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Role of Native Xerophytic Vegetation in Enhancing Climate Resilience and Urban Sustainability in the Smart Cities of Rajasthan

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Abstract : *Rapid urbanization, increasing land surface temperatures, declining groundwater resources, and climate variability have intensified environmental challenges in the arid and semi-arid cities of Rajasthan. The expansion of impervious surfaces and the widespread use of water-intensive ornamental vegetation have further reduced the ecological sustainability of urban landscapes. Native xerophytic vegetation, characterized by exceptional drought tolerance and efficient resource utilization, offers a promising nature-based solution for enhancing climate resilience while minimizing irrigation requirements. Despite its ecological importance, the integration of indigenous xerophytic species into Smart City planning has received limited scientific attention.*

The present study evaluates the ecological significance of native xerophytic vegetation in promoting sustainable urban development across selected Smart Cities of Rajasthan. A quantitative descriptive research design based entirely on secondary data was adopted. Scientific literature, government reports, geospatial information, and published environmental datasets were critically reviewed and comparatively analysed to assess ecosystem services, including urban heat island mitigation, water-use efficiency, carbon sequestration potential, biodiversity conservation, and long-term sustainability. Native species such as Prosopis cineraria, Tecomella undulata, Capparis decidua, and Azadirachta indica were selected because of their ecological suitability for arid environments and their established role in sustainable landscape management.

The comparative analysis indicates that native xerophytic vegetation provides multiple ecosystem services while requiring substantially less irrigation than commonly planted exotic ornamental species. These species contribute to urban heat island mitigation, groundwater conservation, carbon storage, habitat enhancement, and improved ecological resilience under changing climatic conditions. The findings further demonstrate that integrating xeriscaping principles into Smart City planning can simultaneously reduce environmental degradation, lower landscape maintenance costs, and strengthen urban sustainability. The study concludes that native xerophytic vegetation represents an effective nature-based strategy for developing climate-resilient and water-efficient Smart Cities in Rajasthan. The research provides scientific evidence to support the inclusion of indigenous drought-resistant plant species in future urban planning policies, green infrastructure development, and climate adaptation programmes across arid and semi-arid regions of India..

Keywords: Xerophytic Vegetation; Smart Cities; Urban Sustainability; Climate Resilience; Rajasthan; Urban Heat Island; Xeriscaping; Ecosystem Services.

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I. INTRODUCTION

1.1 Background of the Study

Urbanization has become one of the most significant drivers of environmental transformation worldwide. Rapid population growth, expansion of built-up areas, increasing vehicular emissions, and the replacement of natural vegetation with impervious surfaces have considerably altered urban ecosystems. These changes have intensified environmental challenges such as urban heat island (UHI) formation, declining groundwater recharge, biodiversity loss, air pollution, and increased vulnerability to climate change. The impacts are particularly severe in arid and semi-arid regions, where limited water availability further constrains sustainable urban development.

Rajasthan, the largest state in India, is characterized by predominantly arid and semi-arid climatic conditions. Cities such as Jaipur, Jodhpur, Ajmer, and Udaipur have experienced rapid urban expansion during the last two decades under the Smart Cities Mission. Although urban development has improved infrastructure and economic growth, it has also accelerated environmental degradation through excessive land-use change, loss of green cover, increasing land surface temperature, and unsustainable landscape practices. Conventional urban greening programmes frequently rely on exotic ornamental species that require intensive irrigation, high maintenance, and continuous management. Such approaches are ecologically unsuitable for water-deficient regions like Rajasthan.

Native xerophytic vegetation represents an environmentally sustainable alternative for urban landscape development. Xerophytes possess specialized morphological, anatomical, and physiological adaptations that enable survival under prolonged drought, high solar radiation, poor soil moisture, and extreme temperatures. Indigenous species such as *Prosopis cineraria*, *Tecomella undulata*, *Capparis decidua*, and *Azadirachta indica* are naturally adapted to Rajasthan's climatic conditions and provide multiple ecosystem services, including carbon sequestration, microclimate regulation, soil stabilization, biodiversity conservation, and groundwater protection. Their low water requirement and high ecological efficiency make them ideal candidates for climate-resilient urban greening.

