cooling Corridors: Green arterial roads and canals in heat-stressed wards using native canopy trees, bioswales, and reflective pavements.
- Mandatory Green and Cool Roofing: Enforce high-albedo roofs and vegetated terraces in building regulations for core wards.
- Urban Hillock Protection: Conserve hillocks like Gunadala through buffer creation and plantation to combat heat build-up.
- Targeted greening in thermal hotspots helps regulate urban microclimates, reduces energy load, and aligns with Vijayawada's heat action goals.

Air Quality Management: AQI exceeds 85 in Wards 18 (Benz Circle), 19 (Auto Nagar), and 20 due to vehicular congestion, industrial dust, and seasonal inversions.

- Pollution Buffering with Green Screens: Implement multilayer vegetation barriers and vertical gardens in AQI hotspots.
- Low Emission and Regulated Traffic Zones: Pilot low-emission zones in industrial and transport corridors with electric mobility promotion.
- Seasonal Green Drives: Pre-winter and pre-monsoon tree planting in traffic corridors to trap dust and gaseous pollutants.
- Strategic vegetation not only filters pollutants but also improves liveability in high-traffic, high-risk zones—especially for vulnerable populations.
- **7.4 Biodiversity Integration and Habitat Restoration:** CBI score is critically low (32/92) in Wards 8, 12, 20, and 32, indicating fragmentation and absence of ecological connectivity.
- Riparian and Hillock Corridors: Restore green continuity along Krishna River and hillocks, creating migration paths for native species.
- Native Species Plantation: Replace exotic species with local, climate-resilient varieties across all city greening efforts.
- Urban Biodiversity Gardens: Promote small-scale, community-run biodiversity hubs in schools, housing colonies, and public institutions.
- Biodiversity is key to ecological balance. Integrating habitats into the urban fabric fosters resilience, improves air and soil health, and encourages public interaction with nature.

Data-Driven Planning and Monitoring: Lack of real-time data, siloed departmental functioning, and poor community engagement in green infrastructure planning.

- Ward-Level Environmental Dashboards: Integrate NDVI, LST, AQI, and CBI into a live spatial platform accessible to planners and citizens.
- Participatory Mapping: Involve local communities in recording biodiversity, tree counts, and park conditions using mobile tools.
- Institutional Coordination via GIPC: Form a Green Infrastructure Policy Cell within VMC to streamline inter-agency implementation and updates.

When data transparency meets citizen participation, it leads to adaptive, inclusive, and accountable green planning.

Schematic Representation of the Framework

Table 3: Vulnerability Matrix

Pillar	Key Wards Impacted	Indicators Addressed	Primary Tools
Green Equity	8, 12, 20, 32	NDVI, Spatial Access	Zoning, micro-parks
Climate Resilience	8, 20, 32, 36	LST, UHI	Cooling corridors, roofing
Air Quality	18, 19, 20, 22	AQI	Green screens, LEZs
Biodiversity	8, 12, 20, 32, 34, 36	CBI	Corridors, native planting
Governance	All wards	Integrated Monitoring	Dashboards, GIPC

