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Urban Green Infrastructure Planning in Jaipur, India: A GIS-Based Suitability Model for Semi-Arid Cities

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Abstract: Urbanization in Jaipur, India, has led to a 42% decline in green cover over the past two decades, exacerbating urban heat, air pollution, groundwater depletion, and reduced livability. Green Infrastructure (GI) offers a sustainable solution, but effective implementation requires robust, data-driven strategies. This study employs geospatial technologies—GIS, remote sensing, and Multi-Criteria Decision Analysis (MCDA)—to develop a suitability model for Urban Green Infrastructure (UGI) planning. Using an entropy-based weighting approach, the model integrates environmental factors, including the Normalized Difference Vegetation Index (NDVI), which fell by 18% between 2000 and 2020; Land Surface Temperature (LST), which increased by 1.8 °C; soil moisture; precipitation; slope; and land use/land cover (LULC). Proximity to water bodies was found to be a critical determinant of suitability, whereas land surface temperature and soil moisture played significant roles in determining UGI feasibility. The results were validated using NDVI trends and comparative analysis with prior studies so as to ensure accuracy and robustness. The suitability analysis reveals that 35% of Jaipur's urban area, particularly peri-urban regions and river corridors, is highly suitable for UGI interventions, thereby presenting significant opportunities for urban cooling, flood mitigation, and enhanced ecosystem services. These findings align with India's National Urban Policy Framework (2018) and the UN Sustainable Development Goal 11, supporting climate resilience and sustainable urban development. This geospatial approach provides a scalable methodology for integrating green spaces into urban planning frameworks across rapidly urbanizing cities.

Keywords: green infrastructure (GI); remote sensing; geographic information systems (GIS); multi-criteria decision analysis (MCDA); land surface temperature (LST); normalized difference vegetation index (NDVI)

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1. Introduction

Urbanization has become one of the most dominant global trends, dramatically altering landscapes and environmental systems. More than 55% of the world's population now resides in urban areas, a number that is expected to rise significantly in the coming decades [1]. In India, urbanization is occurring at an accelerated pace, with projections indicating that the urban population will increase from 31% in 2011 to 40% by 2030 (https://www.worldbank.org/en/news/opinion/2024/01/30/gearing-up-for-india-s-rapid-urban-transformation, accessed on 1 January 2025) [2,3]. This rapid expansion has resulted in an increased demand for housing, infrastructure, and services, placing immense pressure on natural resources and environmental systems [3–6]. Urban areas, once rich in natural landscapes and ecosystems, are now being transformed into concrete jungles, which disrupt the ecological balance and affects the well-being of urban residents [7–9].

GI emerges as a sustainable solution to address these environmental challenges. GI integrates natural systems into urban environments, aiming to mitigate the negative impacts of urbanization while providing multiple ecological and social benefits [10–13]. UGI specifically focuses on the strategic incorporation of green spaces, such as parks, green corridors, and urban forests, into the urban fabric [14–17]. These interventions are designed to enhance ecological resilience, improve air quality, and promote overall urban sustainability. However, implementing UGI effectively requires a data-driven approach to identify suitable areas and prioritize interventions based on scientific evidence and local context [18].

The concept of GI comprises a range of scales, from broad national or regional ecological networks to more localized urban green spaces and specific stormwater management projects [19,20]. When applied to urban settings, this concept is referred to as UGI. Urban environments are characterized by intricate interactions between social and ecological systems, which present multifaceted challenges [21–26]. Social issues such as population growth, poverty, inequality, and escalating demands for resources like water, food, land, and energy intersect with environmental problems including climate change, biodiversity loss, deforestation, and pollution. Given the intertwined nature of social and ecological systems, addressing these issues requires an integrated approach that considers their multiple interconnections and dependencies [27]. UGI planning is particularly effective in urban areas as it provides a comprehensive framework for understanding and managing these interactions [28].

UGI offers the potential to create innovative connections between social and ecological systems, leading to more effective management compared to traditional planning methods [29]. UGI planning is guided by fundamental principles such as multifunctionality, integration, connectivity, and social inclusion, alongside supporting principles like multi-scale, multi-objective, and multi-disciplinary approaches [30]. These principles can be adapted and combined in various ways to address specific regional challenges [31]. Moreover, the adaptable nature of UGI components allows for customization to fit different local contexts, spatial scales, and issues, making it a valuable strategy for planning resilient urban areas [32–34]. UGI can significantly enhance urban resilience to climate change by improving water management, increasing permeable surfaces, regulating temperatures, enhancing water quality, boosting building efficiency, and creating new habitats for wildlife [35,36]. As a result, UGI represents a powerful tool for designing urban areas that are both adaptive and resilient in the face of climate change impacts [37,38].

International examples of UGI implementation illustrate its successful application in spatial planning to foster sustainable and resilient cities [39]. UGI reestablishes the connection between urban areas and nature, transforming cities into more resilient systems capable of addressing multiple urban challenges [40]. A key principle of UGI is its ability to deliver a variety of benefits and integrate diverse environmental, social, and economic functions [41]. Many cities promote UGI projects due to their potential to tackle a range of urban issues while providing multiple advantages and functions. However, the placement of these projects is often guided by a single benefit, such as stormwater management, rather than considering the full spectrum of potential benefits [42,43].

This study presents a novel approach by integrating multiple geospatial data layers—such as vegetation indices, LST, socio-economic factors, and topographical features (slope and aspect)—into an MCDA framework for assessing the suitability of UGI in Jaipur. While previous studies have utilized GIS and remote sensing techniques in urban planning, this research goes a step further by combining environmental, social, and spatial data in a unified model to identify priority areas for UGI interventions. The inclusion of both environmental parameters like vegetation health and water body detection and socio-economic factors such as population density and land use, provides a comprehensive understanding of the factors influencing UGI suitability. This methodology is particularly relevant for cities like Jaipur, where rapid urbanization poses significant challenges to environmental sustainability [44].

Jaipur, the capital city of Rajasthan, has experienced significant urbanization in recent decades. As of the 2011 Census, the city's population was approximately 3.1 million, and it has been growing at an annual rate of 4.5%. By 2030, it is projected to exceed 5 million residents. The spatial transformation of Jaipur is also evident in its built-up area expansion: in 1991, the built-up area was 78.99 km^2 (16.9% of the total area); by 2000, it increased to 116.84 km^2 (25%), marking an 8.1% change since 1991; in 2011, the built-up area reached 213.15 km^2 (45.6%), a 20.6% increase from 2000 and a 28.7% total change since 1991; and by 2022, the built-up area expanded to 325.77 km^2 (69.7%), reflecting a 24.09% increase from 2011 and a 52.8% total change since 1991. This rapid urban expansion, coupled with increasing demands for infrastructure, housing, and services, has put immense pressure on the city's natural resources, including its green spaces and water bodies. The urban sprawl has led to the loss of green cover, reduced air quality, and rising temperatures, exacerbating environmental challenges. These trends highlight the urgent need for strategic urban planning that integrates GI to mitigate the negative effects of urbanization and enhance ecological resilience. The study's findings provide valuable insights for urban planners, helping them prioritize areas for GI development in response to the city's growing urban footprint [45,46].

The main objectives of this study are to evaluate the current state of urban green cover in Jaipur using remote sensing data, focusing on vegetation indices such as the NDVI and the Modified Normalized Difference Water Index (MNDWI) to measure the extent and health of green spaces. The study integrates environmental parameters—including NDVI to assess vegetation health, MNDWI for water body detection, and LST for thermal characteristics—with socio-economic factors like population density and land-use patterns. Topographical features such as slope and aspect are also incorporated. These layers are combined using a Geographic Information System (GIS) and MCDA framework to develop a comprehensive suitability model for GI. This approach identifies priority areas for UGI interventions, mapping the most suitable locations for GI development. The findings offer critical insights for urban planners and policymakers, providing strategic recommendations for sustainable urban planning in Jaipur and contributing to a broader understanding of geospatial data applications in rapidly urbanizing cities.

2. Materials and Methods

2.1. Study Area

The study area for this research is Jaipur, the capital city of Rajasthan, India. Jaipur is one of India's fastest-growing cities, experiencing rapid urbanization and population growth. It is located in the northwestern part of India, with geographical coordinates ranging from approximately 26.7° N to 27.0° N latitude and 75.7° E to 76.0° E longitude. The city's terrain consists of a mix of plains and hilly regions, with the Aravalli mountain range running through parts of the area. Jaipur's semi-arid climate, characterized by hot summers and mild winters, makes it particularly vulnerable to environmental challenges such as urban heated islands, declining green cover, and increasing pollution levels. The city has witnessed a substantial reduction in green spaces over the past two decades, which has exacerbated environmental issues. This study focuses on mapping and analyzing these changes to support the strategic implementation of UGI for sustainable urban development in Jaipur. Figure 1 shows a location map of the study area.

