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Urban Heat Islands in a Warming World: Remote Sensing Insights and Mitigation Frameworks

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ABSTRACT

Urban Heat Islands (UHI) are a significant environmental challenge in rapidly urbanizing cities, exacerbated by climate change and urbanization. The UHI effect causes the high temperatures of urban regions, causing high energy consumption, health hazards, and degradation of the environment. Remote sensing technology has found it invaluable to monitor and control UHI because it has been used to give spatially continuous data of land surface temperatures, vegetation, and urban morphology. This review paper summarizes the recent innovations in remote sensing techniques of UHI monitoring, empirical evidence of the UHI trends in various climates, and mitigation and adaptation strategies based on remote sensing. Also, it determines the gaps in the existing research, namely the data integration, mixed-pixel issues, and the socio-political barriers, and points out the emerging technologies that suggest potential solutions. The article ends by suggesting an all-encompassing model of urban heat resilience comprising remote sensing, urban planning, and fair policy formulation in tackling the increasing UHI issues amid global warming.

Keywords: Urban Heat Island; Remote Sensing; Mitigation Strategies; Urban Resilience; Climate Change

1. Introduction

Urban Heat Island (UHIs) is defined as an increase in heat concentration in urban areas, whereby the concentration of temperatures in urban areas is considerably higher than in rural or natural environments. This phenomenon is associated with many factors, such as the concentration of heat-absorbing substances, such as concrete, asphalt, less vegetation, and anthropogenic heat sources in the form of buildings, vehicles, and industries. Increasingly popular with the growth in size and population of cities, and worsened by climate change, which has intensified global warming, UHIs are causing numerous environmental, social, and health problems. Among these challenges, higher energy demand, air quality, and health risks in the form of heat, especially among the vulnerable population, are some of the factors that demonstrate the urgency of mitigating and adapting to the impacts of UHI [1–3].

The increasing world temperatures as a result of climate change exacerbate the UHI effect, and hence it is an urgent planning and resilience consideration in urban planning. The recent research indicates that, in many of the largest cities of the world, particularly tropical and temperate cities, urban surface temperatures tend to be much higher than in rural areas; in some cases, the difference may be as much as 10 °C on hot afternoon days. These increased temperatures form a feedback mechanism because the higher the urban temperature, the more energy is required to cool the area, which causes more heat emissions and so on. This causes an urban thermal trap in certain areas where the heat produced by people, in combination with poor urban planning, exacerbates the overall quality of life [4].

Remote sensing has become a central tool for understanding and managing UHIs because it can provide consistent, spatially continuous observations of land surface temperature and land cover over entire metropolitan regions and through time [5]. Thermal infrared imagery from platforms such as Landsat, MODIS, and newer missions allows the derivation of surface UHI patterns at scales ranging from the city region down to individual neighborhoods, while high-resolution satellites and unmanned aerial vehicles (UAVs) reveal fine-scale thermal contrasts between streets, courtyards, roofs, and small green patches. When these thermal datasets are combined with multispectral indices of vegetation, detailed land-use and land-cover maps, digital surface models, and socio-demographic information in a GIS environment, it becomes possible to diagnose the relative contribution of imperviousness, building form, and vegetation structure to observed heat patterns, and to evaluate the performance of mitigation measures such as cool roofs, reflective pavements, blue infrastructure, and urban greening [5,6].

At the same time, there are important conceptual and practical limitations in how UHIs are currently assessed and managed. Most remote-sensing-based studies focus on surface temperature, yet human exposure is governed largely by canopy-layer and indoor thermal conditions, which are shaped by shading, ventilation, humidity, and building performance. The diversity of sensors, retrieval algorithms, and operational definitions of "urban" and "rural" complicates cross-study comparison and the aggregation of evidence into robust design rules. In addition, pixel-level biophysical indicators frequently lack a connection to the planning tools that function at parcel, neighborhood, and city-regional scales. A lot of current models are fundamentally unchanging in that they explain the current trends in UHI without integrating future climate conditions, future urban development, or changing social vulnerability [1,7].

In its larger context, urban green spaces (UGS) occupy a certain niche in defining the urban thermal environments. The urban forest is designed to cool the city by shading, evapotranspiration, and higher surface permeability, as well as local alteration of the wind pattern, parks, street trees, urban forests, river corridors, green roofs, and small residential green patches. Regular studies of remote sensing have always indicated a significant negative correlation between vegetation indices (NDVI) and surface temperature: green pixels are cooler, whereas green neighborhoods have lower-intensity surface UHI. However, the cooling effects of UGS cannot be captured solely by their total area. The spatial arrangement, connectivity, and internal composition of green spaces strongly influence both the magnitude of cooling and the distance over which that cooling is felt [8].

Recent work in rapidly developing cities, including studies in Ardabil, Iran, has used graph-based metrics and landscape indices to document how urbanization from the early 2000s onwards has fragmented and reconfigured green space networks, with measurable implications for local thermal regulation. These analyses show that the loss of connec-

tivity and increased fragmentation of green patches weaken citywide cooling, whereas continuous or well-linked green corridors allow cool air and evapotranspiration effects to penetrate deeper into dense districts. Similar trends are observed at the international level: in most European cities, relatively small parks and networks of street-trees are linked to statistically significant decreases in surface temperatures at the neighborhood scale; in East Asian megacities urban forests and green belts adjacent to rivers are used to create long-run cooling transects, which counter extreme temperature situations in high-rise residential areas; in North American and Australian cities, studies have indicated that biophysical cooling by canopy cover as well as widespread inequities in the distribution of trees, with underprivileged communities experiencing lower canopy cover and higher observed land This evidence taken altogether presupposes a subtle correlation between UHIs and UGS where not only the amount of green space is important, but also where it is, how it is linked and how it is accessed by people are also important[9].

Remotely sensed data offers a natural connection between thermal data and the spatial attributes of UGS. Through a unified examination of demand-side temperature of the land surface, vegetation indices, and a group of graphical and landscape-based measures, including patch size, edge density, connectivity, and accessibility, one can transition out of the naive belief that the greener the area, the cooler the city. Instead, one can derive spatially explicit insights into which configurations of green space (for example, larger but fewer parks versus smaller but well-distributed patches linked by tree-lined streets) deliver the greatest cooling per unit of land or per vulnerable resident. This opens the door to designing green networks and mixed green–blue–gray interventions that are tailored to local morphology, climate, and social context[10].

The rapid expansion of the literature on UHI, remote sensing, and urban green spaces has not yet been matched by a structured, climate-aware framework that connects empirical thermal evidence to multi-scalar mitigation and adaptation planning. Methodological studies on Land Surface Temperature (LST) retrieval and UHI detection are often disconnected from work on practical planning instruments; case studies demonstrating cooling effects of greening, blue infrastructure, and high-albedo materials are rarely synthesized into transferable rules that work across different climates and city types; and many assessments remain anchored in present conditions, with limited attention to how UHIs and UGS functions will evolve under future warming and continued urban expansion. This review responds to these shortcomings by offering a remote-sensing-centered, spatially explicit, and climate-sensitive synthesis of UHI dynamics and mitigation strategies, with particular emphasis on the role and configuration of urban green spaces[5].

Although remote sensing as a method to examine Urban Heat Islands has been extensively applied to study the issue, and many current methods use Local Climate Zone (LCZ) classifications to enable climate-sensitive planning, most of the current methodologies are methodologically isolated or case-specific. The field of LCZ-based research is more concerned with the description of thermal differences between urban shapes, and RS-based UHI tools tend to highlight mapping and trend identification without a clear way of how to go between diagnosis and intervention. Conversely, the framework suggested in this review can contribute to the state of knowledge since it brings the concept of multi-scale thermal indicators, urban green space (UGS) structure, climate context, and decision logic into a single and operational workflow[5,11].

Three aspects make the framework original. To start with, it ties descriptive UHI diagnosis with action plan measures with dynamic RS-derived indicators (LST, SUHI intensity, NDVI, LCZ classes) and intervention-oriented measures (green-space accessibility, connectivity, and component cooling expected performance). Second, it brings climate-zone-specific parameterization, which enables thresholds and priorities of mitigation to be related across urban settings of humid subtropical, arid, temperate, and tropical environments, as opposed to presuming universal applicability of fixed indicators. Third, the framework very clearly includes the social vulnerability and equity factors as well as biophysical measures, meaning that it allows prioritization of mitigation in neighborhoods that are both highly thermally exposed and have low adaptive capacity. Combined, these aspects take LCZ or RS tools a step further by offering a transferable, reproducible, and policy-relevant decision-support framework instead of a more classification-based method of mapping[12].

There are four objectives of the article. It first brings together the fundamental elements of remote sensing to UHI

analysis and demonstrates that thermal, land-cover, morphological, and UGS measures can be calculated and analyzed simultaneously. Second, it incorporates empirical evidence about UHI trends in different climates, urban sizes, and forms, with particular consideration given to the role of the quantity, layout, and connectivity of green spaces in mediating the surface and canopy-layer heat. Third, it critically assesses mitigation and adaptation strategies-green, blue, and reflective- and how remote sensing and landscape measures could be used to inform the prioritization, space design, and assessment of the measures[13]. Last but not least, it points to the main gaps in technical, conceptual, and governance and suggests future research directions, which leverage emerging technologies, including higher-resolution sensors, machine learning, dense sensor networks, and digital twins, and bring closer together UHI management and wider climate-resilience and equity agendas.

The main invention of this manuscript is the manner in which it systematizes and operationalizes these elements. Instead of just providing a graphical overview of known elements, it suggests an integrated UHI resilience framework where remotely sensed land surface temperature and vegetation indexes are directly coupled with landscape and connectivity measures of urban green spaces, and are further linked to tangible planning levers at different spatial scales, such as the pixel or parcel to the neighborhood and city region. The model is climate-conscious, integrating UHI and UGS in credible future climate and urbanization conditions, and equity-oriented, by the systematic combination of thermal pointers with socio-demographic susceptibility. By doing so, the article provides not only an integrative summary but a generalizable, formal approach through which remote sensing and spatial measures can be used to inform the planning, implementation, and assessment of the urban heat mitigation strategies in any of the cities in the world.

2. Methodology

The review takes the form of a focused synthesis rather than a fully systematic meta-analysis. It is intended to be a critical review of representative and data-intensive literature that explicitly substantiates a correlation between thermal indicators of remote sensing and urban form, green cover, and mitigation measures, and is not intended to provide an exhaustive listing of UHI-related publications[14,15]. The method was intended to be clear and reproducible regarding search strategy, selection, and synthesis, and to be able to accommodate the interdisciplinary nature of the topic, being remote sensing, urban climatology, landscape ecology, planning, and environmental justice[1].

2.1. Review Design

The following three questions informed the review: how urban heat islands have been characterized and monitored through remote sensing; how urban green space configuration and connectivity (using spatial data) affect UHI patterns; and how indicators created using remote sensing have been incorporated in mitigation and adaptation at various spatial and governance scales. The scope was defined to prioritize empirical and methodological work that relies on satellite, airborne, or UAV remote sensing for land surface temperature and land-cover characterization, and that either quantifies relationships between UHI and green spaces or uses such information to inform planning and policy[16].

2.2. Data Sources and Search Strategy

Literature searches were performed in Web of Science Core Collection, Scopus, ScienceDirect, IEEE Xplore, and Google Scholar. These databases were selected to provide broad coverage of peer-reviewed work in environmental science, geoinformation, engineering, and urban studies. The core search window spanned January 2000 to June 2024, reflecting the period in which thermal remote sensing for UHI analysis and landscape-metric approaches for urban green spaces became widely available and methodologically mature. Influential earlier works were added through backward and forward citation tracking[17].

Search strings combined terms related to urban heat and climate (for example "urban heat island", "surface urban heat island", "urban thermal environment"), remote sensing and geospatial analysis (for example "remote sensing", "satellite", "thermal infrared", "land surface temperature", "LST", "MODIS", "Landsat", "Sentinel", "UAV", and "GIS"), and green infrastructure and landscape structure (for example "urban green space", "green infrastructure", "urban forest", "park", "street trees", "landscape metrics", "connectivity", "graph-based"). Boolean operators were used to link these

groups, and query syntax was adapted to the requirements of each database. No geographical filters were applied so as to include case studies from a wide range of climatic zones and urbanization contexts[18].

2.3. Inclusion and Exclusion Criteria

The initial search results were screened against predefined inclusion and exclusion criteria. The inclusion criteria were based on the fact that (i) they used satellite or airborne remote sensing data, (ii) they measured the UHI-related measures in the form of LST or SUHI intensity, and (iii) they had explicitly explored the relationship with vegetation, land cover, urban morphology, or mitigation interventions. The emphasis was placed on multi-year analysis, research that has understandable methodological explanations, and the results of the study that provided quantitative indicators that could be compared across cities[19].

The exclusion criteria were studies that were based on point-based measurements of air temperature without spatial analysis, were not based on methodological transparency, and studies that were not based on building-scaled simulations without the validation of the RS. This discriminatory and yet open approach assures depth, analytical and comparability, as well as an explicit rationale of inclusion and exclusion[19].

2.4. Screening, Data Extraction, and Synthesis

After removal of duplicates, titles, and abstracts were screened to discard records that clearly did not meet the inclusion criteria. The remaining articles underwent full-text review. During this stage, reference lists and citation networks of key papers were examined to identify additional relevant studies that might have been missed in the database queries.