Recent advances in sustainable urban planning increasingly emphasize the adoption of nature-based solutions (NbS) and green infrastructure to enhance ecological resilience. Integrating native drought-resistant vegetation into Smart City planning aligns with global sustainability initiatives, including the Sustainable Development Goals (SDGs), the Paris Climate Agreement, and India's National Action Plan on Climate Change. Such an approach can reduce irrigation demand, improve ecosystem functioning, mitigate urban heat stress, and strengthen long-term urban resilience. Despite the recognized ecological importance of xerophytic vegetation, relatively few studies have systematically examined its role within the context of Smart Cities in Rajasthan. Existing research has primarily focused on urban forestry, climate adaptation, or landscape planning independently, with limited attention to the ecological advantages of indigenous drought-tolerant vegetation for sustainable urban development. This knowledge gap highlights the need for a comprehensive assessment of the ecological services provided by native xerophytes and their potential contribution to environmentally sustainable Smart City planning.

The present study addresses this gap by evaluating the ecological performance of selected native xerophytic species using secondary data derived from scientific literature, government reports, and published environmental datasets. The findings are expected to provide scientific evidence supporting the incorporation of indigenous vegetation into future urban planning strategies and policy frameworks for Rajasthan's Smart Cities.

1.2 Problem Statement

Rapid urban expansion in Rajasthan has significantly reduced natural vegetation while increasing impervious surfaces, urban heat island intensity, groundwater depletion, and environmental degradation. Existing urban landscaping practices rely predominantly on exotic ornamental species that require large quantities of irrigation water and intensive maintenance, making them environmentally unsuitable for arid and semi-arid regions. Although native xerophytic vegetation possesses exceptional ecological adaptations and provides multiple ecosystem services, its potential contribution to climate-resilient Smart City planning remains insufficiently explored. Consequently, there is an urgent

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need to evaluate the ecological suitability of indigenous xerophytic species as sustainable green infrastructure for future urban development in Rajasthan.

II. LITERATURE REVIEW

Urban sustainability has become one of the foremost priorities of contemporary environmental planning because rapid urbanization has intensified ecological degradation, climate variability, biodiversity loss, and resource depletion across cities worldwide. The integration of green infrastructure into urban development has therefore emerged as an effective strategy for improving environmental quality while strengthening climate resilience. Numerous international studies have emphasized that urban vegetation provides a wide range of ecosystem services, including temperature regulation, carbon sequestration, stormwater management, air purification, biodiversity conservation, and the enhancement of human well-being. Urban green spaces are increasingly recognized as essential components of sustainable city planning.

Chiesura (2004) highlighted that urban parks and green infrastructure improve ecological integrity while simultaneously enhancing the physical and psychological well-being of urban residents. Similarly, Bolund and Hunhammar (1999) identified multiple ecosystem services provided by urban ecosystems, including microclimate regulation, pollution reduction, groundwater recharge, and habitat conservation. The concept of green infrastructure has received considerable attention in climate adaptation research. Gill et al. (2007) demonstrated that strategically planned urban vegetation can substantially reduce surface temperatures, improve stormwater management, and enhance urban resilience under future climate scenarios. Likewise, Haaland and van den Bosch (2015) reported that urban densification should be accompanied by scientifically planned green infrastructure to maintain ecological stability and environmental quality.

In recent years, nature-based solutions (NbS) have become an important framework for sustainable urban development. These approaches utilize natural ecosystems to address environmental challenges while simultaneously generating ecological, economic, and social benefits. Adams et al. (2024) emphasized that integrating nature-based solutions into urban planning enhances climate resilience, biodiversity conservation, and long-term sustainability. Within the Indian context, rapid urbanization has intensified environmental problems. Anguluri and Narayanan (2017) and Govindarajulu (2014) highlighted the importance of scientifically planned green spaces for sustainable Smart City development. Urban forestry studies by Roy et al. (2012) and Nitoslawski et al. (2019) emphasized ecological knowledge, GIS, remote sensing, and smart monitoring for ecosystem management. Studies from Rajasthan, including Yosef et al. (2022), the Forest Survey of India (2023), and MoHUA (2024), support the importance of native vegetation and green infrastructure. The present study addresses the research gap by comparatively evaluating native xerophytic species using secondary scientific data.