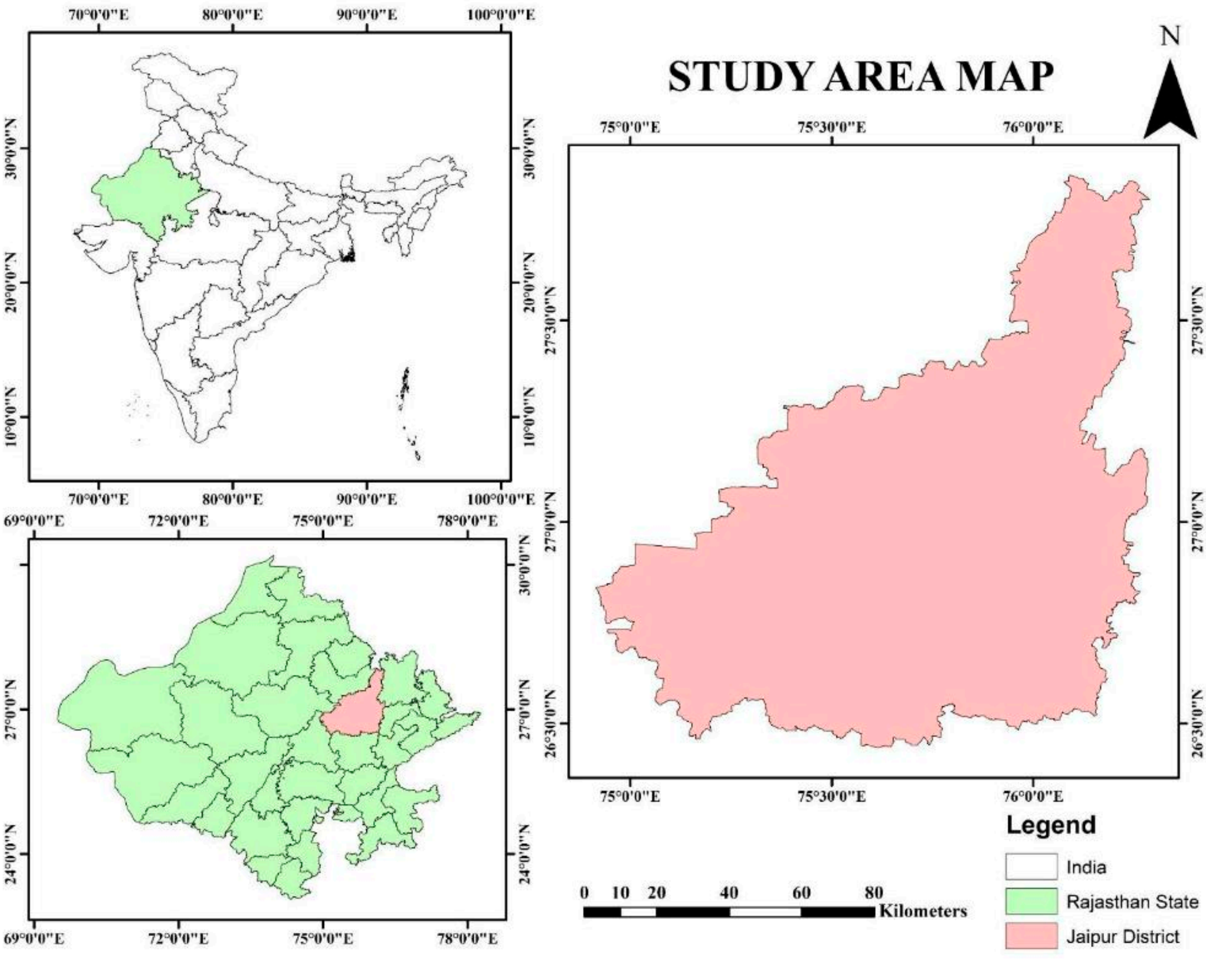

Figure 1. Location Map of Study Area. Upper left inset shows the location of the Rajasthan state with respect to the Union of India. Left bottom inset shows the location of the Jaipur city with respect to the state of Rajasthan. The right inset shows the boundaries of Jaipur city.

2.2. Datasets

To assess the factors influencing GI placement in urban areas, this study used a diverse range of environmental and physical datasets. Each dataset addresses specific aspects that are critical to identifying suitable locations for green spaces, ensuring a holistic approach to urban sustainability. Table 1 summarize svarious datasets used in this study along with their sources.

Table 1. Sources of the datasets used in this study.

Parameter	Dataset Source	Spatial Resolution	Temporal Resolution
Soil Moisture	TerraClimate (IDAHO_EPSCOR/TERRACLIMATE)	~4 km	Monthly
Wind Speed	ERA5-Land (ECMWF/ERA5_LAND/HOURLY)	~10 km (ERA5-Land)	Hourly
LST	MODIS (MODIS/061/MOD11A2)	1 km	8-day composite
LULC	ESA WorldCover (ESA/WorldCover/v200)	10 m	Yearly (2020)
Precipitation	CHIRPS (UCSB-CHG/CHIRPS/DAILY)	~5 km	Daily
Temperature	TerraClimate (IDAHO_EPSCOR/TERRACLIMATE)	~4 km	Monthly
Slope	SRTM (USGS/SRTMGL1_003)	30 m	Static (DEM-derived)

2.2.1. Precipitation

Precipitation is a critical factor for GI, as consistent water availability is essential for the growth, maintenance, and long-term sustainability of vegetation [47]. In urban areas, where water resources are often limited, understanding precipitation patterns is vital for designing GI systems that can adapt to changing climatic conditions, mitigate the risks of waterlogging during heavy rainfall, and address water scarcity during prolonged droughts. This dual challenge underscores the importance of integrating high-resolution precipitation data into GI planning to ensure resilience and adaptability.

To achieve a comprehensive understanding of precipitation patterns in the study region, this study utilized the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) dataset. CHIRPS was selected for its high spatial resolution (0.05°) and daily temporal frequency, which provide detailed insights into rainfall variability at both local and regional scales. This dataset integrates both satellite imagery and ground station data which enhances its accuracy, particularly in regions with sparse meteorological networks, making it highly suitable for semi-arid environments like Jaipur [48,49].

The use of CHIRPS data enabled this study to identify spatial and temporal variations in precipitation, which helped in the placement and design of GI across the study region. For instance, areas with declining rainfall trends were prioritized for drought-resistant vegetation and water-efficient GI solutions, such as rainwater harvesting systems and permeable pavements [50]. Conversely, regions with high rainfall variability were targeted for GI designs that address both water scarcity and flooding risks, such as rain gardens and constructed wetlands. This approach ensured that the GI solutions were tailored to local precipitation patterns, enhancing their effectiveness and sustainability.

Moreover, the integration of CHIRPS data into the MCDA framework allowed for a systematic evaluation of the influence of precipitation on GI suitability. By normalizing precipitation data and assigning weights based on its relative importance, the model ensured that the prioritization of areas for GI development or targeted interventions was based on the precipitation received. This methodological approach not only reflected the dynamic relationship between precipitation patterns and GI suitability but also provided actionable insights for urban planners and policymakers. It is important to mention here that this approach is particularly relevant for semi-arid cities like Jaipur, where water scarcity and extreme weather events pose significant challenges to urban sustainability.

2.2.2. Temperature

Temperature plays a critical role in determining the health and resilience of vegetation, as extreme temperatures can stress plants, inhibiting their growth and reducing their lifespan. Areas with moderate temperatures are generally more conducive to urban greenery, providing a balanced environment for vegetation to flourish. Urban areas often experience elevated temperatures due to the urban heat island (UHI) effect, which increases heat stress on plants and reduces their resilience. TerraClimate temperature data allow us to pinpoint the most heat-affected areas where GI can provide cooling benefits. This information is vital for selecting heat-tolerant plant species and designing shaded green spaces to alleviate UHI effects.

In this study, temperature data were obtained from the TerraClimate dataset, developed at the Climatology Lab at the University of California. This dataset provides monthly meteorological variables including maximum and minimum temperature from 1958 to present with a high spatial resolution (1/24°, ~4 km). Several studies have leveraged this high-resolution temperature data to pinpoint the heat-affected areas where GI can provide cooling benefits [51].

2.2.3. Soil Moisture

TerraClimate provides gridded soil moisture data at high spatial resolution (~4 km). Soil moisture data is crucial for evaluating the ability of soil to retain water and sustain vegetation. In this study, TerraClimate soil moisture data were analyzed to determine areas with favorable moisture conditions for vegetation growth and areas requiring irrigation to support GI. It is important to mention here that in the absence of proper datasets from alternative sources, TerraClimate provides valuable soil moisture data at proper resolutions, thus filling the gap of climate-related variables in the study region. Pertinently, healthy soil with adequate moisture content is essential for the growth of plants, influencing their vitality and ability to withstand drought conditions. This dataset enables researchers to identify areas where soil conditions are favorable or where interventions like soil amendments are required. By ensuring optimal soil moisture levels, GI projects can thrive, particularly in urban areas with varying soil characteristics due to construction activities.

TerraClimate provides gridded soil moisture data at a high spatial resolution of ~4 km, making it a valuable resource for assessing soil water retention and vegetation sustainability. Soil moisture is a critical parameter for evaluating the ability of soil to retain water and support vegetation growth, particularly in urban environments GI plays a vital role in enhancing ecological resilience and mitigating climate impacts [52,53]. In this study, TerraClimate soil moisture data were analyzed to identify areas with favorable moisture conditions for vegetation growth, as well as regions requiring supplemental irrigation or soil amendments to support GI.

The importance of TerraClimate lies in its ability to fill critical data gaps, especially in regions where alternative datasets are either unavailable or lack the necessary resolution. This dataset provides reliable, high-resolution soil moisture estimates, enabling assessment of spatial variability in soil water content and its implications for GI planning [54]. Pertinent to mention here that TerraClimate data allowed this study to identify areas where soil conditions are favorable for vegetation, as well as regions where interventions are required to improve soil moisture levels. This is particularly important in urban areas, where soil characteristics are often altered by construction activities, leading to reduced water retention and increased runoff [55]. Furthermore, by integrating TerraClimate soil moisture data into the MCDA framework, this study ensured that GI planning was driven by robust, spatially explicit data, thus enhancing the feasibility and effectiveness of proposed interventions.

2.2.4. Slope

The slopedata for the study region was derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The SRTM DEM is available at 30 m spatial resolution and was downloaded from https://earthexplorer.usgs.gov (accessed on 1 September 2024). The slope information helps in analyzing terrain conditions to identify suitable locations for GI. Slope maps have been used in several studies to prioritize areas with manageable terrains, such as gentle slopes or flat regions, for sustainable GI development Additionally, slope analysis aids in designing contour-based GI systems that enhance water retention and prevent soil degradation [56].

2.2.5. Wind Speed

The ERA5 dataset, produced by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF), serves as a crucial resource for assessing wind speeds relevant to GI projects. ERA-Land windspeed data set was incorporated in the current study to evaluate areas prone to high wind stress. ERA5-Land wind speed data is available at ~10 km spatial resolution at an hourly temporal resolution. This dataset helps in identifying wind-prone zones where windbreaks or resilient plant species might be required. Incorporating wind data ensures that GI is designed to withstand harsh wind conditions, contributing to its longevity and effectiveness in providing environmental benefits.