For each included study, information was extracted on the study location and climate, type and size of the urban system, remote sensing data used (platform, sensor, spatial and temporal resolution, years of observation), UHI indicators (such as land surface temperature and surface UHI intensity), metrics describing vegetation and urban green spaces (for example Normalized Difference Vegetation Index (NDVI), canopy cover, proportion of green space, and landscape or graph-based connectivity metrics), and any mitigation or adaptation measures investigated. The role of remote sensing in diagnosis, design, and evaluation of interventions was also recorded.

Given the diversity of sensors, spatial scales, definitions, and analytical methods, a formal quantitative meta-analysis was not attempted. Instead, a qualitative thematic synthesis was conducted. Studies were grouped into methodological contributions, empirical case studies, and planning or framework-oriented work. Within and across these groups, results were compared with particular attention to how green-space amount, configuration, and connectivity modulate UHI patterns, and how remote-sensing products are translated into actionable planning guidance. Apparent discrepancies among studies were interpreted in light of climate, urban morphology, data resolution, and analytical choices[5].

2.5. Methodological Limitations

The review methodology has several limitations that should be acknowledged. Restricting the analysis to English-language, peer-reviewed literature likely resulted in an underrepresentation of work published in other languages and in local technical reports, particularly from rapidly urbanizing regions. The heterogeneity of remote sensing platforms, retrieval algorithms, spatial resolutions, and green-space definitions limited the possibility of harmonizing indicators across all studies and precluded a unified effect-size analysis. In addition, the reliance on published descriptions means that some methods could not be fully evaluated where reporting was incomplete. Nevertheless, the combination of multi-database searching, explicit selection criteria, and structured extraction provides a robust basis for the integrative assessment of remote sensing, urban green spaces, and UHI mitigation frameworks presented in the following sections[20,21].

3. Remote Sensing Foundations for UHI Monitoring

The emergence of remote sensing (RS) technology has also changed the way Urban Heat Island (UHI) is monitored, so that detailed observations of the thermal behavior of urban landscapes can be made through space and time. Remote sensing is one of the methods that helps to monitor urban changes in heat continuously, as it offers the necessary infor-

mation to learn about the dynamics of UHI in urban areas around the globe. In this part, we discuss the principles and technology of remote sensing basics to identify and monitor the UHI effect, the methodology involved in retrieving temperatures, and the limitations and difficulties of these technologies [5].

3.1. Evolution of Remote Sensing Platforms & Data Sources

The ability of remote sensing to track the UHI effect depends on a number of platforms and sensors, which have distinct strengths in spatial and temporal resolution. The initial types of remote sensors, including the Advanced Very High-Resolution Radiometer (AVHRR) on the NOAA satellites, offered low-resolution data that only detected broad trends of UHI in large urban regions. They could be useful in the excessively coarse way in which these early sensors could be used to identify the large-scale heat differences between urban and rural areas, but not the finer-scale heterogeneity of urban areas. Through the improvement of increasing-resolution satellite sensors, including the Landsat series and, more recently, the Sentinel satellites of the European Space Agency, the magnitude of observing the thermal conditions of urban areas on the local and regional level has increased significantly with time [1,18].

Examples of such satellites are Landsat satellites, which have traditionally offered thermal infrared (TIR) data, which are essential in estimating land surface temperature (LST) in urban regions. These satellites are released with a spatial resolution of 30 m (Landsat 8), all the way to 60 m (Landsat predecessors), and allow detailed mapping of UHI. Sentinel-2 satellites, in turn, offer multi-spectral data with a 10-m spatial resolution, which can be combined to obtain thermal data, land-use/land-cover (LULC) data, vegetation indices, and impervious surface data. With this mix, the researchers can come up with a more holistic picture of what causes UHI effects [22].

Even greater spatial resolutions to a few centimeters are now being offered by next-generation sensors and platforms, including UAVs (Unmanned Aerial Vehicles), and are invaluable in hyper-localized monitoring of UHI in the urban areas of particular interest. The range of operation and flight duration pose a constraint on UAVs, but when it comes to small-scale research, the accuracy of UAVs is high, and they can be used in conjunction with satellite-collected data in fine-grained urban studies. Besides satellite and UAV platforms, airborne sensors and ground-based monitoring systems are also being incorporated in UHI research. Such systems offer more validation and real-time data, and offer flexibility in specialized studies, which address dynamic or complex urban environments [23,24].

3.2. Methodological Approaches for UHI Monitoring

The core of UHI monitoring is the possibility of a correct description of land surface temperature (LST) that can be the main proxy for assessing the intensity of UHI. Remote sensing data is normally used to retrieve LST using thermal infrared (TIR) bands. Many algorithms have been created to extract LST using these thermal bands; each has its own merits, demerits, and assumptions. The Mono-Window Algorithm (MWA) is one of the most common algorithms used in the extraction of LST using thermal infrared images. The MWA exploits the correlation between the brightness temperature (the temperature as read on the thermal sensor) and the surface temperature and corrects the effects of the atmosphere on the basis of a single thermal band. This algorithm is not very complex and has been used in studies of urban heat islands to a large extent. The Split-Window Algorithm (SWA) is another technique that is commonly utilized and is based on the concept of utilizing two thermal bands to enhance the precision of LST estimates by reducing atmospheric interference, e.g., the amount of water vapor that will alter temperature measurements. The two techniques have been effectively implemented in optical sensors such as Landsat and MODIS that offer useful LST information over time [5,25].

Nevertheless, the difficulty with applying the use of thermal infrared data to monitor UHI is not isolated to the algorithms but is also associated with the change in the land surface emissivity. Various materials used on the surface, like concrete, asphalt, vegetation, and water, have varying capacities to release thermal radiation. Such anisotropic action may lead to big errors in the computation of LST. Correction of emissivity is then important in retrieving the correct temperature, especially in mixed-surface landscapes in a heterogeneous urban environment. To explain these variations, researchers have come up with more advanced models for emissivity correction, which include other datasets like land-

use/land-cover, which are used to explain these variations [7].

UHI intensity is normally determined as the difference between the LST of urban areas and the adjacent rural areas (or a rural background temperature) once LST is retrieved. UHI intensity mapping entails hotspots that are characterized by high LSTs relative to the rural backdrop, which may reflect places with high heat confinement caused by urban structures. Such maps offer a convenient source to be used by urban planners and policy makers to know areas that need an intervention, like the most vulnerable to heat stress areas [5,26,27]. To facilitate method selection and comparison across sensors and retrieval approaches, the principal remote-sensing platforms, LST retrieval methods, and practical trade-offs are presented in **Table 1**.

Table 1. Summary of remote sensing methods for UHI monitoring.

Method	Platform/Sensor	Resolution (Spatial/Temporal)	Strengths	Limitations
Mono-Window Algorithm	Landsat, MODIS	30 m (Landsat), 1 km (MODIS)	Simple, widely used, effective for large-scale monitoring	Assumes uniform atmospheric conditions
Split-Window Algorithm	MODIS, AVHRR	1 km	Reduces atmospheric interference using two thermal bands	Requires accurate atmospheric correction
UAV-based Thermal Imaging	UAVs	5–50 cm	High spatial resolution, ideal for small-scale studies	Limited temporal coverage, expensive
Thermal Infrared (TIR)	Landsat, Sentinel-2	30 m (Landsat), 10 m (Sentinel-2)	Provides high accuracy, suitable for large-area studies	Affected by mixed-pixel issues and urban complexity

3.3. Challenges, Limitations & Trade-Offs

Although the methods of remote sensing and technologies have developed, there are still a number of issues with the accurate monitoring and reduction of the UHI effect. Spatial resolution trade-off is one of the major challenges. Although satellites such as Landsat or UAVs can provide high-resolution information about the city, some urban patterns may not be represented as well in these data as in coarser-resolution data (e.g., Moderate Resolution Imaging Spectroradiometer—MODIS or Advanced Very High Resolution Radiometer—AVHRR). As such, although fine-scale data is essential in detecting localized hotspots related to UHI, it might not help track the trends of a city or region over an extended period of time. On the other hand, data of coarse resolution can have a large coverage area but will be missing fine-scale details of the urban environment. This trade-off frequently requires the data from several sources to be merged, e.g., a high-resolution satellite image to be used with the frequent time resolution of MODIS or Sentinel-2 to get to the point of spatial and time accuracy [28].

The second important issue is the validity of LST retrievals in a complicated urban setting. The cities that are characterized by a high density of buildings present unique microclimates within cities that are challenging to measure with conventional remote sensing techniques. The impact of urban canyons, the narrow and deep areas in between high-rise buildings, has the capacity to produce further temperature differences as they receive little sunlight, and the canyon traps heat. Such complexity can be mixed pixel problems, such that one pixel can have two or more highly reflective surfaces (e.g., roofs, roads) as well as vegetation or water, and this complexity makes the LST retrieval process more difficult. Another important issue is atmospheric interference. Algorithms such as MWA and SWA can alleviate some of the atmospheric effects, but they all rely on the assumption that the atmospheric conditions remain relatively fixed. The atmospheric correction models might not work in areas with large seasonal variations, like those with large seasonal rainfall or temperature inversion, and as a result, the estimates of LST would be inaccurate [29,30].

Also, remote sensing-derived LST is yet to be validated. Temperature measurements using grounds are the most precise method of measuring temperature, but have the disadvantage of spatial coverage since ground stations tend to be sparsely distributed in most cities, particularly in the Global South. Another challenge is the difference between surface and air temperature, especially at the canopy level. Remote sensing is useful in quantifying the temperature of the surface of the land, but it might not adequately quantify the temperature of heights that are of human interest (i.e., air temperature on the street level), which are more related to

human comfort. This gap in the relationship between surface and air temperature underscores the importance of merging RS with ground-based measurements to increase the suitability of UHI-based evaluations in reducing the urban heat impacts on mitigation measures [31].

Finally, combining remote sensing data with other urban data sets, which include land-use, vegetation indices, and socio-economic data, is essential but may also be complex. Every dataset is different in terms of spatial and temporal resolution, and thus, there may be a mismatch between data from dissimilar sources. One potential way to resolve these problems is the creation of data fusion methods that are able to coordinate the information from various sources to give more precise and advanced results.

The introduction of remote sensing technologies into the UHI monitoring transformed the study and comprehension of urban heat islands. The capability of tracing the changes in the temperature on large scales and the development of the sensor technology and data processing methods to enhance the precision of the UHI detection are greatly beneficial. Nonetheless, the issues associated with data resolution, atmospheric interference, mixed pixels, and the spatial-temporal mismatch between dissimilar types of data are yet to be surmounted. With the ongoing development of remote sensing technologies, the given challenges are likely to become a priority for improving the accuracy and relevance of the UHI measurements, which will eventually result in better urban planning and climate adaptation policies [1,5].

4. Empirical Insights from Remote Sensing Studies of Urban Heat Islands

The use of remote sensing has contributed to the gathering of large volumes of data on urban surfaces, which offers important information on the spatial, temporal, and long-term processes of urban heat islands. In this section, empirical data is provided based on remote sensing research on the patterns of UHI and the variation of UHIs is investigated by geographic factors, climate zones, and urban scales. It further looks at the time variability of the UHIs, such as diurnal, seasonal, and long-range changes, and notes the compounding impacts of climate change on the UHI intensification [1,18,32].

4.1. Patterns Across Geographies, Scales, and City Types

The effects of Urban Heat Islands do not occur uniformly across the city and city regions, but rather there is a great deal of variation between cities based on geographic position, scale, climate zone, and urban morphology. These spatial patterns have been determined by remote sensing studies and have been used by researchers to determine what factors lead to the intensity and distribution of UHIs.

Among the most remarkable observations is the difference in the intensity of UHI between the climate zones. Cities are also more subject to the effects of UHI in the tropical and arid regions, which are characterized by high temperatures and little cloud cover. As an example, the intense level of UHI in cities of the Middle East, e.g., Dubai or Riyadh, is partly due to the widespread use of concrete and asphalt that absorb and retain heat. On the contrary, cities located in temperate climates like those in Europe or the northern United States are rather inclined to have milder UHI impacts, but these are becoming increasingly more pronounced with climate warming. Colder winters may also increase the intensity of UHIs in these areas and, hence more use of heating systems, which further intensifies the thermal load on the city [33].

Land cover and land use have been identified in the literature of remote sensing to be important factors that determine the intensity of UHI in various areas. An example is that urban areas that are characterized by a large percentage of impervious areas (e.g., roads, buildings) have stronger heat traps because these surfaces absorb the solar radiation during the day and release it gradually at night. Conversely, urban areas that have a lot of green areas and vegetation have low levels of UHI because evapotranspiration cools the area. Through remote sensing, mapping of these land-use patterns with fine spatial resolutions is possible, and hence, a clear picture is obtained regarding how certain land-cover types contribute to local thermal environments [11].