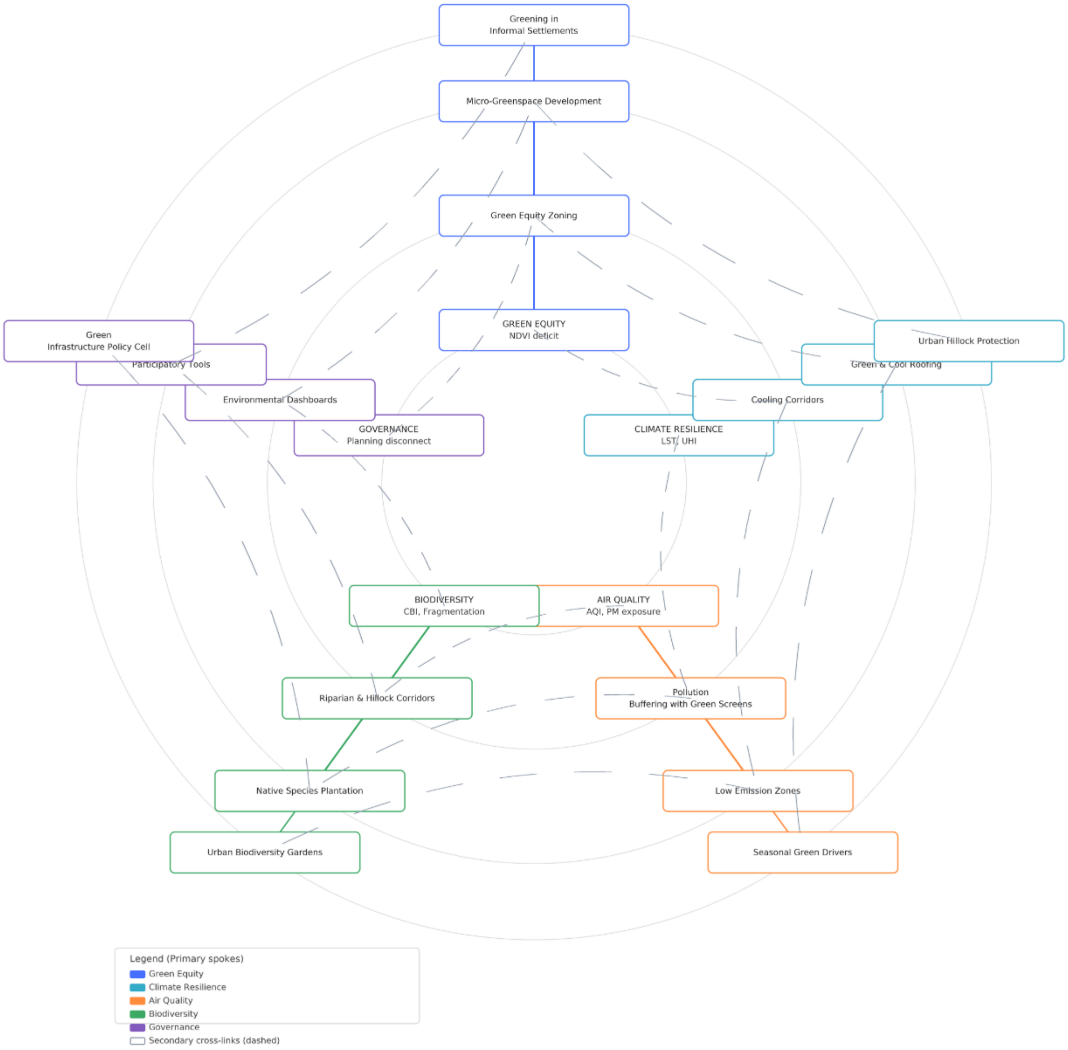
Source: By Authors, 2025.

Recommendations

The recommendations presented in this section are grounded in a comprehensive, multi-indicator assessment of Vijayawada's ecological vulnerabilities, integrating NDVI, LST, UHI, AQI, and CBI datasets. These findings highlight spatial inequities in green infrastructure (GI) distribution, with inner-core wards facing compounded environmental stress from heat exposure, poor air quality, and biodiversity fragmentation. Recognizing that piecemeal or reactive measures cannot adequately address these interlinked challenges, the proposed strategies adopt a systems-based, spatially targeted, and socially inclusive approach [12]; [13]. The guidelines emphasize strengthening ecological resilience through equitable GI zoning, creation of cooling corridors, micro-scale greening in dense neighbourhoods, restoration of biodiversity linkages, and robust air quality management. These are complemented by institutional reforms such as the formation of a dedicated Green Infrastructure Policy Cell within the Vijayawada Municipal Corporation, real-time environmental dashboards, and participatory mapping involving citizens and civil society. The framework aligns with the Sustainable Development Goals, particularly SDG 11 (Sustainable Cities) and SDG 13 (Climate Action), while ensuring context-specific solutions for a Tier-II Indian city. The aim is to embed resilience, equity, and ecological integrity into Vijayawada's developmental fabric, creating a replicable model for other medium-sized cities navigating similar urban–environmental transitions.