2.2.6. LST

LST data were obtained from MODIS LST product, MOD11A2, an 8-day composite dataset available at 1 km spatial resolution, which provides valuable insights into identifying urban heat islands, where surface temperatures are significantly higher than surrounding rural areas. LST data is crucial for prioritizing areas requiring immediate cooling through GI. By identifying heat hotspots, this dataset enables targeted placement of green spaces to maximize their cooling effects, which in turn reduces energy demand for air conditioning, and improves urban livability. Moreover, LST analysis can help in monitoring the effectiveness of implemented GI over time.

2.2.7. LULC

The LULC dataset for the year 2020 was acquired from the ESA WorldCover product, which offers a high spatial resolution of ~10 m. This dataset was generated and validated in near real-time through the integration of multi-temporal observations from Sentinel-1 synthetic aperture radar (SAR) and Sentinel-2 optical imagery, ensuring high accuracy and reliability for land cover classification. Pertinently, this high-resolution dataset provides a robust base for identifying the opportunities for urban greening, prioritizing degraded lands for rehabilitation, and planning multifunctional green spaces that align with urban development goals.

2.2.8. Proximity to Water Bodies

Proximity to water bodies was calculated in the GIS environment and is a critical consideration for GI planning, as areas near water sources tend to support greater vegetation growth, enhanced biodiversity, and improved microclimatic conditions. Water bodies naturally provide moisture, cooler temperatures, and ecological connectivity, making nearby areas more conducive to thriving green spaces. In this methodology, a proximity buffer of 30 m was created around water bodies to identify suitable zones. These buffered areas were assigned higher suitability scores, reflecting their enhanced potential for vegetation support and ecological benefits. This factor is particularly important in urban settings where water bodies act as natural cooling systems, reduce heat stress, and support urban biodiversity. By integrating proximity to water bodies into the model, planners can prioritize locations that maximize ecological synergies, mitigate the urban heat island effect, and contribute to sustainable urban ecosystems while promoting the resilience of GI projects.

2.3. Methods (Multi-Criteria Decision Analysis—MCDA)

In this paper, the suitability assessment of UGI was carried out in light of multi-environmental and physical factors affecting its efficiency. The suitability model integrates several factors including vegetation cover, proximity to water bodies, climatic conditions, land-use patterns, and topography. These factors were normalized and weighed in relation to their respective importance in order to be given equal weight and importance in the final suitability index. These factors were integrated using an MCDA framework that allowed for an orderly evaluation of their influence on urban resilience, heat island mitigation, and ecological sustainability [57–59]. This approach has enhanced the reliability of the model, by ensuring that each factor was weighted and prioritized based on its relative significance, providing a robust and data-driven evaluation for GI planning.

2.3.1. Normalization

Normalization and weighting are critical steps in developing a suitability model for GI planning, as they ensure that diverse factors are evaluated on a common scale and weighted according to their relative importance. In this study, the normalization of factors—such as precipitation, soil moisture, land surface temperature (LST), proximity to water bodies, and population density was carried out using the Min-Max scaling method. This technique transforms each indicator to a standardized range of 0 to 1, allowing for direct comparison despite differences in units or magnitudes. For example, LST values (measured in °C) and precipitation values (measured in mm) were both normalized to a 0–1 scale, ensuring that each factor contributes equally to the final model without bias from their original units [60].

The normalization process was conducted in two steps:

(i) Data preprocessing: raw data for each factor were cleaned and preprocessed to remove outliers and missing values.

(ii) Min-Max Scaling: each factor was normalized using the formula:

$$X_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where X is the original value, and X_{min} and X_{max} are the minimum and maximum values of the factor, respectively.

2.3.2. Applying Weights Using the Entropy Weighting Method

Following normalization, the next critical step in our MCDA framework is to assign weights to each factor using an entropy-based weighting method. This data-driven approach minimizes subjective bias by quantifying the intrinsic variability and information provided by each factor. In essence, factors with greater variability—indicating higher uncertainty and a stronger influence on UGI suitability—are assigned higher weights. The weighting procedure is implemented in several steps:

Step 1: Calculation of Proportions

For each normalized factor *Xi* (where *i* denotes the observation and *j* the factor), the proportion *pij* is calculated as

$$p_{ij} = \frac{X_{ij}}{\sum_{j=1}^{n} X_{ij}}$$

where n is the total number of observations for factor j.

Step 2: Calculation of Entropy

The entropy *Ej* of each factor is computed using the formula:

$$E_j = -\frac{1}{ln(n)} \sum_{i=1}^{n} p_{ij} ln(p_{ij})$$

where E_j is the entropy of factor j, n is the number of observations, and p_{ij} is the proportion of the i-th observation for factor j. A lower entropy value indicates that the factor provides more consistent and relevant information, while a higher entropy value suggests greater variability and less definitive information [61].

Step 3: Degree of Divergence

The degree of divergence (D_j) for each factor is then calculated as

$$D_j = 1 - E_j$$

This metric reflects the contrast or "spread" in the data for each factor, thereby indicating its relative importance.

Step 4: Weight Assignment

Finally, the weights (W_j) for each factors calculated by normalizing its divergence value:

$$W_j = \frac{D_j}{\sum_{j=1}^{m} D_j}$$

where m is the total number of factors. Factors with higher divergence values (e.g., LST and precipitation) received greater weights, reflecting their stronger influence on GI suitability [62]. This step ensures that the sum of all weights equals 1.

In this analysis, the computed entropy-based weights are as follows: Temperature (Max) received 0.20 because this factor was assigned the highest weight due to the critical importance of mitigating extreme heat and urban heat island effects in Jaipur, which directly impact vegetation survival and urban livability. Soil moisture received 0.17, reflecting its essential role in ensuring vegetation health and overall GI sustainability, especially in arid and semi-arid regions where water retention is a major challenge. Land Use and Land Cover (LULC) also received 0.17 since LULC patterns dictate the feasibility of GI interventions by identifying areas where green infrastructure is practical or requires rehabilitation. Land Surface Temperature (LST) received 0.13, as it serves as a key indicator of surface thermal conditions and helps identify areas that require cooling interventions through the incorporation of green spaces. Precipitation received 0.10 because adequate rainfall is crucial for vegetation viability by ensuring consistent moisture availability. Water Proximity received 0.10, given that proximity to water bodies enhances the potential for GI by providing natural moisture and aiding in the moderation of microclimates. Wind Speed received 0.10, as even though it is less variable, it still influences vegetation stability and transpiration rates, thereby affecting local microclimate regulation. Finally, the Slope received 0.07, reflecting its relatively lower variability; however, steep slopes do pose challenges for large-scale greening and may require innovative solutions such as terrace gardening.

The final suitability score was computed by integrating the normalized, weighted factors using a weighted sum model:

$$S_i = \sum_{j=1}^{m} W_j \cdot X_{ij}$$

where S_i is the suitability score for the i-th location, W_j is the weight of factor j, and X_{ij} is the normalized value of factor j at location i.

The use of Min-Max scaling and the Entropy Weighting Method provide strong scientific grounding for GI planning in the study region. By normalizing and weighting factors based on their intrinsic variability, the model minimized bias and ensured that the final suitability scores reflect the relative importance of each factor. This approach is particularly valuable for rapidly urbanizing cities like Jaipur, where data-driven decision-making is essential for sustainable development [63]. The complete methodology flowchart used in this study is illustrated in Figure 2. The final suitability scores are presented in Table 2.

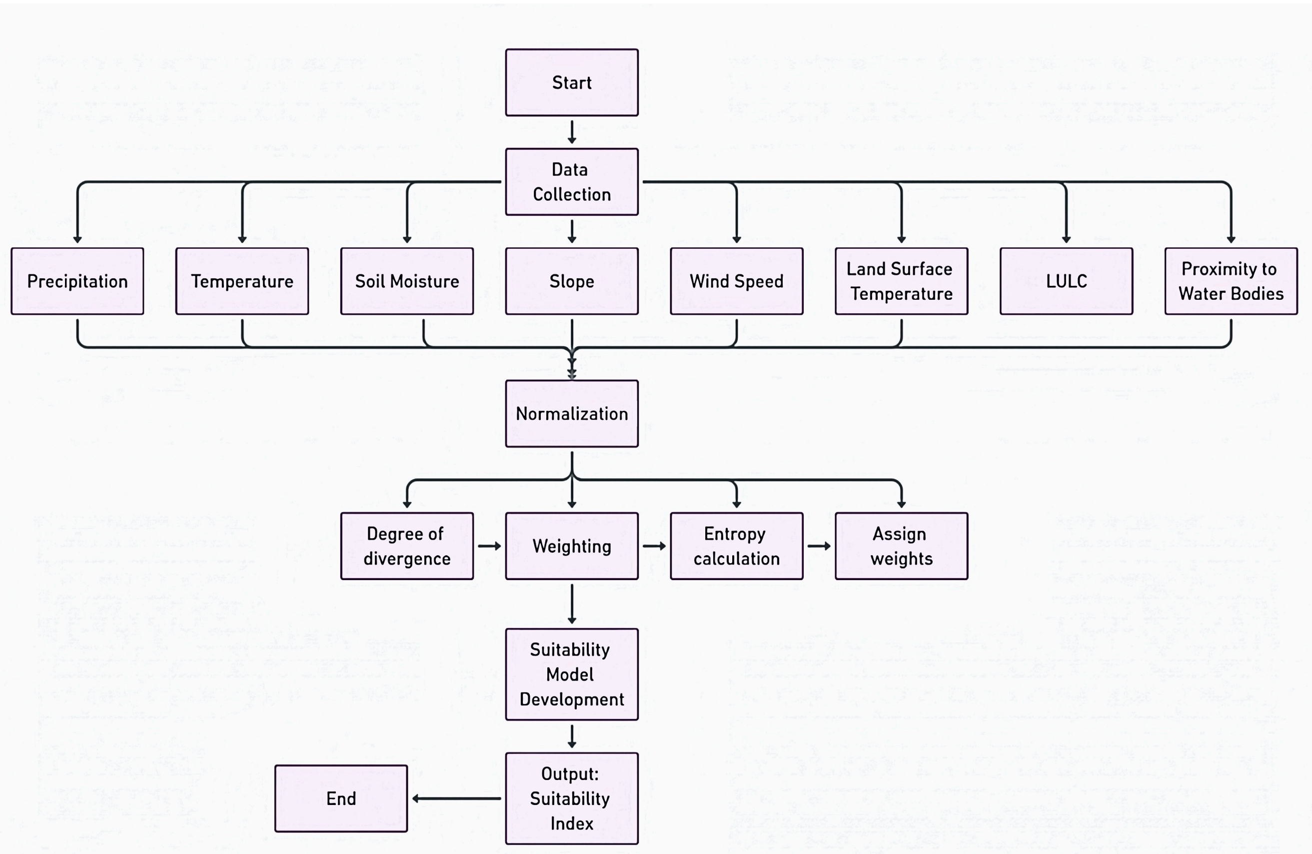

Figure 2. Flowchart of the complete methodology used in this study.