The area and the population density of a city are also major contributors to the UHI effect. Bigger cities where people are more concentrated and urban shapes are more compact are more likely to be affected by UHI. This is due to the fact that cities are more highly built, and this provides an urban heat trap. The remotely sensed records have revealed that megacities like Shanghai, Tokyo, New York, and Mexico City have extensive UHIs, with hotspots being widespread

in central business districts and those with heavy building density. In Shanghai, daytime LSTs for 2007 (nominally 2008), 2008, and 2020 are shown in **Figure 1a**, with high temperatures concentrated in built-up local climate zones (LCZs). The central area of Shanghai was warmer than the suburbs, and from 2008 to 2020, high LST areas expanded westward, while northern Shanghai remained warmer, except for the cooler Chongming district. The nighttime LST map of Shanghai at a 90 m resolution and a violin plot for different LCZ types in 2019, presented in **Figure 1b,c**, reveal significantly higher nighttime LSTs in the city center compared to the suburbs, with the highest temperatures concentrated in LCZ G (water), LCZ E (bare rock or paved), and compact building areas. Smaller cities or less densely populated areas tend to have more spatially heterogeneous UHI distributions, in turn, with weaker but more localized heat islands [34–37].
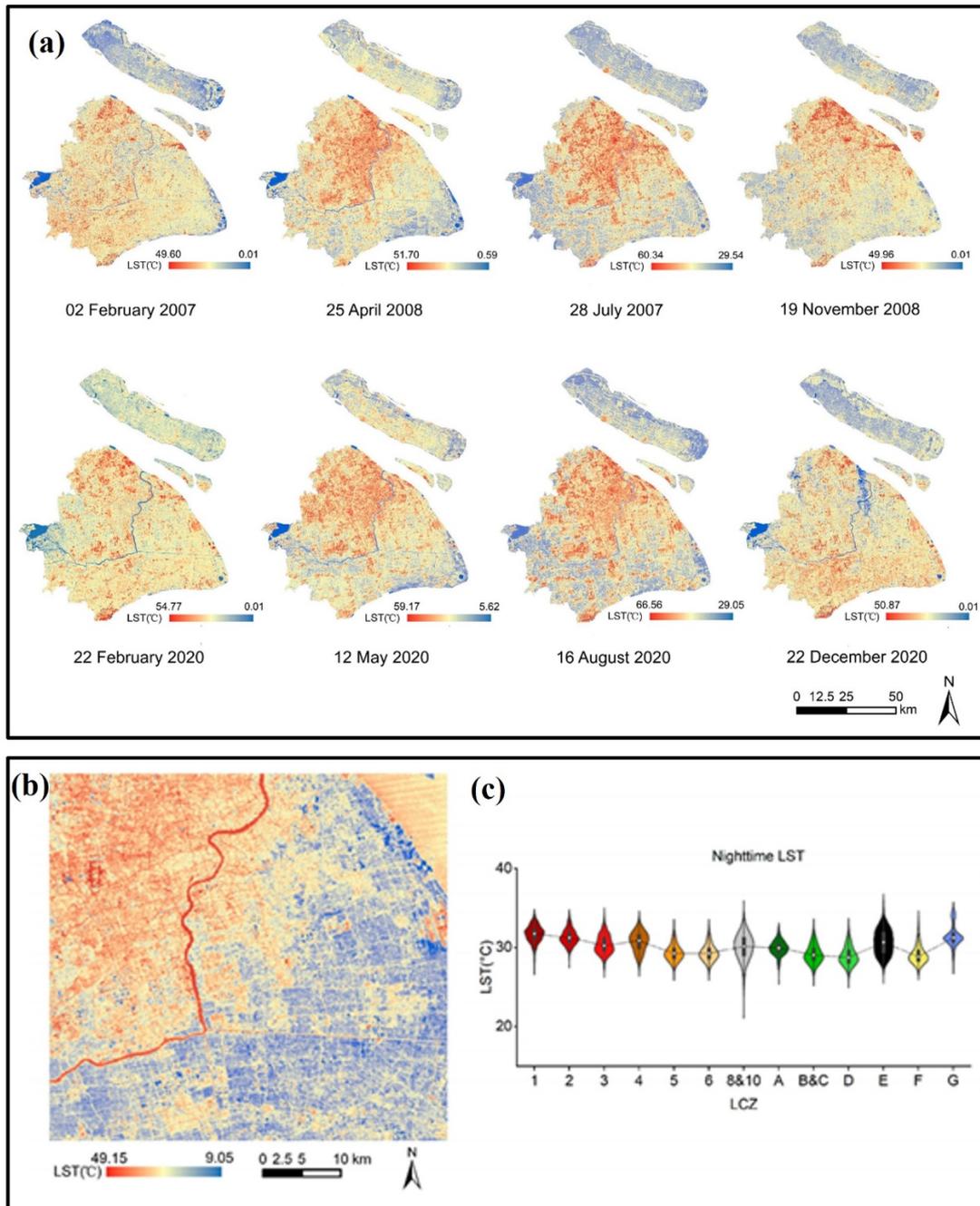

Figure 1. UHI hotspot map; LST-based spatial distribution in Shanghai city: (**a**) Daytime, (**b**) nighttime, and (**c**) Violin plot of the nighttime LSTs for each local climate zone type in 2019 [37].

In addition, the UHI effect is also affected by the vertical aspect of the urban environment, i.e., height of buildings. Skyscrapers form city canyons, which trap heat and slow down air circulation, which increases heat trapping further. The mapping of building heights and the identification of UHI hotspots in canyon regions of urban areas through remote sensing can enable urban planners to target areas that might need special mitigation efforts[38,39]. The dominant UHI drivers and representative urban contexts across major climate zones are summarized in **Table 2**.

Table 2. Key factors influencing UHI intensity across different climate zones.

Climate Zone	Key UHI Drivers	UHI Intensity	Example Cities
Tropical	High solar radiation, dense urbanization, low vegetation	High	Singapore, Jakarta
Arid/Desert	Limited vegetation, high albedo surfaces, intense sunlight	Very High	Phoenix, Riyadh
Temperate	Urban density, limited vegetation during winter	Moderate to High	New York, Berlin
Subtropical/Mediterranean	Urban morphology, seasonal variations in vegetation	Moderate	Los Angeles, Barcelona

4.2. Temporal Dynamics: Diurnal, Seasonal, and Long-Term Trends

The UHI effect is time-varying, both on short time scales (diurnal), and on long time scales (seasonal and multi-year). Remote sensing has given useful information on these temporal variations, such that UHI intensity variations across the day, season, and years can be better understood. Among the most significant diurnal features of the UHI effect should be regarded as the variation of temperatures in the city compared with the temperatures of the countryside in the daytime and at nighttime. At the time of day, the urban areas are usually warmer because of the increased solar reflection on man-made surfaces, whereas at night the difference usually becomes smaller, or even negative. This is due to the fact that urban areas emit heat more gradually as compared to rural ones, a phenomenon commonly referred to as the lag effect. These temperature changes can be analyzed using remote sensing data that can be obtained with satellites such as Landsat and MODIS, which record day and night thermal infrared images. Such diurnal variations are important in determining the actual scale of the UHI effect because sometimes it is the night temperatures that will be most dangerous to human health, especially when it concerns the, so-called vulnerable groups of people who might not have the benefit of air conditioning[40,41].

The seasonal change in the UHI intensity depends on the variation in vegetation coverage, the solar angle, and the consumption pattern of energy. UHI effects are normally stronger during the warmer seasons, as vegetation cover is absent and people use more energy due to urban heating. Nevertheless, the research of remote sensing revealed that the intensity of UHI can also be high during cooler seasons, in particular, in those areas where the urban heating requirements are significant. This is especially in urban areas in colder climates, where structures and other constructions absorb the sun's radiation during daylight and gradually dispel it at night, even in winter.

Vegetation cover which is usually denser during the spring and summer months, is important in alleviating the UHI effect. In such seasons, trees and plants' evapotranspiration contributes to cooling the atmosphere of the area, which lowers the intensity of the UHI. On the other hand, the cooling effect of vegetation is less in winter when vegetation is in the dormant stage, resulting in a stronger UHI effect. Remote sensing instruments, particularly those that measure vegetation indices such as the Normalized Difference Vegetation Index (NDVI), can be used to measure the contribution of green spaces towards seasonal patterns of UHI[42].

Prolonged observation of UHI dynamics has indicated a deplorable situation of rising UHI levels in most metropolitan regions driven by urban growth as well as climatic change. Increased surface temperatures in most of the megacities have been recorded in remote sensing research over several decades since the time of the Landsat imagery, as early as 1980, up to this day. It is argued that this long-term trend is a result of a series of factors, such as increased urbanization (increasing the area covered by impervious surfaces), the rise of anthropogenic heat emissions by vehicles and buildings, and the aggravation of the global warming process[43].

The process of urbanization and climate change particularly affects the cities that are rapidly developing in the Global South, where urban sprawl is not always well thought through or managed properly. In such areas, there is an insufficient number of green areas and the systems used to cool the places are not efficient, and this further worsens the UHI

effect and results in an even greater temperature rise in the urban areas than in the rural environment. Remote sensing offers the requisite protocol to monitor all these changes and predict possible future UHI effects under different climatic conditions to enable policymakers to establish adaptive measures[44].

4.3. Intersection with Climate Change: Interactions and Compounding Effects

Climate change is expected to further amplify the UHI effect, making it an increasingly critical issue for urban resilience. As global temperatures continue to rise, many cities are already experiencing higher baseline temperatures, which will only worsen UHI effects. The intersection between UHI and climate change is multifaceted, with the two phenomena reinforcing each other in a positive feedback loop. Remote sensing has shown that cities are warming at a faster rate than surrounding rural areas, a phenomenon that can be exacerbated by global warming. As urban areas continue to expand, the demand for cooling technologies like air conditioning will increase, contributing to greater energy consumption and additional heat emissions. This, in turn, creates a vicious cycle that exacerbates the UHI effect. The spatial distribution of UHI hotspots, particularly in low-income neighborhoods with limited access to cooling, underscores the need for climate-sensitive urban planning and the integration of cooling strategies[45].

The combination of UHI and climate change increases the frequency and intensity of extreme heat events, which pose serious public health risks. Remote sensing has been instrumental in identifying areas of high vulnerability during heat waves, helping public health agencies target interventions. By analyzing satellite imagery and ground-based heat stress data, researchers can map the area's most at-risk populations from extreme heat and identify the specific populations that may be most vulnerable, such as the elderly, children, or low-income communities without access to air conditioning.

The compounded effect of UHI and climate change underscores the need for integrated urban resilience strategies. Remote sensing data can inform urban planning by providing insights into how urban areas can be redesigned to mitigate the UHI effect and adapt to a warmer world. For example, urban greening initiatives, such as the installation of green roofs and the expansion of parks, can help cool urban environments and absorb excess heat. Additionally, the integration of cool roofing materials, reflective surfaces, and permeable pavements can reduce heat retention and enhance the effectiveness of these strategies[46].

In conclusion, the use of remote sensing in understanding the patterns, variability, and long-term trends of UHIs has provided invaluable insights into the complexities of urban heat dynamics. These insights are essential for identifying vulnerable areas, monitoring changes in UHI intensity, and developing targeted mitigation strategies. As climate change continues to accelerate, the role of remote sensing will become even more critical in helping cities build resilience to the increasingly severe challenges posed by the UHI effect.

4.4. Comparative Analytical Synthesis across Selected Cities

UHI research based on remote-sensing of single cities offers extensive, though frequently piecemeal information on the interaction between land surface temperature, vegetation, and urban morphology. To go beyond a descriptive synthesis, this subsection contains a comparative study of some of the case-study cities mentioned earlier in this review: Shanghai and Beijing (China), Phoenix (USA), Riyadh (Saudi Arabia), Singapore, New York and Los Angeles (USA), and Barcelona (Spain). These cities are exemplars of different Köppen climatic classifications, types of urbanization, and the growth direction of cities, all studied with satellite-derived LST and vegetation indices in the modern literature[47,48].

Across these cities, several robust patterns emerge. First, daytime summer SUHI intensity (expressed as the LST difference between dense urban fabric and nearby rural or low-density references) typically lies between about 3–7 °C, with higher values in hot arid and subtropical climates. Phoenix and Riyadh routinely exhibit daytime ΔT values in excess of 5 °C during summer heat waves, with local hotspots exceeding 8 °C in compact, low-vegetation districts. In contrast, temperate cities such as Berlin and Barcelona generally show more moderate daytime SUHI intensities, though local maxima can still be substantial during extreme events. Second, the spatial organisation of heat closely follows local climate zones and land-cover classes. In Shanghai and Beijing, LCZ-based analyses reveal that compact high-rise and heavy industry classes show the highest LST, while

open low-rise and vegetated LCZs are systematically cooler. Hou et al. [37] reported that between 2008 and 2020, the spatial footprint of high-LST clusters in Shanghai expanded westwards as built-up LCZs intensified, whereas the Chongming district remained comparatively cool due to its lower building density and higher vegetation cover [37,49–53].

Vegetation indicators provide a complementary, quantitative lens on these patterns. In most of the cities considered, the mean NDVI in dense urban cores during summer is in the range of 0.15–0.3, compared with values of 0.4–0.6 in peri-urban forests, parks or agricultural surroundings. Case studies consistently report that neighbourhoods with higher NDVI or tree-canopy cover exhibit lower LST: for example, local analyses in Phoenix and Los Angeles show that increasing tree canopy by 10–20 percentage points is associated with reductions in daytime LST of roughly 1–3 °C at the census-block or neighbourhood scale, while park and green-corridor systems in Barcelona are associated with cooling footprints extending several hundred metres beyond park boundaries. In Singapore, the combination of high baseline greenery and targeted urban-forest and park planning yields local LST reductions of 2–3 °C relative to compact commercial districts with sparse vegetation, despite the overall warm and humid tropical climate [54,55].