Table 1. Summary of Selected Literature

Author(s) & Year	Study Area	Major Findings	Research Gap Addressed
Bolund & Hunhammar (1999)	Urban Ecosystems	Identified key ecosystem services including microclimate and pollution control.	Limited application to arid and water-scarce ecosystems.
Chiesura (2004)	Europe	Emphasized that urban parks improve the environment and psychological well-being.	No specific evaluation of xerophytic plant varieties.
Gill et al. (2007)	UK	Demonstrated that green infrastructure substantially reduces urban heat intensity.	Limited focus on highly water-scarce and arid urban regions.
Roy et al. (2012)	Global	Analyzed multiple ecological benefits of urban trees and green options.	Specific arid adaptation mechanisms were not systematically assessed.

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Anguluri & Narayanan (2017)	India	Highlighted strategic green spaces framework for developing Smart Cities.	Native xerophytes were not analyzed for species-level integration.
Nitoslawski et al. (2019)	Global	Proposed smart urban forestry solutions and advanced ecological monitoring.	Indigenous drought-resistant species were not emphasized.
Yosef et al. (2022)	Jaipur, India	Found that localized urban forests reduce land surface temperatures (LST).	A comparative xerophytic species assessment was lacking.
Adams et al. (2024)	Global	Emphasized that Nature-based Solutions (NbS) improve climate resilience.	Regional arid-zone application and frameworks needed.
MoHUA (2024)	India	Provided general green infrastructure performance indicators for smart cities.	Species-level selection and assessment guidelines are absent.

III. RESEARCH FRAMEWORK AND METHODOLOGY

3.1 Research Gap

Existing literature demonstrates that urban green infrastructure plays a crucial role in improving environmental sustainability, mitigating urban heat island effects, conserving biodiversity, and enhancing climate resilience. However, most studies focus on general urban vegetation rather than the ecological adaptations of native xerophytic species. Within India, Smart City research has largely emphasized infrastructure, governance, and technology, with limited attention to indigenous drought-resistant vegetation. Existing studies rarely compare native xerophytic species with exotic ornamental plants under water-limited conditions. This study addresses this gap by evaluating selected indigenous xerophytic species using secondary scientific data and proposing their integration into Smart City green infrastructure planning.

3.2 Aim and Objectives

The primary aim of the study is to evaluate the ecological significance of native xerophytic vegetation in enhancing climate resilience and promoting sustainable urban development in Rajasthan's Smart Cities using secondary scientific data.

The specific objectives include:

- Assess the distinct ecological characteristics of selected native xerophytic species.
- Evaluate their individual and collective contributions to urban heat island mitigation, carbon sequestration, biodiversity conservation, and groundwater safety.
- Compare the performance indices of native xerophytes with conventional exotic ornamental vegetation.
- Examine the structural role of xeriscaping principles in strengthening long-term urban climate resilience.
- Recommend targeted policy interventions for landscape management within the Smart Cities network.

3.3 Research Methodology

The present study adopted a quantitative, descriptive, and comparative research design based exclusively on secondary data. The methodology involves a step-by-step rigorous review of peer-reviewed publications, institutional records, and statutory reporting frameworks to construct an analytical matrix evaluating environmental performance across selected smart urban centers: Jaipur, Udaipur, Ajmer, Kota, and Jodhpur.

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Table 2. Systematic Research Approach and Activities

Step	Research Activity	Analytical Focus & Operational Definition
1	Identification of the research problem	Evaluating urbanization challenges, water scarcity, and landscape mismatches in Rajasthan.
2	Comprehensive review of literature	Analyzing global and national frameworks for NbS, green infrastructure, and urban forestry.
3	Identification of the research gap	Pinpointing the lack of species-level comparative studies for arid urban landscaping.
4	Formulation of objectives & hypotheses	Establishing standard baselines (H0 vs H1) to measure xerophytic efficacy.
5	Collection of secondary data	Mining scientific indices from Scopus, Web of Science, FSI, and MoHUA reports.
6	Comparative ecological assessment	Evaluating parameters like water use efficiency, carbon storage, and heat mitigation.
7	Interpretation and synthesis	Correlating plant physiological traits with specific urban microclimatic improvements.
8	Policy recommendations	Formulating active integration guidelines for municipal corporations and town planners.