Table 2. Suitability Scores for LULC classes.

LULC Class	Suitability Score	Key Indicators	Ecological Role
Tree Cover	0.8	NDVI > 0.6, LST < 35 °C	Heat island mitigation, carbon sink
Grassland	0.7	NDVI 0.3–0.5, moderate soil moisture	Erosion control, recreational spaces
Shrubland	0.6	NDVI 0.3–0.5, fragmented distribution	Biodiversity corridors
Cropland	0.5	Seasonal NDVI 0.4–0.6	Agroforestry potential

Table 2. *Cont.*

LULC Class	Suitability Score	Key Indicators	Ecological Role
Built-up	0.2	LST > 40 °C, impervious surfaces	Retrofit potential (green roofs)
Bare/Sparse Vegetation	0.1	NDVI < 0.2, low soil moisture	Restoration priority
Permanent Water Bodies	0.9	MNDWI > 0.5, LST < 30 °C	Stormwater management, cooling effects
Herbaceous Wetland	0.7	MNDWI > 0.4, moderate NDVI	Flood mitigation, habitat creation
Moss and Lichen	0.3	Low NDVI, niche microclimates	Aesthetic and microclimate benefits

3. Results

3.1. Influence of LULC on GI Planning

The suitability of different LULC classes for GI planning was evaluated using an MCDA framework. This approach integrated remote sensing indices such as the NDVI, MNDWI, and LST, to assess the ecological potential of each LULC category. The suitability scores reflect their capacity to support GI goals, including urban heat island mitigation, biodiversity conservation, and stormwater management [64]. Table 2 shows the scores calculated for each category of LULC.

Tree cover received the highest suitability score of 0.8 due to its unparalleled ecological benefits, including carbon sequestration, urban heat island mitigation, and habitat provision [65]. NDVI values (>0.6) confirmed dense vegetation health in these areas, while LST analysis revealed significantly lower surface temperatures (2–4 °C cooler than built-up zones). These findings align with studies demonstrating that tree canopy cover reduces ambient temperatures and improves air quality in semi-arid cities [66–68]. In Jaipur, preserving existing tree cover and expanding urban forests in these zones can maximize GI benefits with minimal intervention. Grasslands and shrublands received 0.7 and 0.6 scores, respectively, as they offer moderate suitability for GI, supporting ecosystem services such as erosion control and recreational green spaces. However, their lower NDVI values (0.3–0.5) and fragmented distribution in peri-urban areas necessitate targeted interventions like soil enrichment and irrigation. These scores align with studies emphasizing the role of grasslands in urban biodiversity corridors and their adaptability to semi-arid climates [69,70]. Cropland scored moderately (0.5), reflecting its dual potential for agricultural productivity and agroforestry-based GI. While NDVI values (0.4–0.6) indicate healthy vegetation, the seasonal nature of cropping limits year-round ecological benefits. Transforming marginal croplands into mixed-use green spaces (e.g., community gardens) could enhance urban resilience without compromising food security, as demonstrated in different cities around the globe [71–73].

Built-up areas received a suitability score of 0.2 due to impervious surfaces and limited space for traditional GI. However, innovative solutions like green roofs and vertical gardens can mitigate heat stress (LST values >40 °C) and reduce energy consumption. These findings echo research on retrofitting dense urban areas with GI in water-scarce regions [74–76]. Bare/sparse vegetation areas scored lowest (0.1), reflecting challenges like soil degradation and low NDVI values (<0.2). Restoration strategies such as afforestation and rainwater harvesting are critical to transforming these zones into functional GI [77,78]. Permanent water bodies and herbaceous wetlands scored 0.9 and 0.7, respectively, highly due to their roles in stormwater management and biodiversity support. MNDWI values (>0.5) confirmed their hydrological significance, while LST analysis highlighted their cooling effects (3–5 °C lower than adjacent areas). Protecting these zones aligns with the best global practices for climate-resilient urban planning [79]. Moss and lichen scored (0.3) due to their limited scalability, but their niche role in microclimate regulation and green walls warrants inclusion. Their inclusion reflects the study's holistic approach to GI, even in challenging urban environments.

3.2. Influence of Slope on GI Planning

The analysis of slope as a determinant of GI suitability reveals significant spatial variation across the urban landscape of the Jaipur city. Low-slope regions, particularly in central Jaipur, exhibit high suitability for GI, with scores ranging from 0.70 to 1.00 (Table 3). These areas, characterized by flat or gently undulating terrain, facilitate the establishment of green spaces without significant risks of soil erosion or excessive runoff, making them ideal for parks, green corridors, and urban forests [80,81]. The suitability of low-slope areas aligns with studies demonstrating that gentle terrain reduces construction costs and enhances the long-term sustainability of GI projects in semi-arid regions [82].

Conversely, high-slope regions, such as peripheral zones of the study region, received lower suitability scores (0.30–0.50) due to challenges like soil erosion, instability, and high runoff rates. Steep slopes hinder vegetation establishment and increase maintenance costs, often necessitating structural interventions such as terracing, retaining walls, or soil stabilization techniques to ensure GI viability. Pertinently, terracing has been successfully implemented in India cities, e.g., Bengaluru, to transform sloped terrain into functional green spaces for stormwater management and urban agriculture.

3.3. Influence of LST on GI Planning

LST is a critical determinant of GI suitability, as it directly influences thermal comfort, vegetation health, and urban heat island (UHI) mitigation. In this study, LST data from the MODIS product (MOD11A2)—an 8-day composite dataset at 1 km spatial resolution—were analyzed to prioritize areas for GI interventions. Results revealed that the areas with lower LST values (<35 °C), such as central Jaipur and Amer, demonstrated high GI suitability. These zones are characterized by existing vegetation cover, proximity to water bodies, and shaded built environments, which naturally support cooler microclimates. It is important to mention here that the NDVI values (>0.5) confirmed healthy vegetation in these regions, correlating with LST values 3–5 °C lower than adjacent urbanized areas. Such environments are ideal for implementing urban forests, green corridors, and wetland parks, which enhance thermal comfort and reduce energy demand for cooling.

Conversely, regions with higher LST values (>40 °C), such as Sanganer and Mansarovar, scored poorly due to extensive impervious surfaces, minimal vegetation, and intense heat retention. These areas face challenges like elevated water evaporation rates and reduced soil moisture, which hinder vegetation survival. LST analysis revealed that densely built-up zones experience surface temperatures up to 45 °C, which exacerbates water stress and limits GI effectiveness in these areas (Table 3).

3.4. Influence of Water Bodies on GI Planning

The proximity to water bodies is one of the strongest determinants of GI suitability. Areas close to water bodies, such as Amer, exhibited suitability scores ranging from 0.85 to 1.00, reflecting the positive impact of natural water sources on GI implementation. These areas can easily incorporate GI, as water helps to sustain vegetation, regulates microclimates, and supports biodiversity. However, in areas like Phagi, which are far from any significant water bodies, the suitability score dropped to around 0.30 to 0.40. The absence of water bodies in such regions creates significant barriers for GI, as water availability is critical for the maintenance of green spaces (Table 3).

Table 3. Suitability score range for other variables of the MCDA.