The strength of these relationships is mediated by methodological choices. In Shanghai and Beijing, LCZ-based approaches allow a detailed separation of thermal signatures associated with built form, land cover, and vegetation, and make it possible to compare like-for-like urban typologies across time. In Phoenix and Riyadh, where coarse MODIS products are often used, the strong climate-driven background signal and large pixel size highlight regional-scale patterns but may obscure fine-grained UGS effects, unless supplemented with Landsat or higher-resolution data. North American and European studies often integrate LST and NDVI with socio-demographic datasets, revealing that the hottest, least green neighborhoods tend to host more vulnerable populations. These choices influence not only the level of detail achieved but also the type of conclusions that can be drawn for mitigation and equity [56].

Table 3 summarises a subset of representative remote-sensing studies for the eight cities mentioned above. For each case, it reports the core data sources and spatial resolution, typical summer SUHI intensity (ΔT), indicative NDVI ranges, evidence on the cooling effect of mitigation or green-space configuration, and a concise evaluation of methodological strengths, limitations, and implications for urban heat mitigation frameworks.

Table 3. Comparative analytical summary of selected remote sensing—Based UHI and UGS studies in exemplar cities.

City (Climate Zone)	RS Data & Spatial Resolution (Illustrative)	Key Indicators & Typical Values	Main Methodological Focus	Major Strengths	Key Limitations	Implications For Mitigation Frameworks
Shanghai, China (Humid Subtropical)	Landsat LST (30 m), LCZ classification, multi-year (2008–2020)	Summer daytime SUHI ≈ 3–6 °C between compact built LCZs and rural/low-density LCZs; nighttime SUHI ≈ 1–3 °C; NDVI ≈ 0.15–0.25 in central compact LCZs vs. > 0.4 in greener/peri-urban zones	LCZ-based analysis of spatio-temporal LST clusters and drivers; link between densification, LCZ transitions, and expansion of high-LST clusters	High spatial detail; robust typology for cross-LCZ comparison; multi-year trends capture effects of urban growth	Requires accurate LCZ mapping; LCZ classes still mix fine-scale heterogeneity; limited integration of social vulnerability	Supports LCZ-targeted greening and densification control; highlights need to preserve/expand vegetated LCZs and retrofit compact high-rise LCZs with UGS and cool surfaces
Beijing, China (Humid Continental/Monsoon-Influenced)	Landsat LST (30 m), multi-temporal land cover, LCZs	Daytime SUHI often 4–7 °C between compact built-up and vegetated/open LCZs; NDVI in dense inner-city LCZs < 0.3 vs. > 0.5 in urban forests and peri-urban agriculture	Cluster analysis of LST and controlling factors (impervious fraction, building form, vegetation); LCZ-based comparison of thermal responses	Explicit treatment of spatial heterogeneity and drivers; transferable typology for other megacities	Rural reference choice and seasonal variability affect ΔT; air-temperature exposure not directly measured	Demonstrates strong leverage of vegetation and LCZ design on SUHI; supports prioritisation of tree planting and park expansion in compact LCZs and along ventilation corridors
Phoenix, USA (Hot Desert)	MODIS LST (1 km) + Landsat (30 m) + land-cover maps	Daytime SUHI frequently > 5–7 °C in summer; nighttime SUHI often remains positive; low-NDVI neighbourhoods (NDVI < 0.15) show highest LST; tree-canopy increases of ~10–20% associated with ~1–3 °C local LST reductions	Combined regional-scale (MODIS) and neighbourhood-scale (Landsat) UHI–vegetation analysis; evaluation of tree-canopy scenarios	Clear climate signal emphasises benefit of UGS; multi-scale design captures both regional and local patterns	Coarse products alone cannot resolve fine-grained UGS effects; strong water-use constraints limit simple "more trees" strategies	Supports targeted canopy expansion in hottest, least green residential areas; underscores need to balance greening with water availability and integrate reflective materials and shading
Riyadh, Saudi Arabia (Hot Arid/Desert)	Landsat and MODIS LST; land-cover classification	Very high daytime SUHI, often > 6–8 °C; extremely low NDVI in urban core; small irrigated green patches show local cooling of ~2–4 °C vs. surrounding built-up pixels	Land-cover-based assessment of UHI and sparse green/blue infrastructure in a hot-arid context	Highlights extreme sensitivity of arid cities to surface materials and rare vegetation; clear "oasis" cooling signal	Sparse green space limits analysis of connectivity; limited socio-demographic integration; air temperature rarely observed	Emphasises importance of strategically located, well-watered green and blue infrastructure; supports extensive use of high-albedo materials and shading as complements to limited greening

Table 3. *Cont.*

City (Climate Zone)	RS Data & Spatial Resolution (Illustrative)	Key Indicators & Typical Values	Main Methodological Focus	Major Strengths	Key Limitations	Implications For Mitigation Frameworks
Singapore (Tropical Rainforest)	Landsat / Sentinel LST (10–30 m), high-resolution land-cover and vegetation maps	Urban–rural ΔT typically ≈ 2–4 °C; local LST differences of ~2–3 °C between compact commercial districts and urban forests/parks; NDVI often > 0.4 across much of the city	Fine-scale mapping of UHI and cooling footprints of urban forests, parks, and roadside greenery in a dense but generally green tropical city	Shows that configuration and intensity of vegetation strongly influence LST even in a green city; high spatial detail	High humidity and complex microclimates complicate translation to comfort indices; strong planning control may limit direct transferability	Supports design of continuous green corridors and intensive urban forestry; demonstrates compatibility of compact form with strategically distributed and connected greenery
New York & Los Angeles, USA (Humid Subtropical/Mediterranean)	Landsat / Sentinel LST, high-resolution tree-canopy and land-cover datasets, census data	Summer daytime SUHI typically ≈ 3–6 °C; neighbourhoods with higher canopy cover are ~1–3 °C cooler; roof-surface ΔLST of 10–20 °C between cool/green and conventional roofs	Joint analysis of UHI, NDVI/tree canopy, and socio-economic variables; evaluation of cool-roof and UGS interventions in selected districts	Strong integration of biophysical and socio-demographic data; direct policy relevance; empirical estimates of mitigation effects	Often cross-sectional; intervention evaluations limited in time and space; LCZ or morphology effects sometimes implicit	Underpins equity-oriented greening and cool-roof programmes; highlights co-benefits for energy and health; supports prioritising low-canopy, high-heat, and disadvantaged neighbourhoods
Barcelona, Spain (Mediterranean)	MODIS and Landsat LST; detailed land-use and green-infrastructure layers	Moderate SUHI (~2–4 °C), with higher LST in dense Eixample-type blocks and lower LST in and around parks and coastal zones; NDVI increases from inner city towards peri-urban green belts	Analysis of UHI patterns in relation to compact urban morphology, parks, and green-corridor networks	Shows that compact European morphology can be partially offset by well-designed parks and green corridors; links UHI to specific fabric types	Coarser thermal products limit precision of park-cooling footprints; social vulnerability often treated only coarsely	Supports reinforcement of park systems and green corridors penetrating compact fabric; relevant to other Mediterranean and temperate compact cities

5. Mitigation and Adaptation Frameworks Informed by Remote Sensing

Urban heat island (UHI) mitigation and adaptation options are vital in providing solutions to problems that are caused by high urban temperatures, which encompass health complications, higher energy demands, and decreased livability in urban areas. With the ever-increasing urban population and heightened effects of climate change on issues of heat, remote sensing (RS) is crucial in the development of regions that are prone to heat, the application of mitigation measures, and the assessment of their effectiveness. The section examines different UHI mitigation and adaptation measures, their interactions with the remote sensing tools, and the difficulties of implementing them[57].

5.1. Types of Mitigation and Adaptation Strategies

The UHI effect can be mitigated in the strategies directed at lowering the urban temperatures, whereas adaptation should create more resilience to urban heat stress. Remote sensing data can be useful in both forms of strategies to determine priority areas to intervene in and the effect of different actions in the long run.

5.1.1. Green Infrastructure

Green infrastructure can be defined as the establishment or improvement of urban green areas (in the form of parks, street trees, green roofs, and urban forests). Plants are important in minimizing the intensity of UHI due to the process of evapotranspiration (discharge of water vapor by plants), which cools both the air and surfaces around it. Besides, the green cover in cities offers shade, which helps in lowering the volume of solar radiation that gets reflected by the impervious surfaces, which include roads and buildings. The availability and health of the green spaces in urban areas can be evaluated using remote sensing technologies, especially in the evaluation of the availability and health of green spaces. Normalized Difference Vegetation Index (NDVI) is our vegetation index, which is obtained through satellite images, detailing the density and the condition of vegetation. NDVI is applicable in detecting sparsely vegetated areas, which would warrant the introduction of more green vegetation or the improvement of the current areas. It is also through remote sensing that one can monitor the expansion and contraction of green infrastructure over the years and subsequently evaluate the efficacy of the interventions to cool the urban surroundings[58,59].

5.1.2. Cool Roofs and Pavements

Cool roofs and cool pavements are developed to decrease the heat gained in buildings and streets. Cool roofs, which have high-reflective surfaces, reduce the heat absorption of roof surfaces, and cool pavements (coating them with permeable paving or reflective materials) purport to reduce the amount of heat absorbed by the ground surface. An

example of how remote sensing may be used to assess the efficacy of these interventions would be by mapping land surface temperature (LST) before and after cool roofs and pavements are installed to determine the changes. With the use of satellite imagery, which has thermal infrared bands, areas of reduced temperature can be detected by thermal infrared images where these materials have been used. Moreover, one more fact that can be obtained based on the data collected by remote sensing is albedo, the reflectivity of a surface, where further understanding of the role of reflective surfaces in decreasing urban temperatures is provided. Remote sensing can also provide feedback on the durability and efficiency of cool roofs and pavements through continuous monitoring, which can be useful in urban planning to increase or optimize these cooling measures [60,61].

5.1.3. Urban Water Bodies and Blue Infrastructure

UHI effects can also be mitigated by the introduction of urban water bodies, e.g., lakes, ponds, canals, or fountains. Such blue infrastructures have a cooling effect on their environment as a result of the evaporation process that absorbs the heat in their atmosphere. Water bodies possess strong thermal capacities, hence are able to absorb and store a great deal of heat without undergoing radical temperature rises, and thus are useful in cooling cities. The cooling effect of the water bodies in urban areas can be monitored through remote sensing, where the temperature is monitored as time goes by through the use of a thermal infrared image. Also, remote sensing may be used to examine a change in water area, the evolution of new water features, or the deterioration

of old ones. With water temperature data and the data of local LST, remote sensing can be used to quantify how urban water bodies affect local microclimates and determine where new water features should be located in locations that are most susceptible to UHI [62].

5.1.4. Urban Planning and Zoning

The overall objectives of urban planning and zoning are to integrate the UHI mitigation into the fabric of the city as such. Such measures involve modifying the urban morphology (e.g., by decreasing building density or height in some regions), encouraging the use of cool materials in building construction, and green corridors or buffers between constructed spaces. Also, zoning rules can give precedence to sustainable and cool buildings, preservation of available green spaces, and increased open spaces to take up more heat and offer shade. Remote sensing is significant in determining areas with high impervious areas, scarce vegetation cover, and thick clusters of buildings—areas that would get most of the UHI mitigation interventions. Through high-resolution satellite images, urban planners can also map land use and land cover (LULC), determine heat hotspots, and determine the level of green spaces within the city. It can be incorporated into zoning codes to get a better design and encourage more sustainable cities. It is also possible to evaluate the impact of zoning alteration and trace the development of the urban environment with the help of the remote sensing tools [63–65]. Across mitigation options, differences in biophysical cooling pathways, implementation constraints, and monitoring indicators motivate a comparative synthesis (see **Table 4**).

Table 4. Common UHI mitigation strategies and their effectiveness (and RS evaluation role).

Mitigation Strategy	Effectiveness	Typical Challenges	Role of Remote Sensing
Green Infrastructure	High (reduces temperature, increases evapotranspiration)	Requires land, long-term maintenance	Monitors changes in vegetation density, tracks cooling effects
Cool Roofs	Moderate to High (reduces roof surface temperature)	High initial cost, maintenance	Evaluates temperature reduction, maps albedo changes
Cool Pavements	Moderate (reduces heat absorption in urban areas)	Material availability, installation costs	Tracks temperature changes, assesses surface reflectivity
Urban Water Bodies	High (cooling effect through evaporation)	Water management, cost, space limitations	Monitors water temperature, analyzes cooling effects in surrounding areas

5.2. Role of Remote Sensing & GIS in Mitigation Planning

The combination of remote sensing and Geographic Information Systems (GIS) offers a great means of pinpointing the UHI hotspots, tracking the changes, and designing specific interventions. Spatial analysis would be impossible without GIS, and remote sensing data may be combined with other data to help in making decisions: population density,

income levels, and urban infrastructure are examples [57].