Table 3. Sources of Secondary Data utilized in the study

S.No.	Data Source Platform / Agency	Purpose and Core Information Derived
1	Scopus Database	Peer-reviewed indexed journals on international urban ecology and plant physiology.
2	Web of Science	High-impact environmental studies, climate change vulnerability, and mitigation research.
3	Google Scholar	Cross-referencing academic publications, gray literature, and localized botanical studies.
4	Forest Survey of India (FSI)	Regional forest statistics, canopy cover dynamics, and indigenous tree density data.
5	Ministry of Housing and Urban Affairs (MoHUA)	Smart Cities guidelines, operational datasets, and green infrastructure assessment frameworks.
6	Food and Agriculture Organization (FAO)	Global databases on dryland forestry, conservation practices, and ecosystem values.
7	Intergovernmental Panel on Climate Change (IPCC)	Global and regional climate adaptation pathways and standard mitigation criteria.
8	United Nations (UN Publications)	Sustainable Development Goals (SDGs 11, 13, 15) implementation indicators.
9	Remote Sensing & GIS Datasets	Published land-use/land-cover (LULC) changes and Land Surface Temperature (LST) mapping indices.
10	Government / Botanical Reference Manuals	Flora of Rajasthan records, morphological definitions, and local silvicultural reports.

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3.4 Selection of Target Species and Key Variables

To ensure a sound empirical evaluation, six native xerophytic species were selected based on their distribution, adaptive traits, and availability of secondary scientific literature. The variables under consideration reflect both the environmental stressors of Rajasthan and the desired ecological benefits of urban green infrastructure spaces.

Table 4. Profile of Selected Native Xerophytic Species

S.No.	Scientific Name	Common/Local Name	Primary Ecological Importance & Functional Role
1	*Prosopis cineraria*	Khejri	Exceptional drought resistance, deep rooting, high carbon sequestration potential.
2	*Tecomella undulata*	Rohida	High thermal tolerance, timber value, crucial local biodiversity support.
3	*Capparis decidua*	Ker	Excellent sand and soil stabilization, negligible leaf transpiration, erosion control.
4	*Azadirachta indica*	Neem	High microclimate regulation capacity, broad-canopy air purification, pollution control.
5	*Acacia senegal*	Kumatiye	Nitrogen-fixing capabilities, soil conservation, survival in degraded rocky substrates.
6	*Salvadora persica*	Pilu / Jhal	High salinity tolerance, ecological restoration of waterlogged or saline arid zones.

Table 5. Description of Evaluation Variables and Significance

S.No.	Evaluated Variable	Functional Significance in Smart City Environment
1	Water-use Efficiency	Minimizing groundwater extraction for landscaping; resilience under acute drought.
2	Drought Tolerance	Survival without artificial irrigation systems under extreme summer heat.
3	Carbon Sequestration Potential	Mitigating urban carbon footprints and localized vehicular greenhouse emissions.
4	Urban Heat Island (UHI) Mitigation	Reducing ambient and land surface temperatures via sensible heat alteration.
5	Biodiversity Support	Providing critical microhabitats, food sources, and nesting spaces for native fauna.
6	Soil Conservation	Preventing wind and stormwater soil erosion within city perimeters.
7	Air Pollution Reduction	Particulate matter (PM2.5/PM10) interception and gaseous pollutant absorption.
8	Maintenance Requirement	Lowering municipal budget spending on fertilizers, pesticides, and constant pruning.
9	Climate Resilience	Long-term survival and stability against unpredictable delayed or deficient monsoon cycles.
10	Ecological Sustainability	Aligning urban expansion with the carrying capacity of regional arid ecosystems.

IV. RESULTS

4.1 Comparative Ecological Characteristics of Selected Native Xerophytic Species

The comparative assessment of selected native xerophytic species revealed notable variations in their ecological characteristics and environmental performance. Despite these differences, all selected species exhibited remarkable

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adaptability to arid climatic conditions and demonstrated significant potential for sustainable urban landscaping. Their low irrigation requirements, high drought tolerance, and ability to provide multiple ecosystem services make them highly suitable for developing climate-resilient green infrastructure in the Smart Cities of Rajasthan.

Among the evaluated species, *Prosopis cineraria* exhibited the highest overall ecological suitability owing to its exceptional drought tolerance, minimal water requirement, high carbon sequestration potential, and strong capacity to support urban biodiversity under harsh environmental conditions.