Variable	Score Range	Key Indicators	Ecological Role
Slope	0.0–0.30 (Very Unfavorable) 0.30–0.70 (Moderately Suitable) 0.70–1.00 (Highly Suitable)	Very Unfavorable zones are those that have steep terrain with high erosion risk. Moderately Suitable zones are those with slopes that may require additional management. Highly Suitable zones are those with flat or gently undulating terrain that facilitate the establishment of green spaces.	Highly Suitable zones support the establishment of parks, green corridors, and urban forests with minimal intervention, whereas Very Unfavorable zones may require terracing or soil stabilization to enable green infrastructure development.
Land Surface Temperature (LST)	0.0–0.30 (Very Unfavorable) 0.30–0.80 (Moderately Suitable) 0.80–1.00 (Highly Suitable)	Very Unfavorable zones are those where LST exceeds 40 °C, indicating extreme heat stress (e.g., in Sanganer or Mansarovar). Moderately Suitable zones are those with intermediate LST values that might require mitigation. Highly Suitable zones are those with LST below 35 °C and healthy vegetation (NDVI > 0.5).	Highly Suitable zones support cooler microclimates and reduce urban heat island effects, whereas Very Unfavorable zones experience heat stress that hinders vegetation survival and limits the effectiveness of green infrastructure.
Proximity to Water Bodies	0.0–0.30 (Very Unfavorable) 0.30–0.70 (Moderately Suitable) 0.70–1.00 (Highly Suitable)	Very Unfavorable zones are those that are far from water sources (e.g., areas like Phagi). Moderately Suitable zones are those at an intermediate distance from water bodies. Highly Suitable zones are those in close proximity to water sources, typically within a 30 m buffer (e.g., as seen in Amer).	Highly Suitable zones benefit from enhanced moisture availability, support stormwater management, and help moderate local microclimates, whereas Very Unfavorable zones lack sufficient water for sustaining vegetation and supporting effective green infrastructure.
Precipitation	0.0–0.30 (Very Unfavorable) 0.30–0.80 (Moderately Suitable) 0.80–1.00 (Highly Suitable)	Very Unfavorable zones are those that receive low rainfall (e.g., areas like Chaksu). Moderately Suitable zones are those with variable or moderate rainfall. Highly Suitable zones are those with consistent, moderate precipitation (e.g., central Jaipur).	Highly Suitable zones maintain sufficient soil moisture for vegetation growth with minimal additional irrigation, whereas Very Unfavorable zones experience water stress that hinders the sustainability of green infrastructure and limits vegetation survival.
Temperature	0.0–0.30 (Very Unfavorable) 0.30–0.80 (Moderately Suitable) 0.80–1.00 (Highly Suitable)	Very Unfavorable zones are those with high air temperatures (e.g., areas like Chaksu). Moderately Suitable zones are those with intermediate temperature conditions. Highly Suitable zones are those with moderate air temperatures (e.g., in Jaipur and Amer) that support healthy vegetation growth.	Highly Suitable zones provide optimal conditions for vegetation growth, reducing water demand and heat stress, whereas Very Unfavorable zones result in increased evaporation and plant stress, thereby hindering the effectiveness of green infrastructure.
Soil Moisture	0.0–0.30 (Very Unfavorable) 0.30–0.70 (Moderately Suitable) 0.70–1.00 (Highly Suitable)	Very Unfavorable zones are those that exhibit low soil moisture (e.g., in areas like Chaksu or Phagi). Moderately Suitable zones have moderate soil moisture levels. Highly Suitable zones are those with high soil moisture levels, as observed in central urban areas.	Highly Suitable zones support robust vegetation growth and reduce the need for additional irrigation, whereas Very Unfavorable zones limit the sustainability and viability of green infrastructure due to insufficient soil moisture.
Wind Speed	0.0–0.30 (Very Unfavorable) 0.30–0.60 (Moderately Suitable) 0.60–1.00 (Highly Suitable)	Very Unfavorable zones are those that experience high wind speeds (e.g., in exposed peripheral areas like the outskirts of Amer/Jaipur). Moderately Suitable zones experience moderate wind speeds. Highly Suitable zones are those with low to moderate wind speeds (e.g., parts of Jaipur City) that are conducive to vegetation growth.	Highly Suitable zones benefit from wind conditions that support vegetation health and natural cooling, whereas Very Unfavorable zones are subjected to wind speeds that can damage vegetation and increase evaporation rates, thus negatively affecting green infrastructure.

3.5. Influence of Precipitation on GI Planning

Precipitation is a crucial climatic factor influencing the suitability of GI. Analysis of precipitation data revealed that the areas with moderate precipitation, such as central Jaipur, demonstrated high suitability for GI, with scores ranging from 0.80 to 1.00. This moderate precipitation supports consistent soil moisture, which is essential for vegetation growth and reduces the need for excessive irrigation, thereby making the GI more sustainable. The ample availability of water allows for the establishment of diverse GI elements, such as parks, green roofs, and urban gardens, without the risk of water scarcity that could hinder their success.

In contrast, areas with lower precipitation levels, such as Chaksu, showed lower suitability scores ranging from 0.30 to 0.50. These regions experience water stress, making it difficult to maintain GI without additional water resources (Table 3)

3.6. Influence of Temperature on GI Planning

Air Temperature is another critical climatic factor that influences GI suitability. The suitability scores based on air temperature varied from 0.30 (high-temperature areas) to 1.00 (moderate temperature zones). The central parts of Jaipur and Amer experience favorable temperatures and scored between 0.80 to 1.00 in suitability. These moderate temperatures provide optimal conditions for vegetation growth and reduce the water demand for irrigation. As a result, these regions are ideal for establishing GI, the comparatively cooler conditions in these areas support the development of sustainable green spaces, improving the overall quality of life by providing cooler microclimates and reducing the urban heat island effect. However, high-temperature zones, such as Chaksu, scored 0.30 to 0.50, indicating lower suitability for GI (Table 3).

3.7. Influence of Soil Moisture on GI Planning

The role of soil moisture in determining GI suitability is crucial, as it directly influences plant growth and the sustainability of green spaces. Results showed that the areas with high soil moisture, particularly in central urban areas like Jaipur and Amer, received suitability scores ranging from 0.70 to 1.00. The ample moisture content in the soil supports healthy vegetation and reduces the need for irrigation, making GI more sustainable and efficient. In contrast, regions with low soil moisture, such as Chaksu and Phagi, received much lower suitability scores, ranging from 0.30 to 0.50 (Table 3).

3.8. Influence of Wind Speed on GI Planning

The impact of wind speed on GI suitability showed significant variations across different urban zones. Urban areas exposed to high wind speeds, such as the open outskirts of Amer and Jaipur, received lower suitability scores ranging from 0.30 to 0.50. High wind speeds can damage vegetation, increase evaporation, and reduce the effectiveness of GI, which is particularly critical for areas trying to combat urban heat islands. On the other hand, areas with moderate wind speeds, such as parts of Jaipur City, scored higher, ranging from 0.60 to 0.80, as the mild winds support healthier plant growth and provide natural cooling effects (Table 3). The suitability score maps of all the input variables of the MCDA are shown in Figure 3.

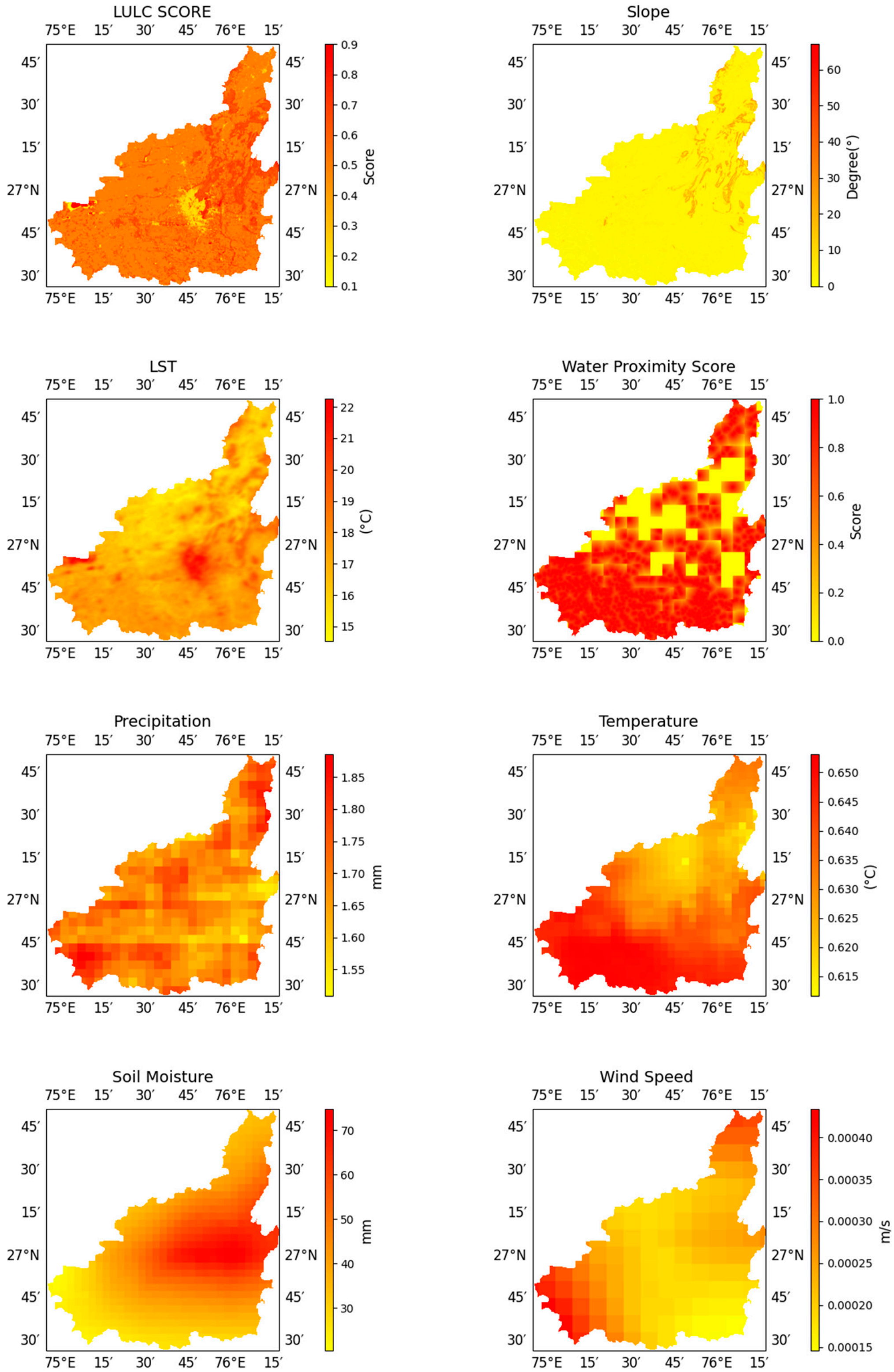

Figure 3. Suitability score maps all the input svariables used in this study.

3.9. Urban Green Infrastructure Suitability Index—Combined Influence of All the Parameters

The suitability index map (Figure 4) was generated by integrating normalized and weighted factors through the MCDA framework, following established methodologies for geospatial analysis. This UGI Suitability Index provides critical insights into the spatial variation of green infrastructure potential across the Jaipur district. The analysis highlights distinct patterns of suitability across sub-regions, reflecting their unique environmental, climatic, and land-use characteristics. The suitability index ranges from 0 (low suitability) to 1 (high suitability), representing the normalized scores for prioritizing UGI interventions. For ease of interpretation, these scores are expressed as percentages, where 1 corresponds to 100% suitability (Table 4).