5.2.1. Mapping UHI Hotspots

Detection of UHI hotspots, which are regions where urban temperatures exceed those of surrounding rural areas, is one of the most important remote sensing applications in the mitigation of UHI. When we examine the LST data of satellites such as Landsat, MODIS, or Sentinel, researchers are able to create detailed maps that are used to identify temperature differences in cities. This type of map yields important information on the urban settings that are the most susceptible to extreme heat, and that should be addressed urgently. Socio-economic information, including population density, health data, and income level, can also be incorporated in remote sensing to determine those communities that are vulnerable to being disproportionately affected by UHI. This information can be integrated with UHI hotspots mapping so as to develop more focused and equitable mitigation strategies to support the needs of the most vulnerable populations [66].

5.2.2. Evaluating Mitigation Effectiveness

Remote sensing also offers the option of measuring the effectiveness of the UHI mitigation strategies over time. As an example, after establishing green roofs, cool pavement, or an urban water body, it would be possible to monitor the temperature changes through remote sensing data and check whether the cooling effect will be maintained in the long term. With time-series data of satellites, urban planners are able to track the pre-intervention and post-intervention LST and compare the effectiveness of various cooling methods. Also, the albedo measured by satellites can be used to test the qualities of the cool materials, which will provide even more information about the effectiveness of certain interventions. This constant observation is used to optimize strategies and to give data that may justify extra investment in cooling technologies [5,67,68].

5.2.3. Simulating Urban Heat Mitigation Scenarios

Remote sensing is also applicable in simulating future UHI mitigation strategies, besides tracking current mitigation measures. By integrating climate models with satellite data and projections of urban growth, urban planners will be able to predict how the intensity of UHI is going to evolve in various intervention conditions. As an example, they are able to simulate how urban greenery or a water body will affect the future UHI intensity. Such simulations can be utilized to test the different mitigation strategies and identify which ones will produce the most significant effect under the future climate conditions. This prediction power enables cities to be able to plan to be resilient to climate in the long run and choose the best type of interventions that they can make before applying them at a large scale [5,18,65].

5.3. New and Developed Reducing Frameworks

The two aspects of fast-growing urbanization and a shifting climate persisting in urban settings, new and more innovative mitigation models are coming forth that incorporate innovative technologies such as machine learning (ML), artificial intelligence (AI), and simulation modeling. The frameworks provide more dynamic and data-driven ways of UHI mitigation and can allow cities to be responsive to changing conditions [69].

5.3.1. Machine Learning and Artificial Intelligence

Machine learning and AI algorithms can now be used as potent tools in the comprehension of intricate urban heat processes and forecasting the UHI behavior. These technologies can detect patterns and trends that cannot be easily perceived by conventional approaches by using large data sources of remote sensing, climate models, and urban infrastructure. As an illustration, the ML algorithms may be used to determine the most powerful factors of UHI, including the land-use, building density, or even the presence of green spaces so that urban planners can focus more on the interventions [70].

Another application of AI is to determine in advance the consequences of UHI in the future and compare mitigation measures in different circumstances. These predictive models, applied together with remote sensing data, would enable the cities to establish adaptive, data-driven mitigation frameworks in response to the changing urban conditions and climate projections.

5.3.2. Simulation and Predictive Modeling

Urban planners can predict possible effects of different UHI mitigation measures with the help of advanced simulation and predictive modeling techniques, since they allow evaluating the effects before the implementation. These

models are a synthesis of remote sensing data, urban growth predictions, and climate change scenarios to simulate the effects of various alternatives on UHI in the future, i.e., adding vegetation covers or improving urban water features. The intervention options are numerous and can be tested by the cities using simulation tools, and their effectiveness can be evaluated under various conditions. Such models may be useful in prioritizing the interventions that offer more cooling advantages as well as factoring in the costs, practicability, and sustainability [65,71,72].

5.3.3. Urban Digital Twins and Decision Support Systems

The emergence of urban digital twins, virtual and data-driven urban models, has presented new opportunities for the real-time monitoring and mitigation of UHI. Digital twins combine data from remote sensing, urban infrastructure, and IoT sensors in order to generate a model that is dynamic of the environment of the city. These models can simulate the UHI effects in real-time; as such, the urban planners can test various mitigation measures and see the real-time effects on the urban temperatures. The systems also enable participatory planning in which the stakeholders have access to the data and give their input on decision-making. Through digital twins and decision support technology, the city can adjust faster to new heat threats, which will make UHI mitigation measures efficient and flexible to new circumstances [71,73].

5.4. Challenges, Trade-Offs, and Barriers to Implementation

Although remote sensing and the relevant mitigation measures have immense potential, there are still a few challenges in the implementation of UHI mitigation at a large scale. The cost of interventions, especially those of large-scale green infrastructure or the implementation of cool roofs and pavements, is one of the major barriers. The implementation and maintenance cost of these interventions may also prove to be expensive, particularly in cities that have few resources, although the long-term benefits are effective. Another important issue is social equity. The mitigation plans should also be able to make sure that the urban environments become cooler to the benefit of the citizens, especially those living in low-income or vulnerable communities. Unless interventions are fairly shared, one population may still experience extreme heat, which further worsens the social inequalities. The policy and governance concerns are also very important in the implementation of UHI mitigation measures. Planning activities in various sectors, such as urban planning, housing, transportation, and health of the populace, involves good governance and cooperation. Moreover, cities need to make sure that the UHI mitigation measures are in line with the overall climate adaptation and sustainability objectives [1].

Remote sensing is a vital factor in identifying, planning, and monitoring the UHI mitigation measures. Remote sensing will assist urban areas to come up with effective, localized interventions aimed at reducing the severity of UHI by giving urban areas spatially explicit data on urban temperatures, vegetation, land-use, and infrastructure. Although the cost, equity, and governance issues still exist, new opportunities, including machine learning, predictive modeling, and urban digital twins, are available to improve the UHI mitigation efforts. Remote sensing will feature prominently as cities evolve to survive the changes in climate and create cooler, stable cities [18,74].

5.5. Limitations

It is necessary to note that the quantitative variables of LST, SUHI intensity, and NDVI presented in the analysed papers are measured with the aid of various sensors (e.g., Landsat, MODIS, Sentinel), and their spatial resolution varies between 30 m and 1 km, their temporal coverage varies, and their seasonal and diurnal conditions are variable. There are also differences in NDVI calculation and SUHI definition, because of the differences in atmospheric correction, land rule classification, and selection of the reference areas. Such differences add inhomogeneity and possible methodological bias, which we solve through reading reported values as ranges of indicative values and relative trends of values, but not as explicit numerical values. Comparative analyses are put in place in terms of climate zone, city typology, and LCZ class to make the synthesis meaningful. These are recognized as limitations expressly and are used to interpret the patterns in cross-studies with caution.

6. Synthesis: Toward a Framework for Urban Heat Resilience

With the increasing pressure of climate change on Urban Heat Islands (UHI) in urban areas, there is an upward trend of mitigation and adaptation of urban heat islands to urban resilience strategies. The UHI effect is not only to comprehend and fill the existing gaps in mitigating the issue of urban thermal comfort but also to add to the overall objectives of climate resilience, energy efficiency, and human health. This part summarizes the major findings of remote sensing research on UHI, and suggests a framework of urban heat resilience that considers the mitigation as well as adaptive planning. Another important aspect that we touch upon is the significance of governance, equity, and policy integration in the realization of long-term success in UHI management[16,75].

6.1. Key Insights from Remote Sensing-Based UHI Research

Remote sensing has contributed to the field of understanding the UHI dynamics by giving spatially continuous data on land surface temperature (LST), vegetation, land cover, and urban morphology. These studies have revealed several important lessons that are very important in the design of effective UHI mitigation strategies:

Spatial Varying of UHI: UHI is not the same throughout the cities. It differs widely in terms of urban morphology, land cover, population density, and climate. The most pronounced effects of UHI are usually observed in high-density urban centres where there is little or no green area, large percentages of impervious surfaces, and little vegetation. These hotspots can be identified by the use of remote sensing, and urban planners can target areas where such hotspots occur so that interventions can be done in those places where they will be most effective.

Vegetation/Green Spaces Role: Remote sensing has already demonstrated the cooling effect of urban vegetation, and it is always found that the densely vegetated areas are colder than the impervious areas. Green infrastructure and mitigation of UHI depend on the cover of tree canopy, the diversity of plant species, and the care of the gardens. Cities that are more heavily vegetated (i.e., NDVI is higher) are likely to have less UHI because of evapotranspiration and shading. This observation highlights the need to incorporate green spaces into urban planning.

Efficacy of Cool Surfaces: The use of cool roofs and pavements, which reflect more sunlight and absorb less heat, has been demonstrated to reduce the UHI intensity. The research on remote sensing has given useful information about the surface temperature decreases accumulated by these technologies. Particularly, cool roofs have worked well in lowering the temperatures of the roof surfaces and contributing to the cooling effects in the cities. The insights enable urban planners to consider the advantages of cool surfaces in various kinds of urban environments.

UHI Intensification Due to Climate Change: It has also been shown through remote sensing that UHIs also increase in number over time, particularly in rapidly urbanizing areas. The UHI effect is worsened by the rising number and severity of heatwaves, coupled with the rise in baseline temperature as a result of climate change. Tracking this trend with the help of the remote sensing data enables cities to predict the risks in the future, and they can also put into focus the areas that are most prone to dangers, in terms of mitigation measures[1,76,77].

These lessons highlight the importance of the multi-pronged approach to UHI reduction, which implies the integration of green infrastructure, reflective surfaces, and adaptive urban planning. The data offered by remote sensing is used to design selected interventions, evaluate their success, and observe the situation over a long period of time.

6.2. Proposed Integrated Mitigation & Resilience Framework

To be able to tackle the UHI effect and make cities more resilient to extreme heat, the city should employ a comprehensive framework that would involve mitigation and adaptation policies. It is a framework that should integrate the information obtained through remote sensing and climate models, urban plans, and policy-making. The proposed framework will include three major stages: assessment, planning and implementation, and adaptive management and ongoing monitoring as a priority[78–80]. The proposed remote-sensing-enabled workflow linking diagnosis, prioritization, intervention design, and adaptive evaluation is summarized in **Figure 2**.
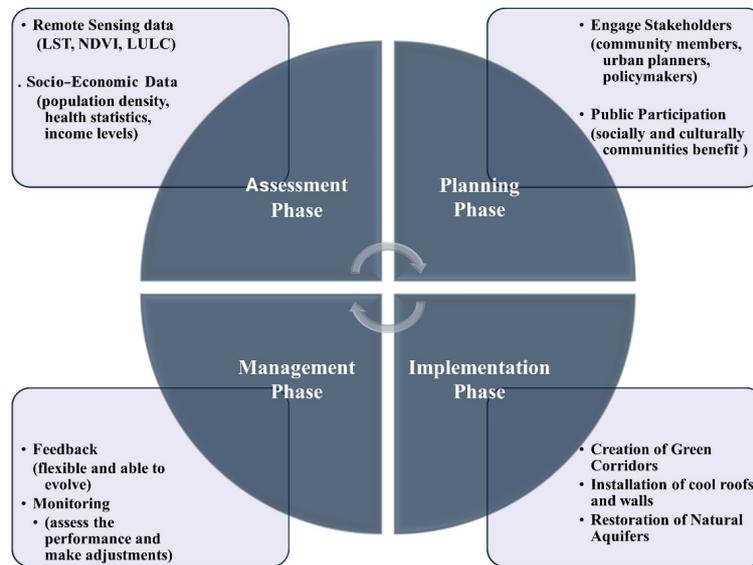
Figure 2. Integrated framework for UHI resilience: Assessment, planning, implementation, and feedback loop.

6.2.1. Assessment Phase

The initial part of the framework is to perform an extensive assessment of the urban heat environment. This involves an aspect of remote sensing data to map out the intensity of UHI at the city level and sensitive locations, which may be low-income neighborhoods or areas with limited access to cooling systems. Land surface temperature (LST) maps, vegetation indices (e.g., NDVI), and land-use/land-cover (LULC) information can help urban planners to detect UHI hotspots. Also, population density, health statistics, and income levels as socio-economic data are to be shown together with thermal data to determine how various communities are vulnerable. The integration of thermal data with demographic data can help cities determine the regions that have the highest risk of heat-related health problems and surges in energy demand. Some of the assessment stages also include the identification of possible cooling measures, which may include the development of expansion of copes spaces, the installation of cool roofs, or the introduction of urban water bodies[81].

6.2.2. Planning Phase

After identification of the UHI hotspots and vulnerable areas, the next stage is planning, which revolves around coming up with interventions that would help to minimize the UHI and enhance resilience. This step involves the implementation of cooling measures in urban planning and zoning, i.e., encouraging green roofs, cool pavements, and urban forestry. The data from remote sensing is used in this stage because it can be used to determine the areas in which these interventions are most likely to result in the desired outcome based on spatial distribution and socio-economic conditions. Also, remote sensing simulation models that combine the remote sensing data with climate forecasts can assist cities in determining the performance of various UHI mitigation measures under future climate conditions. The modeling of these mitigation options will help cities identify the strategies that will be the most effective in decreasing UHI and withstanding the rising temperatures in the future[70].

The stage should also include the involvement of the stakeholders, such as community members, urban planners, and policymakers, so that the proposed interventions will be just and address the needs of all residents. The involvement of the people in the planning process assists in making sure that the interventions are socially and culturally acceptable and that the disadvantaged groups of people enjoy the cooling strategies.