Table 6. Comparative Ecological Performance Matrix of Selected Species

Species Name	Drought Tolerance	Water Requirement	Carbon Sequestration	Biodiversity Support	Overall Urban Suitability
Prosopis cineraria	Very High	Very Low	High	High	Excellent
Tecomella undulata	High	Low	Moderate	High	Excellent
Capparis decidua	Very High	Very Low	Moderate	Moderate	Very Good
Azadirachta indica	High	Moderate	High	High	Excellent
Acacia senegal	High	Low	Moderate	Moderate	Very Good
Salvadora persica	High	Very Low	Moderate	Moderate	Good

4.2 Performance Analysis Against Exotic Ornamental Vegetation

A central problem in current landscape management within Rajasthan's smart cities is the widespread use of exotic ornamental flora (e.g., *Delonix regia*, *Conocarpus erectus*, various lawn grasses) which impose unsustainable structural stresses. This research systematically compared native xerophytes against these exotic indicators.

Table 7. Matrix of Native Xerophytic Species vs. Exotic Ornamental Species

Ecological Indicator	Native Xerophytic Species	Exotic Ornamental Species	Arid-Zone Structural Implications
Irrigation Requirement	Very Low (Rain-fed after establishment)	High (Requires frequent fresh water)	Saves critical city groundwater tables.
Drought Tolerance	Very High (Survives severe wilting phases)	Moderate to Low (Suffers high mortality)	Guarantees green infrastructure survival.
Maintenance Cost	Low (Minimal inputs needed)	High (Requires pruning, fertilizers)	Optimizes municipal financial budgets.
Climate Adaptability	Excellent (Naturally evolved over millennia)	Moderate to Poor (Vulnerable to temperature spikes)	Maintains consistent eco-performance.
Biodiversity Support	High (Co-evolved with local fauna)	Moderate to Low (Can cause ecological deserts)	Re-establishes urban avian and insect webs.
Soil Conservation	High (Deep and wide root configurations)	Moderate (Shallow root limits holding capacity)	Reduces urban dust and topsoil erosion.
Long-term Sustainability	Excellent (Self-sustaining lifecycle)	Moderate to Low (Prone to collapse/disease)	Ensures long-term climate buffers.
Urban Heat Mitigation	High (Effective canopy cooling and transpiration)	Moderate (Limited performance under drought)	Lowers urban land surface temperatures.

4.3 Quantifiable Ecosystem Services and Climate Resilience Pathways

The analysis indicates that native xerophytic vegetation significantly enhances climate resilience through deep root systems, efficient water-use mechanisms, reduced transpiration, and physiological drought adaptations. The functional

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pathways can be categorized into major themes: reduction of urban surface temperatures, groundwater conservation through structural irrigation reduction, soil erosion mitigation, and improvement of atmospheric air quality via particulate filtration.

V. DISCUSSION

The present study demonstrates that native xerophytic vegetation has substantial potential to enhance climate resilience and promote sustainable urban development in the Smart Cities of Rajasthan. Based on a comparative analysis of secondary scientific literature, indigenous drought-tolerant plant species consistently exhibited superior ecological performance compared with widely planted exotic ornamental species. Their inherent adaptation to arid and semi-arid climatic conditions makes them particularly suitable for urban landscapes facing increasing water scarcity, rising temperatures, and environmental degradation.

The findings indicate that native xerophytic species require considerably less irrigation while maintaining high ecological functionality. This observation aligns with previous studies reporting that climate-adapted native vegetation enhances water-use efficiency, minimizes irrigation demand, and reduces long-term landscape maintenance costs (Roy et al., 2012; Haaland & van den Bosch, 2015). These characteristics are especially relevant in Rajasthan, where declining groundwater levels and irregular rainfall patterns present significant challenges to urban environmental sustainability.

The comparative assessment further revealed that indigenous xerophytic vegetation provides a wide range of ecosystem services beyond ornamental value. These services include mitigation of the urban heat island effect, carbon sequestration, biodiversity conservation, soil stabilization, dust suppression, and improvement of urban microclimatic conditions. Similar findings have been reported by Anguluri and Narayanan (2017) and Yosef et al. (2022). Among the evaluated species, *Prosopis cineraria* emerged as the most ecologically suitable species for arid urban environments. Its exceptional drought tolerance, deep root system, minimal irrigation requirement, and ability to support associated biodiversity make it highly appropriate for sustainable urban greening programmes in Rajasthan. Other native species, including *Tecomella undulata*, *Capparis decidua*, *Acacia senegal*, and *Salvadora persica*, also exhibited considerable ecological potential.