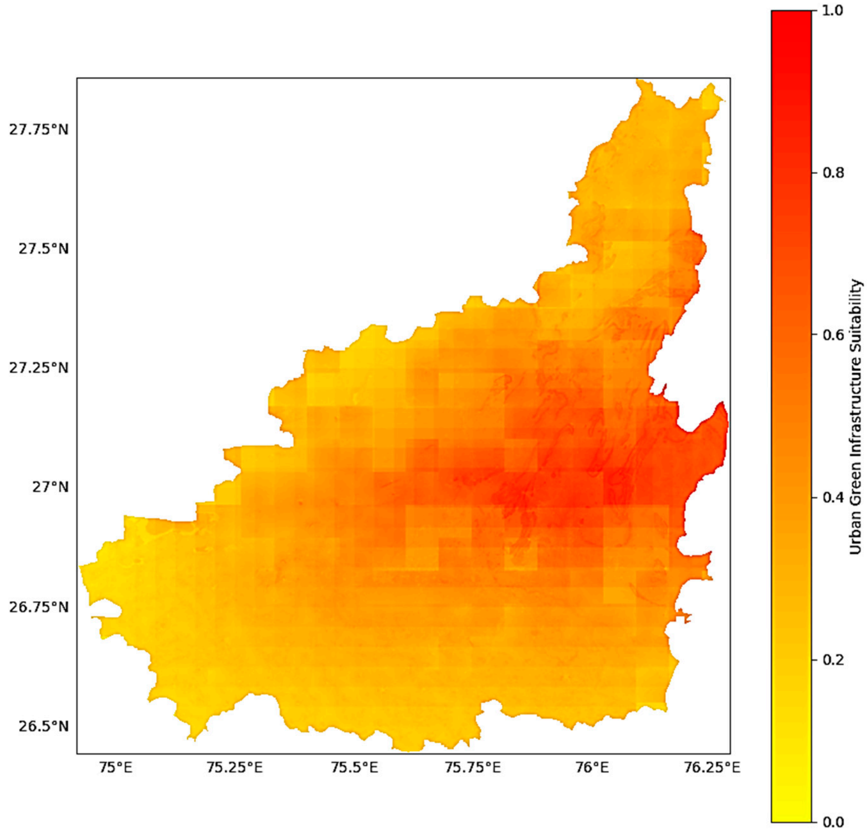

Figure 4. UGI suitability map of the study area generated used the MCDA framework.

Table 4. UGI suitability ranges across various regions in Jaipur.

Name	Min	Max	Range
Amer	58.25	93.73	35.48
Bassi	50.28	85.09	34.81
Chaksu	35.08	59.35	24.28
Chomu	48.28	80.68	32.40
Jaipur	56.05	89.65	33.60
JamwaRamgarh	63.28	93.98	30.70
Phagi	30.16	54.46	24.30
Sambhar	33.15	50.98	24.35
Sanganer	50.21	68.81	18.61
Viratnagar	47.68	75.18	27.50

Sub-regions such as Jamwa Ramgarh, Amer, and Jaipur City emerged as the most suitable areas for UGI development, with maximum scores of 93.98%, 93.73%, and 89.65%, respectively. These regions demonstrate significant potential due to favorable environmental conditions, such as higher vegetation cover, proximity to water bodies, moderate slopes, and reduced land surface temperatures. For instance, Jamwa Ramgarh's suitability can be attributed to its gently sloping terrain, higher soil moisture content, and existing vegetation, which are conducive to urban greening. Amer, with its moderate precipitation and favorable land-use patterns, offers opportunities for developing biodiversity corridors and community green spaces. Similarly, Jaipur City stands out due to its population density and existing urban parks, making it a critical area for enhancing urban cooling and ecological resilience. These findings align with similar studies conducted in semi-arid regions, which emphasize the role of microclimatic conditions, soil moisture, and land-use patterns in driving UGI suitability. Moreover, the high variability observed in Amer and Jaipur City, as indicated by their range values of 35.48% and 33.60%, respectively, suggests the need for site-specific interventions within these sub-regions.

Sub-regions such as Chomu, Bassi, and Viratnagar exhibit moderate suitability for UGI projects, with maximum scores ranging from 75.18% to 85.09%. These areas present a mix of high- and low-suitability zones due to fragmented land-use patterns, variations in LST, and limited vegetation cover. For example, Bassi's suitability stems from its moderate soil moisture levels and proximity to seasonal water bodies, which provide opportunities for rain gardens and wetland restoration. However, higher slopes in certain areas reduce the feasibility of large-scale projects, necessitating innovative solutions like contour-based greening or vertical gardens. Chomu and Viratnagar display similar patterns of variability, driven by differences in precipitation and vegetation health. This aligns with the findings by Hansen et al. (2017), who highlighted the importance of site-specific planning in regions with fragmented land-use and heterogeneous climatic conditions [23,24]. Targeted interventions, such as agroforestry and riparian buffers, could enhance UGI's potential in these areas.

Regions such as Phagi and Chaksu emerged as the least suitable for UGI, with maximum scores of 54.46% and 59.35%, respectively. These areas face significant challenges, including high land surface temperatures, minimal vegetation cover, and low soil moisture availability. Such conditions limit the feasibility of traditional UGI projects, necessitating adaptive strategies like the use of drought-tolerant plant species, artificial water recharge systems, and soil amendments. The relatively narrow range of suitability in these sub-regions suggests a consistent lack of favorable conditions across the landscape, further underscoring the need for specialized approaches.

Sanganer presents a unique case with a maximum suitability score of 68.81% and the smallest range of 18.61%. This narrow range indicates a relatively uniform distribution of suitability, making it a promising candidate for evenly distributed green infrastructure interventions. Despite its moderate suitability, Sanganer's flat terrain and proximity to Jaipur City make it well-suited for integrating smaller green projects, such as pocket parks, green roofs, and urban gardens, to address urban heat island effects and enhance local biodiversity.

The variation in UGI suitability across the Jaipur district is influenced by several key factors, as highlighted by previous studies. Regions with higher green cover and favorable land-use patterns, such as Jamwa Ramgarh and Amer, scored higher due to their ecological readiness for UGI interventions. Higher temperatures and lower soil moisture negatively impacted suitability in arid regions like Phagi, while cooler areas with moderate precipitation, such as Amer, showed greater potential. Sub-regions near rivers, lakes, or seasonal water bodies demonstrated higher suitability scores, emphasizing the role of natural hydrological features in enhancing urban sustainability.

Figure 4 provides a valuable tool for urban planners and policymakers in identifying priority areas for green infrastructure development. High-suitability regions, such as Jamwa Ramgarh, Amer, and Jaipur City, should be prioritized for immediate interventions, including the development of urban forests, riparian corridors, and cooling zones. In contrast, moderate-suitability areas like Bassi and Chomu would benefit from targeted projects, such as agroforestry and rainwater harvesting. Low-suitability regions like Phagi and Chaksu require adaptive strategies, focusing on water-efficient vegetation and soil restoration to improve conditions for green infrastructure.

4. Discussion

4.1. Relationship Between Urban UGI Index and Soil Moisture

The relationship between the UGI Suitability Index and soil moisture was analyzed using statistical regression analysis (Figure 5). The regression equation $y = -7.68177 + 36.8392x$ describes a positive linear relationship, indicating that areas with a higher UGI suitability index tend to exhibit higher soil moisture content. The coefficient of determination (R^2) is 19.91%, meaning that approximately 19.91% of the variability in soil moisture is explained by the UGI suitability index. This result supports the hypothesis that well-planned GI positively influences soil moisture retention. However, the relatively modest R^2 value highlights that other factors may also contribute significantly to soil moisture variability, suggesting that the current model could be enhanced by incorporating additional variables.

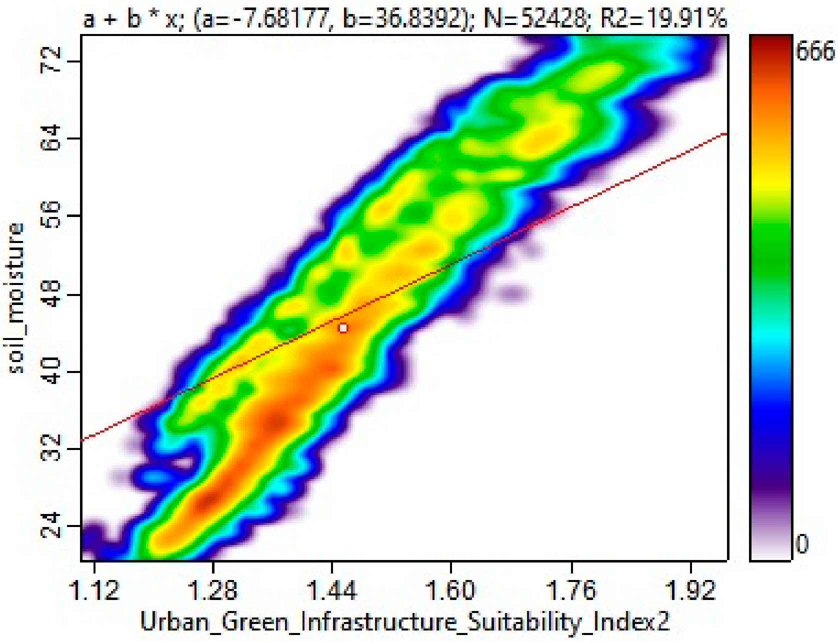

Figure 5. Relationship between UGI Suitability Index and Soil Moisture.

4.2. Relationship Between UGI Suitability Index and Land Surface Temperature (LST)

The relationship between LST and the UGI Suitability Index was analyzed using regression analysis (Figure 6). The regression equation $y = 0.684097 - 0.0328813x$ indicates a slight negative correlation, implying that an increase in the suitability index is associated with a marginal decrease in surface temperature. The R^2 value of 23.12% shows that 23.12% of the surface temperature variability can be attributed to changes in UGI suitability. This finding aligns with urban heat island mitigation strategies, where GI helps reduce local surface temperatures. Despite the moderate R^2, the observed relationship validates the role of UGI in surface temperature regulation, while also acknowledging that additional environmental and anthropogenic factors should be considered to enhance predictive accuracy. The regression analysis confirms that UGI suitability has a meaningful impact on both parameters, even though the moderate R^2 values suggest a need for more comprehensive modeling. These results highlight the importance of integrating UGI planning in sustainable urban development to enhance environmental resilience, particularly in mitigating temperature increases and improving soil moisture retention.