6.2.3. Implementation and Adaptive Management Phase

The implementation phase involves the real execution of UHI reduction measures, including the building of new green areas, installing cool roofs, and the growth of water bodies. Information on remote sensing is sensitive at this stage to keep an eye on the performance of interventions. Urban planners are able to monitor the effectiveness of cooling strategies by comparing the pre- and post-intervention LST

data and modifying their strategies when the need arises. The main aspect of this phase is adaptive management. With the cities undergoing climate change, urban growth, and socio-economic conditions changes, the UHI mitigation strategies should be adaptable and capable of change. The data obtained through remote sensing will be the continuous monitoring of cooling measures that are needed to measure the performance of the cooling measures and make changes that are required. This planning, implementation, and adaptation process is repeated to make sure that cities are resilient to the increasing threat of UHI and extreme heat[63,82].

6.3. Functional Structure and Execution Algorithm of the Proposed UHI Resilience Framework

The framework outlined in Section 5 aims to provide cities with a structured, remote-sensing-enabled approach to diagnosing, prioritising and mitigating urban heat in a climate-aware and equity-sensitive manner. To make this framework operational, it is necessary to specify its functional structure, main parameters and execution algorithm.

The framework is organised as a modular workflow with four core stages: (i) data ingestion and indicator construction; (ii) heat and vulnerability assessment; (iii) intervention portfolio design and simulation; and (iv) implementation monitoring and adaptive updating. At its core, the model ingests multi-source geospatial data—including remote sensing products (LST, NDVI or other vegetation indices, land-cover or LCZ maps, digital elevation/surface models), socio-demographic datasets (population density, age structure, income, housing type) and, where available, local climate projections—and transforms them into a set of harmonised indicators that can be used within GIS-based decision rules[83].

In the first stage, input datasets are preprocessed to a common spatial grid (for example, 30 m or 100 m) and temporal reference (for example, typical summer-day conditions). Remote-sensing thermal data are converted into land surface temperature fields, and UHI intensity is expressed as ΔT between each grid cell and an appropriate reference, which may be a rural or low-density LCZ, depending on data availability and context. Vegetation variables are computed using indices such as NDVI and, where possible, tree-canopy cover. In cities such as Shanghai, Beijing, Phoenix or Barcelona, LCZ

mapping is employed to encode urban morphology, allowing separate parameterisation of compact and open forms. Socio-demographic layers are resampled or aggregated to the same grid, and basic vulnerability indicators (for example, elderly population share, low-income households, lack of cooling access) are calculated[84].

In the second stage, the model combines these indicators into composite heat-risk scores. A typical formulation defines a thermal stress index as a function of ΔT and absolute LST, with thresholds adapted to the city's baseline climate (for instance, "high thermal stress" might correspond to ΔT > 4 °C and LST above a climate-zone-specific percentile, based on empirical distributions derived for the city). A green deficit index is derived from NDVI or canopy cover, again using thresholds informed by evidence from Section 4.4—for example, NDVI < 0.2 or canopy cover < 10% for inner districts in Shanghai or Phoenix may be treated as critical thresholds for intervention. A social vulnerability index combines demographic and socio-economic indicators, following standard practice in climate-risk assessment. These component indices are then normalised and aggregated (with weights chosen in consultation with local stakeholders or policy priorities) to yield a composite heat–vulnerability score for each grid cell or LCZ[85].

The third stage focuses on intervention design and simulation. Based on the spatial distribution of heat–vulnerability scores, the algorithm identifies priority zones, rank-ordered according to their scores and constrained by practical considerations such as land availability, existing regulations and infrastructure. For each priority zone, the model defines a set of candidate interventions appropriate to the local morphology and climate: for example, increasing canopy cover to at least 20–30% in residential neighbourhoods of Phoenix and Los Angeles; establishing or expanding parks and green corridors within and between compact LCZs in Shanghai, Beijing and Barcelona; deploying cool roofs on large flat-roofed buildings in New York, Los Angeles and Riyadh; or enhancing blue infrastructure in tropical and coastal contexts such as Singapore. Parameterisation of these interventions—such as target NDVI increases, canopy-cover gains or albedo changes—is informed by the empirical ranges of ΔLST and ΔT reported in Section 4.4 and the wider literature.

The potential effect of each intervention portfolio is then estimated using simple empirical response functions or

more sophisticated urban-climate models, depending on data and capacity. For example, if increasing canopy cover by 15% points in a given LCZ typology is associated with an observed reduction of 2–3 °C in daytime LST, the model can apply this empirically derived relationship to simulate the impact of reaching a canopy target in the candidate zones. In contexts where such relationships are not yet well quantified, ranges can be used and refined as new monitoring data become available. Similarly, cool-roof interventions can be parameterised using observed roof-surface ΔLST and associated neighbourhood-scale cooling effects derived from remote sensing in cities such as Los Angeles and New York.

The fourth stage implements a monitoring and feedback loop. Once specific interventions are implemented, updated remote-sensing data (for example, new Landsat/Sentinel LST and NDVI images for subsequent summers) are ingested into the framework. The same indicator-construction and heat–vulnerability assessment pipeline is run again [86], and changes in ΔT, NDVI, canopy cover and composite risk scores are evaluated for the intervention areas and suitable control zones. This evaluation allows the empirical parameters used in the response functions to be revised and the weights in the composite indices to be adapted, effectively "learning" from the local performance of interventions. In Shanghai, for instance, repeated LCZ-based LST mapping can be used to quantify how much additional cooling is achieved when green corridors are extended into compact districts; in Phoenix, new canopy and LST data can refine estimates of the marginal cooling per percentage point of canopy increase under different water-use regimes; and in Barcelona, repeated assessment of park-cooling footprints can inform corridor and park-extension design [86].

Operationally, the execution algorithm can be implemented within a GIS/RS environment using standard tools for raster processing, zonal statistics, multi-criteria evaluation, and scenario analysis. It is designed to be modular: cities with fewer data resources can implement a simplified version that focuses on LST, NDVI, and basic socio-demographic indicators, while data-rich cities can integrate LCZ maps, detailed 3D morphology, dynamic sensor networks, and climate projections. By making explicit the model inputs, intermediate indicators, parameter choices, and decision rules, this section transforms the proposed framework from a purely conceptual diagram into a functional, transparent, and adaptable decision-support algorithm for UHI mitigation and urban heat resilience.

6.4. Equity, Governance, and Socio-Political Considerations

Although technical responses to mitigation of the UHI are vital, the social, political, and governance aspects are also pertinent in making sure that the interventions are fair, sustainable, and effective. Low-income and vulnerable populations are affected by the UHI effect disproportionately and can be unable to access cooling infrastructure or live in a neighborhood with less green space or have fewer resources to manage extreme heat events. That is why any UHI mitigation plan should be non-discriminatory and focus on equality. The vulnerable communities can be identified through remote sensing, and the UHI interventions can be targeted to the areas where they are most needed. Planners need to make sure that mitigation planning is not skewed towards serving the richer areas of a city and leaving the poor or marginalized areas vulnerable to heat stress. An example of such instances is that green spaces must be established in both areas, which are well off and those disadvantaged in terms of service, and where the heat burden is the worst. On the same note, low-income housing areas should also have cool roofs and pavements in order to lower the amount of energy used in cooling. UHI mitigation measures need effective governance and partnership between various sectors, such as urban planning, public health, energy, and environmental protection, to succeed. The local governments need to engage the community organizations, businesses, and residents in formulating and executing solutions that are responsive to the needs and priorities of the population. Good governance entails proper policies, rules, and incentives to help achieve UHI mitigation, and the introduction of long-term monitoring systems to check the process and hold people responsible. The participation of the population is one of the key success factors of UHI mitigation efforts. Education of citizens about the advantages of green infrastructure, cool roofs, and other cooling technologies can be done via public awareness campaigns. Furthermore, the engagement of the communities in decision-making processes is beneficial because it ensures that the interventions will be based on local needs and priorities. The effectiveness and sustainability of the UHI mitigation approaches can also be improved by

improving citizen involvement in monitoring activities like crowd-sourced collection of temperature data or volunteer-led greening efforts[87,88].

The UHI effect presents serious problems to urban sustainability, the health of the population, and climate resilience. The remote sensing technologies have been able to offer invaluable information on the dynamics of UHI, as well as help cities to plan and execute specific mitigation and adaptation measures. Nevertheless, these strategies need to become part of a larger framework of urban resilience that includes equity, adaptive planning, and community participation in order to work. With the involvement of technological development in remote sensing and the use of inclusive governance and adaptive management, the cities can transform into cooler, more resilient urban landscapes that will be in a better position to deal with the challenges of a warming world. This combined method provides the most opportunity in reducing the UHI effect and the construction of cities that are not just cooler but more habitable, sustainable, and resilient to changes in climate in the future[89,90].

7. Gaps, Challenges, and Future Research Directions

The issue of Urban Heat Islands (UHI), which is becoming a serious challenge in the cities of the world due to rampant urbanization and climate change, the finding workable mitigation measures to such a problem increasingly imperative. Although much has been done to analyze the dynamics of UHI and apply remote sensing tools to identify and limit its impact, various substantial gaps and challenges still exist that restrict the achievement of full resilience in UHI. Here, we discuss the most significant technical, methodological, and socio-political issues that still exist, and propose the direction of future research that might address these issues. The listing highlights the gaps that can be resolved to make UHI mitigation efforts more precise, productive, and fair to assist the cities with the growing extreme levels of heat that global warming causes[89,91,92].

7.1. Technical/Methodological Gaps

Although remote sensing has made a massive contribution to UHI research by offering high-resolution high-volume data on urban heat patterns, many technical challenges that require redressing exist to improve the accuracy and applicability of the UHI monitoring and mitigation initiatives.

7.1.1. Surface Temperature vs. Air Temperature

Among the deepest gaps in the UHI studies is the disparity between land surface temperature (LST), which is generally measured using remote sensing, and air temperature, which is more pertinent to human health, comfort, and energy usage. The LST is normally significantly greater than the air temperature, particularly when the sky is bright, because asphalt and concrete, being the surfaces, absorb and trap the heat, which is then slowly released over time. Although remote sensing satellites provide in-depth LST data, they fail to directly record the canopy-level air temperature, the temperature that human beings experience. This is a crucial anomaly since the LST does not entirely reflect the heat that the occupants feel on the ground, which depends on shading, wind, and humidity[93,94].

To close this gap, the research should be conducted in the future with the emphasis on multi-sensor integration, i.e., a combination of remote sensing and in-situ weather stations, mobile temperature meters, or a UAV-based monitoring that would be able to measure air temperature at the street level directly. Also, modeling strategies that integrate LST with meteorological data may be used in order to come up with more precise estimates of the thermal exposure at human height, which will enhance our comprehension of the UHI impact on human health.

7.1.2. Mixed-Pixel Issues and Urban Surface Heterogeneity

The city is an intricate environment that consists of a combination of surfaces, including roads, buildings, vegetation, and water bodies. Data obtained by remote sensing (especially low-resolution satellites) may be subject to mixed-pixel effects where one pixel has more than one type of surface that has different thermal characteristics. As an example, a pixel in a highly populated city may depict an extension rooftop (heats fast) and a green area (keeps cooler), thus it is hard to draw the correct temperature readings. The developments in spatial resolution and data fusion methods can be used to mitigate such challenges. Satellite-based high-resolution images (Sentinel-2 or UAVs) can minimize the scope of mixed-pixel issues, although the high-resolution

data might require even higher resolution. To make LST retrieval more precise, machine learning (ML) and image classification methods might also be applied to be able to differentiate the various types of urban surface much better. But more effort is required on how to make these techniques applicable on a large scale and in an urbanized setup [95,96].

7.1.3. Data Integration and Standardization

It is also essential to combine data on different levels, such as thermal infrared data, multi-spectral data, land-use/land-cover (LULC) maps, and socio-economic data, to make the use of remote sensing the most effective way to study UHI. Nevertheless, these datasets can reside on various platforms (e.g., Landsat, MODIS, Sentinel) and differ in spatial, temporal, and spectral resolution, and this may be problematic in trying to merge them into a consistent, multi-dimensional model of urban heat. There is also a critical discrepancy in information harmonization and standardization: the algorithms for incorporating this varying information are still in their infancy, and discrepancies between the resolutions of the data may cause a major error. Research projects in the future must aim at creating standardized protocols for combining datasets and maintaining consistency among the sources of data. This may include the development of data fusion techniques and the development of best practices in the application of remote sensing to urban heat research [97–99].

7.1.4. Validation of Remote Sensing Data

Remote sensing may give a lot of data on the urban heat in high resolution, but it is challenging to prove it. The accuracy of the LST data would require ground-based measurements of temperature, and a large number of cities are deficient in dense meteorological networks. Ground stations are sometimes few and far between, especially in low-income areas, and some areas of the city, like high-rise districts or informal settlements, might not be well captured in the current processes of monitoring. To manage this, studies should aim at enhancing the validation of the remote sensing information by conducting all-inclusive field campaigns and crowdsourced information (e.g., by applying citizen science or smartphone-based temperature applications), and the application of low-cost sensors. Citizen-generated data would be more localized and real-time validated by satellite and UAV-based imagery, extending the area of coverage and enhancing the quality of monitoring systems [1,74].