Next Page

Figure 2: Comprehensive Framework of Green Infrastructure Planning for Mitigation of Environmental Stress, 2025



Source: Generated by Authors,2025.

Strategies & Planning Guidelines

The integrated assessment of Vijayawada's environmental conditions, including vegetation cover, heat stress, air quality, and biodiversity, underscores the urgent need for a spatially balanced and ecologically informed intervention strategy. The following recommendations provide a clear, field-relevant roadmap for municipal authorities, planners, and ecological stakeholders to build an equitable, resilient, and sustainable urban ecosystem.

Prioritizing Environmentally Vulnerable Wards

Wards repeatedly flagged for poor NDVI (<0.1), elevated LST (>29°C), high UHI (>7°C), low biodiversity (CBI <35/92), and poor air quality (AQI >220) must be formally identified as critical ecological hotspots. These are largely concentrated in the urban core and industrial corridors. A phased action plan for these wards should focus on urgent greening, biodiversity revival, and infrastructure cooling to reduce stress and restore urban liveability

Cooling Corridors and Greening Streetscapes

A system of cooling corridors must be established along key traffic and pedestrian routes. These should include roadside tree plantations using native, drought-tolerant species, **b**ioswales and permeable medians to reduce runoff and enhance infiltration, vertical green walls in high-rise commercial zones, greenway linkages between hillocks, riverbanks, and residual green pockets. These corridors can reduce thermal stress by 2–4°C and enhance walkability in low-income zones.

Promoting Micro-Scale Green Interventions

In high-density areas where land is scarce, small but impactful greening solutions are vital. It includes conversion of vacant lots and buffer areas into neighborhood pocket parks, offer incentives for rooftop gardening, especially in educational and institutional buildings. Develop school and college gardens as biodiversity nodes and learning spaces and facilitate resident-managed biodiversity gardens to foster community ownership and ecological awareness. These decentralized green assets not only improve environmental conditions but also support emotional well-being and biodiversity access. Such interventions improve mental health, biodiversity access, and local microclimate.

Biodiversity Corridors and Ecological Restoration

Reconnecting fragmented patches across hillocks (Gunadala, Indrakeeladri) through green belts, which includes Riparian buffer restoration along the Krishna River and canal zones, protection and rehabilitation of existing wetlands and natural open lands from encroachment. Integrating CBI performance targets into urban planning metrics to ensure measurable biodiversity enhancement.

Air Quality Mitigation and Monitoring Enhancements

With AQI levels remaining in the moderate to very poor category post-2020, the city must:

- Increase green buffers along traffic-heavy roads (Benz Circle, Auto Nagar).
- Promote clean public transport and reduce vehicle dependency in high AQI zones.
- Expand AQI monitoring infrastructure at ward scale to better correlate urban form with pollution trends.
- Urban forestry and GI-linked air purification strategies must be integrated into transportation and zoning regulations.

Spatial Equity and Inclusive Planning

The spatial analysis reveals disproportionate environmental burdens on lower-income populations. To address this:

- Equitable GI standards must be enforced—ensuring every ward meets a minimum green space threshold of 9 m² per capita, as per WHO.
- GI allocation in Master Plan revisions must be based on multi-indicator stress zones—not just availability of land.
- Engage residents in co-creating green spaces, ensuring community ownership and maintenance.