The findings further support the growing global emphasis on Nature-based Solutions (NbS) as an effective strategy for addressing urban environmental challenges. Integrating native vegetation into urban planning enhances ecosystem services, improves climate resilience, conserves natural resources, and contributes to sustainable development. Xerophytic vegetation represents a practical Nature-based Solution for water-limited cities. An important policy implication concerns conventional urban landscaping practices. Existing landscape designs frequently prioritize aesthetic appeal over ecological suitability, resulting in the widespread use of exotic ornamental species requiring intensive irrigation, fertilization, and maintenance. In contrast, xeriscaping using indigenous vegetation significantly reduces water consumption while enhancing ecological stability and urban environmental quality.

The present findings are consistent with the Climate Smart Cities Assessment Framework (MoHUA) and contribute directly to SDG 11, SDG 13, and SDG 15 by improving biodiversity conservation, water-use efficiency, reducing urban heat stress, and strengthening ecosystem resilience. Despite these significant findings, the study has certain limitations. The analysis is based exclusively on secondary scientific data and therefore does not incorporate primary field observations or experimental measurements. Future investigations should integrate field-based ecological experiments, GIS, remote sensing, and long-term environmental monitoring.

Overall, this study provides robust scientific evidence that native xerophytic vegetation should be recognized as a fundamental component of climate-resilient urban green infrastructure rather than merely an alternative landscaping option. Integrating indigenous drought-resistant plant species into Smart City planning can improve environmental sustainability, conserve water resources, strengthen ecosystem services, support biodiversity conservation, and enhance the long-term resilience of Rajasthan's rapidly expanding cities under changing climatic conditions.

VI. CONCLUSIONS AND RECOMMENDATIONS

The study clearly establishes that native xerophytic vegetation provides an optimal ecological buffer for the Smart Cities of Rajasthan. To translate these scientific insights into practice, the following policy recommendations are proposed:

Mandate Xeriscaping in Smart City Master Plans: Municipal authorities in Jaipur, Jodhpur, Udaipur, Ajmer, and Kota should formulate zoning mandates requiring a minimum of 60% of all public green spaces to feature native xerophytic species.

Phased Replacement of High-Water Exotic Flora: Public parks and median strips currently populated by water-intensive ornamental plants should undergo gradual, phased restoration utilizing drought-tolerant native canopy trees like Khejri and Rohida.

Establishment of Specialized Municipal Nurseries: To counter the market scarcity of indigenous varieties, smart city budgets should fund dedicated botanical nurseries for propagating high-quality saplings of local species.

Integration into Building Bye-Laws: Incentives such as property tax rebates can be offered to residential and commercial real estate developers who achieve high scores on local 'Xeriscape Indices' in private campus landscapes.

Long-Term Multidisciplinary Research: Institutional collaboration between local state universities, botany departments, and urban development authorities must be funded to monitor microclimatic variations via GIS and field experiments.

Declarations & Key Administrative Disclosures

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Data Availability Statement: All data used in this study were obtained from publicly available secondary sources, including peer-reviewed scientific literature, government reports, environmental databases, and published datasets.

Ethical Approval: This study is based exclusively on secondary scientific data obtained from publicly available sources. It does not involve human participants or animal experimentation; therefore, ethical approval was not required.

Author Contributions: Author Conceptualization; Methodology; Literature Review; Data Collection; Secondary Data Analysis; Data Interpretation; Writing—Original Draft Preparation; Writing—Review and Editing; Visualization; and Final Approval of the Manuscript.

Abbreviations: CSCAF: Climate Smart Cities Assessment Framework; FAO: Food and Agriculture Organization; FSI: Forest Survey of India; GIS: Geographic Information System; IPCC: Intergovernmental Panel on Climate Change; LST: Land Surface Temperature; NbS: Nature-based Solutions; SDGs: Sustainable Development Goals; UHI: Urban Heat Island; UN: United Nations.

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