7.2. Opportunities from Emerging Technologies

In the development of machine learning, imaging at high resolution, and real-time monitoring systems, there is a great opportunity to advance the UHI research and mitigation. The above innovations can assist in addressing most of the technical loopholes highlighted above and create new opportunities for managing UHI dynamically.

7.2.1. Machine Learning and Artificial Intelligence

Machine learning (ML) and artificial intelligence (AI) can transform the research of the UHI by giving the opportunity to process big, unstructured datasets in a way never before feasible. Based on historical temperature records, satellite images, land patterns, and climate models, ML algorithms can be trained to identify patterns in UHI dynamics. The future trends of UHI can then be estimated with respect to different urban development and climate change conditions. Also, the UHI mitigation strategies can be designed and implemented optimally by AI-based algorithms. An example is AI-based decision support systems that may be used to determine the most efficient cooling interventions, such as tree planting, the location of cool roofs, or water features, based on real-time remote-sensing and urban infrastructure data. This predictive ability can also be applied in determining the effectiveness of mitigation measures in advance, before they are put in place, so that urban planners can act on them [100,101].

7.2.2. High-Resolution Remote Sensing

The technological developments in satellite technology and drone-based sensors are now making it possible to obtain data of very high resolution, which can further break down the information on the spatial distribution of UHI in cities. Although conventional remote sensing platforms such as Landsat and MODIS have significant data to offer, the data frequently has a low resolution to observe small urban spaces (e.g., heat patterns at street level or small green areas). With thermal infrared sensors attached to the UAVs, there is an opportunity to obtain very detailed temperature information down to the street or neighborhood scale, which will give a more accurate picture of the UHI dynamics in high-density cities [1,5].

In addition, hyperspectral instruments (that record a wider part of the electromagnetic spectrum) can give more information on the materials on the surface and their thermal characteristics. Such sensors will be able to better discriminate between various urban materials (e.g., concrete, asphalt, vegetation) and map UHI hotspots more accurately, as well as understand a greater role of urban surfaces in the process of heat retention.

7.2.3. IoT and Sensor Networks

The Internet of Things (IoT) has huge potential to monitor UHI in cities in real-time and in a fine-grained fashion. The remote sensing data can be supplemented by distributed sensor networks, which can gauge the air temperature, humidity, and other environmental indicators in urban areas to give local information at the street level on heat. Such sensors may be placed in risky points, like the most populated urban areas, low-income areas, or heat-prone areas, to keep track of the microclimates and enhance forecasts of heat exposure. At real times, these sensors are capable of transmitting information, thus allowing cities to dynamically respond to the prevailing conditions when making mitigation decisions. The IoT sensor networks, when combined with remote sensing data, can offer a more holistic perspective on UHI to enable urban managers to make optimal decisions and act in real-time to mitigate the consequences of heat events as they happen [102,103].

7.2.4. Citizen Science and Crowdsourced Data

Another potential direction of UHI research expansion is citizen science. Mobile applications that are used by residents to share temperature readings or report heat-related problems in their cities have the potential to significantly augment the breadth and depth of UHI monitoring. The smartphone or wearable sensor-based data, crowdsourced, or a community-based monitoring campaign, can be used to supplement the conventional remote sensing techniques and give important information on the lived experience of urban heat. The use of crowdsourced information in UHI research can also be especially useful in places with poor coverage of other monitoring systems. It also strengthens the local communities by providing them with a voice in the process of decision-making and assists the urban planners in creating more inclusive and context-based interventions [104].

7.3. Integration with Climate Change Research and Urban Resilience Planning

UHI reduction should be incorporated into the larger city resiliency policies that combat climate change effects. UHI is a very important aspect of climate adaptation planning, as the world's temperatures become increasingly higher, and cities will have to endure heatwaves more often and more severely. By integrating remote sensing with climate change forecasts, the urban planners are able to predict the future UHI risks and put cooling mechanisms that are adaptable to the future climatic conditions. In addition, mitigation efforts implemented by UHI ought to be in consonance with more sustained sustainability objectives, including energy efficiency, improvement of air quality, and greenhouse gas reduction. UHI mitigation in the climate action plans will assist cities in creating a multi-dimensional resilience to reduce heat stress, aid energy conservation, and add to urban sustainability in general [105].

7.4. Socio-Political and Policy Research Gaps

Besides technical and scientific issues, there are socio-political and policy aspects that must be considered when applying UHI mitigation strategies. UHI affects vulnerable communities disproportionately, and such mitigation measures should be equity-based, with benefits being distributed among the residents. Studies need to be done on the socio-economic determinants of vulnerability to UHI, including income, housing, and access to green spaces. The study of these dynamics will be useful in encouraging policymakers to develop more equal interventions that can meet the needs of disadvantaged groups. As an example, green infrastructure investments need to be directed towards those neighborhoods that are the most affected by UHI and have less access to cooling. Good governance and coordination in various sectors such as urban planning, environmental management, public health, and infrastructure are essential in UHI mitigation. The study of institutional barriers, including disjointed roles, absence of funding, political intervention, etc., can be used to determine how to streamline the decision-making process and enforce the effective implementation of mitigation measures related to UHI. The issue of funding has been a major impediment to the UHI mitigation at the scale. Studies of innovative financing

schemes, including green bonds, public-private alliances, or international climate finance, would assist the cities in finding the resources to mitigate UHI. The investments in cooling technologies and infrastructure could be justified by the cost-benefit study showing the long-run savings of decreased energy consumption, decreased health care expenditures and enhanced general health of the population[106].

These technical and socio-political, and research challenges are the challenges that will determine the future of UHI mitigation. Although the application of remote sensing, machine learning, and sensor networks has improved greatly to track and curb the UHI, there are still a few gaps that need

to be filled to enhance the accuracy, scale, and equity of these initiatives. Cities can start to create cooler and more resilient urban environments that can adapt to the demands of a warming planet by advancing new technologies, refining methodologies, and addressing policy impediments. By remaining research-intensive and creating novel methods of alleviating such stress, urban climate resilience will be able to include UHI mitigation as a core element in protecting the health, well-being, and sustainability of future generations[107,108]. For clarity, the major technical and governance barriers together with corresponding research priorities are tabulated in **Table 5**.

Table 5. Key challenges and future research directions.

Challenge	Description	Future Research Direction
Data Integration and Standardization	Difficulty in combining data from multiple remote sensing platforms	Develop standardized protocols for integrating datasets
Validation of Remote Sensing Data	Ground-truthing remains challenging due to sparse meteorological stations	Expand sensor networks, integrate crowdsourced data for validation
Mixed-Pixel and Urban Complexity	Difficulty in accurately detecting urban heat patterns in heterogeneous surfaces	Advance algorithms to handle mixed pixels and complex urban surfaces
Equity in UHI Mitigation	Ensuring that vulnerable populations benefit from cooling interventions	Conduct research into the social equity aspects of UHI mitigation

8. Conclusion

Urban Heat Islands (UHI) are a major issue in cities across the globe, given that increased temperatures, caused by urbanization as well as climate change, are posing a threat to the health of humans, energy use, and the general livability in cities. The UHI effect affects vulnerable populations unevenly, heightens the energy demand, and aggravates the vulnerability of extreme heat events. The incorporation of remote sensing technologies has, however, supplied priceless information on understanding and rectifying these challenges. Aided by the constant observation of land surface temperatures, urban morphology, and vegetation, remote sensing has enabled cities to estimate the UHI intensity and distribution more accurately than ever before with the help of remote sensing, so that better mitigation and adaptation measures can be developed.

This review has examined the critical role of remote sensing in UHI research, including its applications in the identification of UHI hotspots, assessment of mitigation interventions, and the provision of important data to support city planning and urban policy decisions. Remote sensing is a dynamic instrument in charting the spatial variability

of UHI, tracing the long-term patterns, and modeling the future of UHI, which is fundamental in the planning of effective urban heat resilience. Further, remote sensing is also being integrated with other new technologies, including machine learning and data fusion, and IoT-based monitoring networks, which present promising opportunities to enhance UHI mitigation measures and accommodation to evolving urban climates. Although such advances have been made, many technical, methodological, and socio-political issues are still left. Narrowing the distance between surface and air temperature, enhancing data integration, and solving mixed pixels are only some of the technical challenges that should be surmounted. Also, it is necessary to deal with the socio-economic inequalities of the UHI vulnerability, provide equal access to cooling opportunities, and gather sufficient funds to finance the large-scale mitigation activities to have long-term success in UHI management. Future studies should be aimed at addressing these limitations and making the UHI mitigation measures inclusive, flexible, and consistent with larger urban sustainability and climate resilience objectives.

In the future, cities will need to adopt a holistic approach of both innovative technologies and effective governance, engagement of stakeholders, and the ability to commit

to social equity. UHI mitigation should be incorporated into more comprehensive urban resilience strategies that take into account adaptation to climate change, energy efficiency, human health, and environmental sustainability. Through remote sensing, modern simulation frameworks, and collaborative decision-making hubs, cities can make the urban space cooler and more resilient so that it can better face the needs of a warming world. By doing so, the UHI battle can be embedded as the foundation of urban climate action and help create healthier, livelier, and more sustainable cities for the generations to come.

Funding

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Zhou, D., Xiao, J., Bonafoni, S., et al., 2018. Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives. Remote Sensing. 11(1), 48.

[2] Jabbar, H.K., Hamoodi, M.N., Al-Hameedawi, A.N., 2023. Urban heat islands: A review of contributing factors, effects and data. IOP Conference Series: Earth and Environmental Science. 1129, 012038.

[3] Liu, C., Lu, S., Tian, J., et al., 2024. Research overview on urban heat islands driven by computational intelligence. Land. 13(12), 2176.

[4] Aboulnaga, M., Trombadore, A., Mostafa,M., et al., 2024. Understanding Urban Heat Island effect: Causes, impacts, factors, and strategies for better livability and climate change mitigation and adaptation. In Livable Cities: Urban Heat Islands Mitigation for Climate Change Adaptation through Urban Greening. Springer International Publishing: Cham, Switzerland. pp. 283–366.

[5] de Almeida, C.R., Teodoro, A.C., Gonçalves, A., 2021. Study of the Urban Heat Island (UHI) using remote sensing data/techniques: A systematic review. Environments. 8(10), 105.

[6] Shi, H., Xian, G., Auch, R., et al., 2021. Urban Heat Island and its regional impacts using remotely sensed thermal data—A review of recent developments and methodology. Land. 10(8), 867.

[7] Mohamed, A.A., Odindi, J., Mutanga, O., 2017. Land surface temperature and emissivity estimation for Urban Heat Island assessment using medium-and low-resolution space-borne sensors: A review. Geocarto International. 32(4), 455–470.

[8] Yang, C., He, X., Wang, R., et al., 2017. The effect of urban green spaces on the urban thermal environment and its seasonal variations. Forests. 8(5), 153.

[9] Mostafazadeh, R., Alaei, N., Mirchooli, F., et al., 2024. Changes in urban green space configuration and connectivity using spatial graph-based metrics in Ardabil developing city, Iran. Environmental Monitoring and Assessment. 196(9), 778.

[10] Cai, Y., Chen, Y., Tong, C., 2019. Spatiotemporal evolution of urban green space and its impact on the urban thermal environment based on remote sensing data: A case study of Fuzhou City, China. Urban Forestry and Urban Greening. 41, 333–343.

[11] Chen, X.-L., Zhao, H.-M., Li, P.-X., et al., 2006. Remote sensing image-based analysis of the relationship between Urban Heat Island and land use/cover changes. Remote Sensing of Environment. 104(2), 133–146.

[12] de Almeida, C.R., Bulatov, D., Andriambololonaharisoamalala, R., et al., 2025. Assessment of the Urban Heat Island (UHI) effect in Perth, Australia (2000–2024). In Proceedings of the Earth Resources and Environmental Remote Sensing/GIS Applications XVI, Madrid, Spain, 15–19 September 2025.

[13] Huang, Q., Lu, Y., Verichev, K., et al., 2018. Urban Heat Island research from 1991 to 2015: A bibliometric analysis. Theoretical and Applied Climatology. 131(3), 1055–1067.

[14] Moncada-Morales, G.A., Verichev, K., López-Guerrero, R.E., et al., 2025. A global review of vegetation's interaction effect on urban heat mitigation across different climates. Urban Science. 9(9), 361.

[15] Guan, S., Zhang, X., Zhang, T., et al., 2025. Considering the supply and demand of Urban Heat Island mitigation: A study on the construction of "Source-flow-sink" cooling corridor network of blue and green

landscape. Ecological Indicators. 174, 113448.

[16] Fu, Q., Zheng, Z., Sarker, M.N.I., et al., 2024. Combating urban heat: Systematic review of urban resilience and adaptation strategies. Heliyon. 10(17), e37001.

[17] Sharma, P., Sengar, A., 2025. Trends and insights in renewable energy research: A comprehensive bibliometric analysis (2000–2023). International Journal of Energy Sector Management. 19(4), 751–771.

[18] Zhao, L., Fan, X., Hong, T., 2025. Urban heat island effect: Remote sensing monitoring and assessment—Methods, applications, and future directions. Atmosphere. 16(7), 791.