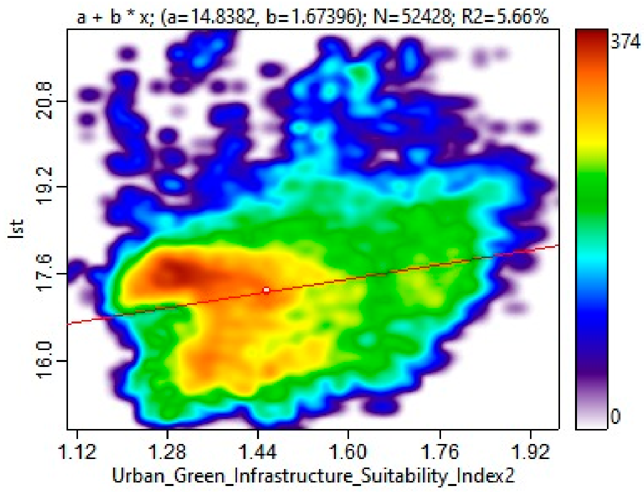

Figure 6. Relationship between UGI Suitability Index and LST.

4.3. Relationship Between UGI Suitability Index and Precipitation

The relationship between precipitation and the UGI Suitability Index in shown in Figure 7. This relationship reveals how GI suitability influences rainfall distribution in an urban environment. The color scale indicates the density of data points, with warmer colors (orange and red) reflecting higher frequencies of values. The regression line is described by the equation: $y = 1.89442 - 0.139229x$ revealed a negative linear relationship between these two variables. As the UGI suitability index increases, there is a slight decline in precipitation values. The coefficient of determination (R^2) is 11.54%, suggesting that only 11.54% of the variation in precipitation is explained by changes in the UGI suitability index. This low R^2 value implies that while there may be some association, the predictive capacity of the model for precipitation based solely on the UGI suitability index is limited, and other atmospheric, geographic, and climatic factors significantly influence rainfall patterns. In terms of validation, the negative relationship observed may highlight the spatial distribution dynamics of precipitation in urban regions influenced by green infrastructure planning. However, due to the minimal explanatory power of the regression model, further analysis incorporating additional meteorological and hydrological variables would be necessary to enhance model accuracy. Overall, this graph supports the exploration of green infrastructure impacts on precipitation variability while underlining the complexity of rainfall processes that require multi-factorial analysis.

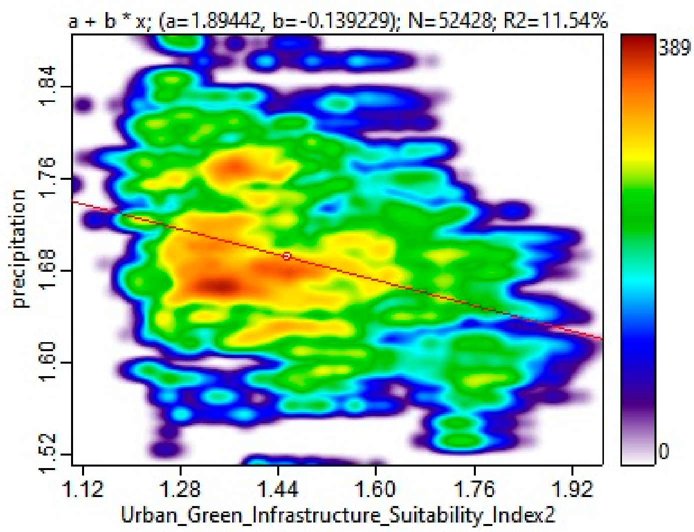

Figure 7. Graph showing the relation between UGI Suitability Index and Precipitation (R^2 = 11.54%).

4.4. Relationship Between UGI Suitability Index and Air Temperature

The relationship between air temperature and the UGI Suitability Index is shown in Figure 8. The warmer colors indicate higher concentrations of values. The regression equation demonstrates a negative linear relationship between these two variables, which suggests that as the UGI Suitability Index increases, temperature tends to decrease slightly.

$$\mathbf{y = 0.684 - 0.0328x}$$

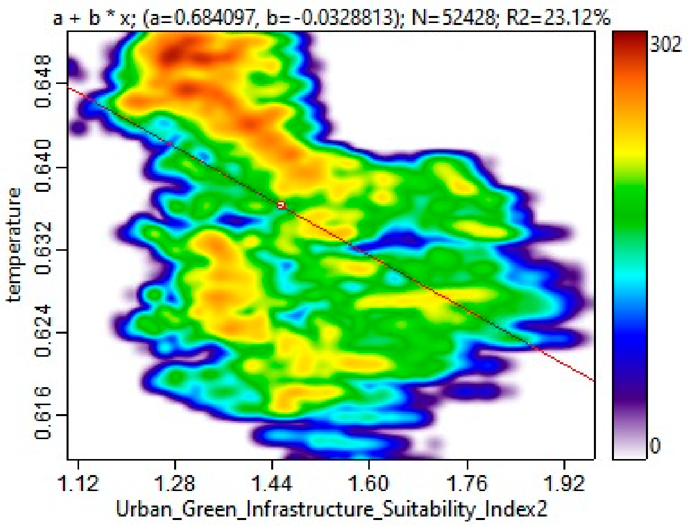

Figure 8. Graph showing the relation between UGI Suitability Index and Air Temperature (R^2 = 23.12%).

The R^2 calculated is 23.12%, indicating that 23.12% of the temperature variation can be explained by the changes in UGI suitability. This moderate R^2 value supports the idea that UGI plays a role in reducing temperatures, likely due to increased vegetation cover mitigating the urban heat island effect. While the relationship is evident, the moderate R^2 also implies that other factors, such as land cover types, urban morphology, and local climatic conditions, significantly influence temperature dynamics. This graph validates the impact of green infrastructure suitability on temperature regulation, reinforcing the importance of green spaces in sustainable urban planning for climate resilience.

4.5. Relationship Between the UGI Suitability Index and the Water Proximity Score

The relationship between the UGI Suitability Index and the water proximity score is illustrated in Figure 9. The regression analysis reveals a weak negative linear relationship (R^2 = 0.33%), indicating that only 0.33% of the variability in water proximity scores can be explained by the UGI suitability index. This minimal correlation suggests that proximity to water bodies has limited influence on GI suitability in the semi-arid urban context of the study region, where water scarcity and uneven distribution of water resources dominate the hydrological landscape.

The negligible R^2 value highlights that while water bodies are ecologically valuable, their spatial distribution in Jaipur does not align strongly with areas deemed suitable for GI. This contrasts with studies in regions, where water proximity often plays a central role in GI planning. Furthermore, in semi-arid cities like Jaipur, natural water bodies are sparse, and existing ones (e.g., seasonal lakes, and canals) are often fragmented or degraded. This reduces their impact on GI suitability compared to other factors. It is important to mention here that the water proximity score was derived using a 30 m buffer analysis, which does not fully capture the hydrological complexity of urban areas like groundwater availability or artificial water systems (e.g., rainwater harvesting structures) were not included in the model.

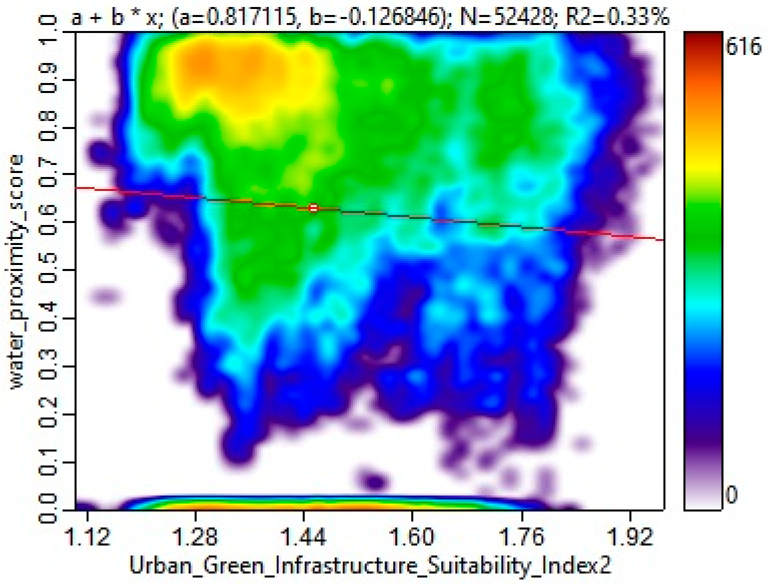

Figure 9. Graph showing the relation between UGI Suitability Index and Water Proximity Score.

4.6. Implications of UGI Suitability in Light of Recent Research

The spatial analysis of UGI suitability in Jaipur district reveals critical insights into the interplay of environmental, climatic, and socio-economic factors shaping green space potential. Using a geospatial MCDA framework, this study integrates indicators such as LST, soil moisture, precipitation, slope, and proximity to water bodies to identify priority zones for UGI interventions. The findings highlight stark contrasts between high-suitability zones (e.g., Jamwa Ramgarh, Amer) and low-suitability regions (e.g., Phagi, Chaksu), driven by microclimatic conditions, terrain complexity, and water availability. This study advances UGI planning in semi-arid cities which remain understudied in general. By employing the Entropy Weighting Method, the model objectively prioritizes factors based on their intrinsic variability, reducing subjectivity common in expert-driven approaches. For instance, LST and soil moisture emerged as the most influential factors, reflecting their critical roles in semi-arid vegetation survival; a finding consistent with studies carried out in other semi-arid regions around the globe, where water scarcity and heat stress dominate GI challenges.