Institutional and Policy Mechanisms

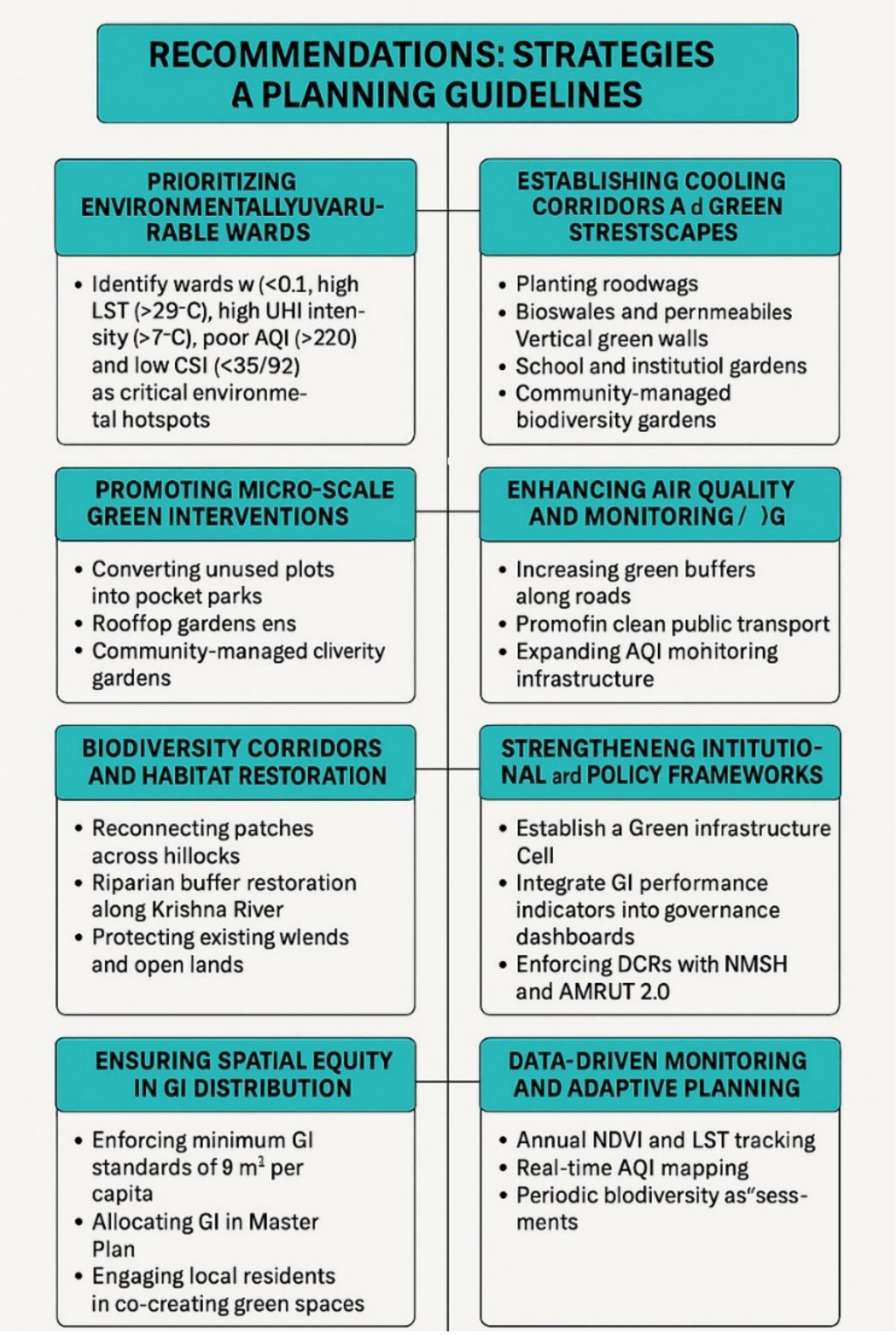
To implement this framework sustainably, enabling mechanisms are essential:

- A Green Infrastructure Cell within VMC to coordinate implementation, monitoring, and inter-departmental collaboration.
- Integration of GI performance indicators (NDVI, CBI, AQI) into ward-level governance dashboards.
- Enforce Development Control Regulations (DCRs) that mandate green buffers, pervious surface ratios, and biodiversity audits in new urban projects.
- Align strategies with National Mission for Sustainable Habitat (NMSH) and AMRUT 2.0 objectives for funding and compliance.:

Data-Driven Monitoring and Adaptive Planning

Building on the GIS-based synthesis approach, the city should adopt annual NDVI and LST tracking using satellite tools integrated into urban planning systems, real-time AQI mapping through low-cost sensors to guide immediate interventions and periodic biodiversity assessments involving academic institutions and civil society. These tools will support adaptive planning—where policies evolve based on emerging stress data and citizen feedback. The recommendations stem from empirical analysis and a robust spatial-environmental synthesis of Vijayawada's ecological condition. They represent a layered, localized, and actionable roadmap for restoring ecological balance, mitigating urban stressors, and embedding green infrastructure into the city's developmental DNA. Ensuring spatial equity, environmental resilience, and public health through this lens will position Vijayawada as a model for sustainable Tier-II urban transformation.

Figure 3: Strategic Framework for reduction of Environmental Stress for Vijayawada City



Source: By Authors,2025

Conclusion

Urban green spaces play a vital role in mitigating the environmental, social, and health challenges associated with climate change. These areas serve as carbon sinks, help regulate urban temperatures, and enhance biodiversity, thereby contributing to climate resilience and sustainability. Beyond their ecological benefits, green spaces foster social cohesion, encourage physical activity, and improve mental well-being, significantly enhancing the quality of life for urban residents. As cities continue to grow, the intentional integration of green spaces into urban planning and policy will be crucial for building resilient and sustainable environments. Prioritizing these spaces can help cities effectively address the impacts of climate change while promoting public health and social equity, ensuring that all residents have access to the benefits that green spaces provide. The integrated environmental assessment undertaken in this study reveals an urgent and multi-dimensional challenge facing Vijayawada: the convergence of heat stress, declining vegetation cover, deteriorating air quality, and weakened biodiversity within its urban core. By deploying a multi-indicator spatial framework—encompassing NDVI, LST, UHI, AQI, and CBI—this research offers a granular, ward-level diagnosis of ecological vulnerability that goes beyond conventional, city-wide averages. The evidence indicates that the most severe stressors are concentrated in high-density, low-income wards where per capita green space remains well below the WHO-recommended 9 m^2 threshold. In these areas, NDVI values have fallen below 0.1, LST exceeds 30 °C, UHI intensities range from 7–9 °C, AQI levels surpass health-safe limits, and biodiversity scores remain critically low. These conditions are not isolated phenomena but the cumulative outcome of unplanned urban expansion, weak enforcement of land-use regulations, and fragmented green infrastructure. The transformation of vegetated and open lands into impervious surfaces has reduced the city's natural cooling capacity, impaired ecological corridors, and heightened susceptibility to climate-induced hazards. This underscores the necessity of a paradigm shift in urban planning, from reactive greening measures to proactive, data-driven, and equity-focused environmental governance. The Green Infrastructure Planning Framework developed through this research directly responds to the patterns revealed by the vulnerability analysis. It provides a structured approach for intervention, organized into five strategic pillars: Green Equity and Spatial Access, Urban Heat and Climate Resilience, Air Quality Management, Biodiversity Integration and Habitat Restoration, and Data-Driven Planning and Monitoring. Each pillar is tailored to the city's distinct environmental zones, ranging from highly vulnerable urban cores to ecologically stable peripheral wards, ensuring that resources are allocated according to need and impact potential.