Furthermore, the integration of high-resolution remote sensing datasets like MODIS, CHIRPS, WorldCover LULC, and TerraClimate addresses the key limitations introduced by data constraints in semi-arid zones. Moreover, region-specific dominance of factors was identified and analyzed in the current study like proximity to water bodies showed minimal influence in Jaipur. This contrasts with the studies carried over the regions where the factor proximity to water bodies is a dominant GI driver. This discrepancy highlights the need for regionally tailored models in semi-arid cities, where engineered water systems (e.g., rainwater harvesting) often outweigh natural water bodies. Pertinently, the practical implications for urban planning involve the expansion of urban forests and wetland parks in Jamwa Ramgarh and Amer areas of the study region as these areas are designated as high suitability zones characterized by gentle to moderate slopes and the existing vegetation (NDWI > 0.6). Similarly, in low-suitability zones, namely Phagi and Chaksu, implementation of adaptive strategies like the plantation of drought-tolerant species, and construction of artificial recharge systems can prove extremely beneficial for the establishment of GI in the study region. Additionally, targeting zones which have high LST with cool roofs and green walls can reduce surface temperatures by a few degrees [83,84].

These findings align with the Jaipur Master Plan 2025, which emphasizes the development of urban green corridors and sustainable water management systems. Incorporating UGI interventions like green roofs, rainwater harvesting systems, and community parks into ongoing projects would enhance ecological resilience as well as support socio-economic well-being by creating recreational spaces and reducing urban heat stress. The findings also highlight the importance of multi-scale UGI implementation, from city-wide planning to neighborhood-level interventions. For example, while high-suitability zones like Jamwa Ramgarh may support large-scale green corridors, low-suitability zones like Phagi and Chaksu could benefit from smaller-scale initiatives such as community rain gardens and micro green spaces. Such multi-scale strategies ensure that UGI interventions are adaptable to varying spatial, environmental, and social contexts. Moreover, UGI development has the potential to yield significant public health benefits by improving air quality, reducing heat stress, and promoting physical and mental well-being. Incorporating health-focused metrics into UGI planning could strengthen its role in enhancing urban livability. For example, prioritizing areas with high population densities for green interventions would maximize these co-benefits, particularly in vulnerable communities.

4.7. Validation with Comparative Analysis

To validate the UGI suitability model, results were compared with NDVI-based vegetation analysis conducted in this study as well as findings from prior research on urban green infrastructure (UGI) planning in semi-arid regions. The NDVI trends derived from MODIS datasets confirm that areas identified as highly suitable for UGI, such as Jamwa Ramgarh, Amer, and Jaipur City, also exhibit higher NDVI values (>0.5), indicating denser vegetation cover. The alignment between modeled suitability scores and actual vegetation distribution underscores the robustness of the entropy-weighted MCDA approach in prioritizing green infrastructure interventions. Additionally, NDVI change analysis from 2000 to 2020 indicates an 18% decline in vegetation cover across Jaipur, with the most pronounced reductions observed in low-suitability areas such as Phagi and Chaksu, where land surface temperatures remain high and precipitation levels are low. This agreement between NDVI trends and modeled suitability scores supports the sensitivity of the model to ongoing environmental degradation in the study region.

The results of this study align with and extend prior research on urban heat island effects, LST trends, and the role of UGI in Jaipur. Several studies have analyzed the interplay between LULC transitions, urban expansion, and thermal variations in Jaipur, emphasizing the intensification of heat stress due to vegetation loss and built-up proliferation [85]. Khajuria and Kaushik (2025) [86] highlighted that between 1991 and 2022, Jaipur experienced a significant increase in built-up land by 52.8%, leading to an average rise in LST of 5.9 °C. Their study demonstrated that the highest LST values were recorded in barren and sparsely vegetated areas, while vegetated patches exhibited lower temperatures, reinforcing the cooling effect of UGI. The findings of the present study corroborate these results, showing a strong negative correlation between UGI suitability scores and LST values. Similarly, Jalan and Sharma (2014) [35] documented that Jaipur's built-up expansion over the last decade resulted in a summer temperature increase of approximately 2.99 °C, with suburban areas witnessing LST rises between 2 °C and 4 °C. Their research noted that the decline in dense vegetation was a key driver of thermal intensification, a pattern consistent with the present findings. However, while their study relied on conventional NDVI-based assessments, this research incorporates multiple biophysical and socio-environmental indicators, providing a more comprehensive evaluation of UGI potential. Gupta et al. (2020) [87] further underscored the role of impervious surface expansion in amplifying urban heat effects, demonstrating that Jaipur's urban growth between 2008 and 2011 led to significant LST increases across all LULC classes. They reported an average temperature rise of 2.6 °C in winter and 1.47 °C in summer, with impervious surface area (ISA) growth correlating strongly with LST escalation. The present study reinforces these observations by mapping LST trends over a longer temporal scale (1991–2022) and linking them explicitly with UGI interventions for potential mitigation. Lastly, studies have emphasized the importance of urban cooling strategies, such as water bodies, reflective surfaces, and strategic vegetation placement, in mitigating heat stress. The work of Chandra et al., 2022 [88] noted that Jaipur's historical water management systems, including stepwells and artificial lakes, played a critical role in regulating microclimates, advocating for their restoration as a modern climate adaptation measure. The present study builds upon this perspective by integrating these features into a spatially optimized UGI planning framework.

4.8. Limitations and Future Research

Despite the robust methodology employed to provide detailed recommendations for GI implementation in Jaipur, this study has certain limitations. One of the key limitations is the reliance on satellite-derived datasets, which, while offering broad spatial coverage, lack the granularity required for fine-scale or ward-level planning. The spatial resolution constraints of remotely sensed datasets such as MODIS LST (1 km), CHIRPS precipitation (~5 km), and TerraClimate soil moisture (~4 km) introduce uncertainties in local-scale analyses, potentially affecting the accuracy of suitability predictions in dense urban environments. Additionally, the model assumes linear interactions between variables, which may oversimplify the complex, dynamic ecological processes governing GI suitability. Future research could integrate machine learning algorithms, such as Random Forest or Gradient Boosting models, to capture potential non-linear relationships among urban environmental variables, as demonstrated in recent UGI studies in Bengaluru and other rapidly urbanizing cities. Another significant limitation is the lack of comprehensive ground-based validation. While the study incorporates remote sensing indices such as NDVI and LST to infer vegetation health and urban heat island effects, direct field-based measurements of vegetation cover, soil moisture, and thermal properties were not conducted. Ground-truthing using in-situ soil moisture sensors, temperature loggers, and vegetation health assessments would provide critical validation for the remote sensing-derived indicators and enhance the robustness of UGI suitability modeling. This approach has been successfully employed in other studies of urban ecological resilience and should be considered for future research. Further, the model does not explicitly account for social and economic variables such as population density, household income levels, and public access to green spaces. These factors play a crucial role in shaping urban sustainability and equity in UGI planning. Additionally, the inclusion of detailed social variables such as population density, household income levels, and public access to green spaces could provide a more comprehensive understanding of the socio-environmental dynamics of UGI planning. These variables would enable targeted interventions that address both environmental sustainability and equity, ensuring that vulnerable populations benefit from green infrastructure development. Future studies should incorporate high-resolution demographic and socio-economic datasets to ensure that GI interventions not only address environmental priorities but also contribute to urban livability and social inclusivity. Despite these limitations, this study provides a robust geospatial framework for UGI suitability assessment in Jaipur. The methodology is scalable and can be applied to other semi-arid cities facing similar urbanization challenges. Future research directions should focus on refining model accuracy through higher-resolution datasets, incorporating socio-economic considerations, and integrating real-time sensor networks for in-depth environmental validation.

5. Conclusions

This study evaluates the feasibility of UGI implementation in the Jaipur district, integrating environmental and spatial dimensions to support sustainable urban planning. The findings highlight that areas with high vegetation cover, moderate climatic conditions, and proximity to water bodies exhibit the highest suitability for UGI interventions. The study demonstrates that integrating multiple environmental variables, such as LST, soil moisture, and LULC, within an MCDA framework provides an effective strategy for identifying priority areas for UGI development. The results indicate that high-suitability regions such as Jamwa Ramgarh, Amer, and Jaipur City should be prioritized for large-scale UGI interventions, including urban forests, riparian corridors, and climate-resilient parks. Conversely, areas with lower suitability, such as Phagi and Chaksu, require adaptive greening strategies, such as the use of drought-tolerant vegetation and artificial water recharge systems. These findings provide a roadmap for targeted GI planning, ensuring that interventions align with the specific environmental constraints and opportunities of each sub-region. From a methodological perspective, the entropy-based weighting approach employed in this study offers an objective mechanism for determining the relative importance of environmental factors, reducing the subjectivity often associated with expert-based weighting methods. This model is scalable and can be adapted to other semi-arid cities experiencing rapid urbanization and climate stress. By integrating high-resolution geospatial datasets and advanced analytical techniques, urban planners can apply this framework to optimize green infrastructure development in diverse urban contexts. The study also underscores key policy implications. In alignment with national policies such as the National Urban Policy Framework (2018) and the National Mission for Sustainable Habitat (NAPCC), these findings reinforce the critical role of GI in enhancing urban resilience. At the global level, this research supports UN Sustainable Development Goal (SDG) 11, which promotes sustainable cities and communities. Policymakers should incorporate these insights into city master plans, prioritizing nature-based solutions for climate adaptation, biodiversity conservation, and public well-being. While this study provides a robust framework for UGI suitability assessment, certain limitations remain. The reliance on satellite-based datasets necessitates further validation through ground-based measurements to improve local accuracy. Additionally, incorporating socio-economic variables, such as population density and accessibility to green spaces, would enhance the social inclusivity of GI planning. Future research should explore machine learning-based approaches to refine suitability assessments and expand real-time monitoring capabilities for dynamic UGI planning. This study contributes to a growing body of research on sustainable city development. Its findings and methodological approach offer a replicable framework that can be tailored to the unique environmental and socio-economic characteristics of other urban regions, particularly those in arid and semi-arid climates.

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