Green Equity and Spatial Access initiatives, such as micro-parks, rooftop gardens, and community-managed greens, are critical in high-density wards where land availability is limited. By re-purposing marginal spaces like school grounds, road medians, and utility corridors, these interventions can significantly improve per capita green cover, reduce localized heat accumulation, and foster social cohesion. Urban Heat and Climate Resilience strategies, including cooling corridors, high-albedo roofing, and hillock preservation, directly target thermal stress hotspots. These measures not only moderate surface temperatures but also reduce energy demand for artificial cooling, aligning with broader climate mitigation goals. Air Quality Management interventions—such as multilayer green buffers, low-emission zones, and seasonal planting drives, address both particulate and gaseous pollutants in traffic-heavy and industrial corridors. These actions, when coupled with stricter vehicular emission controls, can substantially improve respiratory health outcomes in the most affected wards. Biodiversity Integration efforts focus on restoring riparian and hillock corridors, replacing exotic plantings with native species, and establishing biodiversity gardens in schools and public institutions. Such measures enhance ecological connectivity, strengthen resilience to climate shocks, and contribute to long-term environmental sustainability. The Data-Driven Planning and Monitoring pillar institutionalizes continuous environmental tracking through ward-level dashboards, participatory biodiversity mapping, and integration of NDVI, LST, and AQI metrics into municipal decision-making. This transparency fosters public trust, enables adaptive management, and ensures accountability in policy implementation. Collectively, these pillars shift the perception of green infrastructure from an aesthetic amenity to a core urban service—equally vital as water supply, sanitation, and transportation. By embedding ecological considerations into zoning regulations, development control rules, and master planning, Vijayawada can safeguard environmental health while accommodating urban growth. Importantly, this research situates Vijayawada within a broader discourse on sustainable urbanization in Tier-II Indian cities. Such cities, often overlooked in national climate and infrastructure policies, are experiencing rapid demographic shifts without proportionate investment in environmental resilience. The multi-indicator framework presented here offers a replicable template for other cities facing similar ecological stress profiles. By adapting the methodology, satellite-derived vegetation and thermal indices, air quality mapping, biodiversity scoring, and integrated spatial overlays, urban planners elsewhere can generate locally relevant, evidence-based strategies for green infrastructure deployment.

The absence of green areas has made in Vijayawada city a gloomily dull city. Regretfully, India lacks national and local policies that may be an effective means of resolving this issue, in the system. Setting attainable and realistic goals is vital for Vijayawada city rather than creating rushed plans. It is also crucial to safeguard the current green spaces in study region to make Vijayawada city more liveable. This study also reinforces the interdependence of environmental and social equity. The spatial analysis makes clear that environmentally degraded wards are frequently those with lower-income populations, limited access to healthcare, and inadequate basic services. Without deliberate interventions, these communities face a disproportionate share of climate risks, deepening existing socio-economic inequalities. Embedding environmental justice into planning, through equitable distribution of green spaces, prioritization of vulnerable wards, and participatory decision-making can help bridge this gap. From a policy perspective, the findings argue strongly for the institutionalization of a Green Infrastructure Policy Cell within the Vijayawada Municipal Corporation. This entity could act as a central node for inter-departmental coordination, performance monitoring, funding mobilization, and community engagement. Aligning local strategies with national programs such as the National Mission for Sustainable Habitat (NMSH) and AMRUT 2.0 can further enhance resource access and compliance. Ultimately, the conclusion of this study is both a warning and an opportunity. The warning lies in the data: if current trends of green space depletion, thermal intensification, and biodiversity loss continue, Vijayawada will face escalating public health crises, infrastructural strain, and reduced climate resilience. The opportunity lies in the solutions: by adopting the proposed framework, leveraging spatial data for targeted interventions, and fostering inclusive governance, the city can reverse these trends and set a precedent for sustainable urban transformation. The path forward must therefore be deliberate, inclusive, and adaptive—recognizing that urban ecosystems are dynamic and that resilience is built through iterative learning, cross-sector collaboration, and sustained investment in nature-based solutions. The vision is a Vijayawada where green infrastructure is not merely reactive beautification, but a proactive strategy for safeguarding environmental health, enhancing liveability, and ensuring that the benefits of urban development are equitably shared across all communities. The findings of our study resonate with global urbanization trends, where rapid urban growth often leads to the degradation of green infrastructure. The situation in Vijayawada city is particularly acute due to its high population density and limited land availability, which exacerbate the challenges of maintaining adequate green spaces. This decline has profound implications for the city's liveability, environmental sustainability, and the well-being of its residents, highlighting the urgent need for effective policy interventions.

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