[19] Peprah, M.S., 2025. Assessing the impact of land use and land cover change on land surface temperature in Africa: A systematic review and meta-analysis with a focus on Ghana. International Journal of Earth Sciences Knowledge and Applications. 7(3), 415–436.

[20] Montgomery, S.L., 2013. Does Science Need a Global Language? English and the Future of Research. University of Chicago Press: Chicago, IL, USA.

[21] Wang, X., Hu, Q., Zhang, R., et al., 2025. Ecosystem services in urban blue-green infrastructure: A bibliometric review. Water. 17(15), 2273.

[22] Li, Z.-L., Wu, H., Duan, S.-B., et al., 2023. Satellite remote sensing of global land surface temperature: Definition, methods, products, and applications. Reviews of Geophysics. 61(1), e2022RG000777.

[23] Sharma, P., Yogeswaran, N., Singh, R., 2025. Longitudinal study of urban heat island phenomena in rapidly developing cities: The case of Gurugram. Civil Engineering and Architecture. 13(4), 2862–2875.

[24] Argyrou, A., Agapiou, A., 2022. A review of artificial intelligence and remote sensing for archaeological research. Remote Sensing. 14(23), 6000.

[25] Schwarz, N., Lautenbach, S., Seppelt, R., 2011. Exploring indicators for quantifying surface urban heat islands of European cities with MODIS land surface temperatures. Remote Sensing of Environment. 115(12), 3175–3186.

[26] Martin-Vide, J., Sarricolea, P., Moreno-García, M.C., 2015. On the definition of urban heat island intensity: The "rural" reference. Frontiers in Earth Science. 3, 24.

[27] Smigaj, M., Agarwal, A., Bartholomeus, H., et al., 2024. Thermal infrared remote sensing of stress responses in forest environments: A review of developments, challenges, and opportunities. Current Forestry Reports. 10(1), 56–76.

[28] Tian, J., Zhu, X., Wu, J., et al., 2020. Coarse-resolution satellite images overestimate urbanization effects on vegetation spring phenology. Remote Sensing. 12(1), 117.

[29] Pu, R., Gong, P., Michishita, R., et al., 2006. Assessment of multi-resolution and multi-sensor data for urban surface temperature retrieval. Remote Sensing of Environment. 104(2), 211–225.

[30] Schulte, R.M., Kummerow, C.D., 2019. An optimal estimation retrieval algorithm for microwave humidity sounding channels with minimal scan position bias. Journal of Atmospheric and Oceanic Technology. 36(3), 409–425.

[31] Shandas, V., Voelkel, J., Williams, J., et al., 2019. Integrating satellite and ground measurements for predicting locations of extreme urban heat. Climate. 7(1), 5.

[32] Rasul, A., Balzter, H., Smith, C., et al., 2017. A review on remote sensing of urban heat and cool islands. Land. 6(2), 38.

[33] Heisler, G.M., Brazel, A.J., 2010. The urban physical environment: Temperature and urban heat islands. In: Aitkenhead-Peterson, J., Volder, A. (Eds.). Urban Ecosystem Ecology, Vol. 55. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America: Madison, WI, USA. pp. 29–56.

[34] Wu, Z., Yao, L., Ren, Y., 2020. Characterizing the spatial heterogeneity and controlling factors of land surface temperature clusters: A case study in Beijing. Building and Environment. 169, 106598.

[35] Zhao, Z., Sharifi, A., Dong, X., et al., 2021. Spatial variability and temporal heterogeneity of surface urban heat island patterns and the suitability of local climate zones for land surface temperature characterization. Remote Sensing. 13(21), 4338.

[36] Wei, C., Chen, W., Lu, Y., et al., 2021. Synergies between urban heat island and urban heat wave effects in 9 global mega-regions from 2003 to 2020. Remote Sensing. 14(1), 70.

[37] Hou, X., Xie, X., Bagan, H., et al., 2023. Exploring spatiotemporal variations in land surface temperature based on local climate zones in Shanghai from 2008 to 2020. Remote Sensing. 15(12), 3106.

[38] Yang, F., Chen, L., 2020. High-Rise Urban Form and Microclimate: Climate-Responsive Design for Asian Mega-Cities. Springer: Singapore.

[39] He, T., Zhou, R., Ma, Q., et al., 2023. Quantifying the effects of urban development intensity on the surface urban heat island across building climate zones. Applied Geography. 158, 103052.

[40] Tong, X., Wang, P., Wu, S., et al., 2022. Urbanization effects on high-frequency temperature variability over South China. Urban Climate. 42, 101092.

[41] Weng, Q., Fu, P., Gao, F., 2014. Generating daily land surface temperature at Landsat resolution by fusing Landsat and MODIS data. Remote Sensing of Environment. 145, 55–67.

[42] Mathew, A., Khandelwal, S., Kaul, N., 2017. Investigating spatial and seasonal variations of urban heat island effect over Jaipur city and its relationship with vegetation, urbanization and elevation parameters.

Sustainable Cities and Society. 35, 157–177.

[43] Li, L., Zhan, W., Du, H., et al., 2022. Long-term and fine-scale surface urban heat island dynamics revealed by Landsat data since the 1980s: A comparison of four megacities in China. Journal of Geophysical Research: Atmospheres. 127(5), e2021JD035598.

[44] Satterthwaite, D., 2008. Climate change and urbanization: Effects and implications for urban governance. In Proceedings of the United Nations Expert Group Meeting on Population Distribution, Urbanization, Internal Migration and Development, New York, NY, USA, 21–23 January 2008.

[45] Versey, H.S., 2021. Missing pieces in the discussion on climate change and risk: Intersectionality and compounded vulnerability. Policy Insights from the Behavioral and Brain Sciences. 8(1), 67–75.

[46] Karimi, A., Moreno-Rangel, D., García-Martínez, A., 2025. Granular mapping of UHI and heatwave effects: Implications for building performance and urban resilience. Building and Environment. 273, 112705.

[47] Riva Sanseverino, E., Riva Sanseverino, R., Vaccaro, V., et al., 2016. Smart cities: Case studies. In: Riva Sanseverino, E., Riva Sanseverino, R., Vaccaro, V. (Eds.). Smart Cities Atlas: Western and Eastern Intelligent Communities. Springer: Cham, Switzerland. pp. 47–140.

[48] Ren, X., 2018. From Chicago to China and India: Studying the city in the twenty-first century. Annual Review of Sociology. 44(1), 497–513.

[49] Zhou, Y., Zhao, H., Mao, S., et al., 2022. Exploring surface urban heat island (SUHI) intensity and its implications based on urban 3D neighborhood metrics: An investigation of 57 Chinese cities. Science of the Total Environment. 847, 157662.

[50] Gao, K., 2022. The Mitigation Potential of Greenery during Heat Waves [PhD Thesis]. University of New South Wales: Kensington, Australia.

[51] Xu, Y., Hou, H., Zhang, Y., et al., 2025. Changes in the urban dew chemical composition in Northeast China from 2013 to 2023. Journal of Environmental Sciences. 157, 633–644.

[52] Zhang, Z., Dong, C., Li, C., et al., 2025. Impacts and spatiotemporal differentiation of built environments on the urban heat island effect in cold-climate cities based on local climate zones. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 18, 5406–5422.

[53] Chang, Y., Guo, X., 2025. Disparities in the impact of urban heat island effect on particulate pollutants at different pollution stages: A case study of the "2+36" cities. Urban Climate. 59, 102273.

[54] Sedláček, J., Štefl, L., Klepárník, R., et al., 2024. Advancing urban ecology research with UAV: A study on NDVI and individual tree vitality assessment in species-rich parks. Journal of Digital Landscape Architecture. 592–604. Available from: https://gispoint.de/fileadmin/user_upload/paper_gis_open/DLA_2024/537752054.pdf

[55] El-Shirbeny, M.A., Biradar, C., Amer, K., et al., 2022. Evapotranspiration and vegetation cover classifications maps based on cloud computing at the Arab countries scale. Earth Systems and Environment. 6(4), 837–849.

[56] Soltanifard, H., Amani-Beni, M., 2025. The cooling effect of urban green spaces as nature-based solutions for mitigating urban heat: Insights from a decade-long systematic review. Climate Risk Management. 49, 100731.

[57] Abdalla, R., 2024. Framework for assessing the impacts of climate change on urban agglomerations: A GIS and remote sensing perspective. In: Castanho, R.A. (Ed.). Urban Agglomeration-Extracting Lessons for Sustainable Development. IntechOpen: London, UK.

[58] Taubenböck, H., Post, J., Roth, A., et al., 2008. A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing. Natural Hazards and Earth System Sciences. 8(3), 409–420.

[59] Sanesi, G., Colangelo, G., Lafortezza, R., et al., 2017. Urban green infrastructure and urban forests: A case study of the metropolitan area of Milan. Landscape Research. 42(2), 164–175.

[60] Santamouris, M., 2013. Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. Renewable and Sustainable Energy Reviews. 26, 224–240.

[61] Giorio, M., Paparella, R., 2023. Climate mitigation strategies: The use of cool pavements. Sustainability. 15(9), 7641.

[62] Jandaghian, Z., Colombo, A., 2024. The role of water bodies in climate regulation: Insights from recent studies on urban heat island mitigation. Buildings. 14(9), 2945.

[63] He, B.-J., 2019. Towards the next generation of green building for urban heat island mitigation: Zero UHI impact building. Sustainable Cities and Society. 50, 101647.

[64] Vecellio, D.J., Vanos, J.K., 2024. Aligning thermal physiology and biometeorological research for heat adaptation and resilience in a changing climate. Journal of Applied Physiology. 136(6), 1322–1328.

[65] O'Malley, C., Piroozfar, P., Farr, E.R.P., et al., 2015. Urban heat island (UHI) mitigating strategies: A case-based comparative analysis. Sustainable Cities and Society. 19, 222–235.

[66] Keramitsoglou, I., Kiranoudis, C.T., Ceriola, G., et al., 2011. Identification and analysis of urban surface temperature patterns in Greater Athens, Greece, using MODIS imagery. Remote Sensing of Environment. 115(12), 3080–3090.

[67] Bäckman, E., 2025. Physical climate risk in investment portfolios—exposure and financial impact: A scenario-based framework for forward-looking risk assessment at SEB Asset Management [Master's Thesis]. Umeå University: Umea, Sweden.

[68] Khan, A., Carlosena, L., Khorat, S., et al., 2023. Urban cooling potential and cost comparison of heat mitigation techniques for their impact on the lower atmosphere. Computational Urban Science. 3(1), 26.

[69] Roy, M., 2009. Planning for sustainable urbanisation in fast growing cities: Mitigation and adaptation issues addressed in Dhaka, Bangladesh. Habitat International. 33(3), 276–286.

[70] Li, F., Yigitcanlar, T., Yigitcanlar, M., et al., 2024. A novel urban heat vulnerability analysis: Integrating machine learning and remote sensing for enhanced insights. Remote Sensing. 16(16), 3032.

[71] Omrany, H., Al-Obaidi, K.M., 2024. Application of digital twin technology for urban heat island mitigation: Review and conceptual framework. Smart and Sustainable Built Environment. 14(7), 2145–2175.

[72] Hayes, A.T., Jandaghian, Z., Lacasse, M.A., et al., 2022. Nature-based solutions (NBSs) to mitigate urban heat island (UHI) effects in Canadian cities. Buildings. 12(7), 925.

[73] Mazzetto, S., 2024. A review of urban digital twins integration, challenges, and future directions in smart city development. Sustainability. 16(19), 8337.

[74] Coutts, A.M., Harris, R.J., Phan, T., et al., 2016. Thermal infrared remote sensing of urban heat: Hotspots, vegetation, and an assessment of techniques for use in urban planning. Remote Sensing of Environment. 186, 637–651.

[75] Tyler, S., Moench, M., 2012. A framework for urban climate resilience. Climate and Development. 4(4), 311–326.

[76] Huang, X., Wang, Y., 2019. Investigating the effects of 3D urban morphology on the surface urban heat island effect in urban functional zones by using high-resolution remote sensing data: A case study of Wuhan, Central China. ISPRS Journal of Photogrammetry and Remote Sensing. 152, 119–131.

[77] Dogan, S., Kilicoglu, C., Akinci, H., et al., 2024. Comprehensive risk assessment for identifying suitable residential zones in Manavgat, Mediterranean Region. Evaluation and Program Planning. 106, 102465.

[78] Ouria, M., de Almeida, A.T., Moura, P., et al., 2025. How to mitigate UHI and heat-related mortalities with urban strategies and policy adaptations? A review. Mitigation and Adaptation Strategies for Global Change. 30(7), 60.

[79] Ştefan, A.-M., Rusu, N.-R., Ovreiu, E., et al., 2024. Empowering healthcare: A comprehensive guide to implementing a robust medical information system—Components, benefits, objectives, evaluation criteria, and seamless deployment strategies. Applied System Innovation. 7(3), 51.

[80] Kishore, K.S., Venkatesan, S., Kumar, T., 2024. Human-AI collaboration in mitigating urban heat islands using satellite sensing and imagery data. In: Hamdan, A., Braendle, U. (Eds.). Harnessing AI, Machine Learning, and IoT for Intelligent Business: Volume 550. Springer: Cham, Switzerland. pp. 469–480.

[81] Tran, D.X., Pla, F., Latorre-Carmona, P., et al., 2017. Characterizing the relationship between land use land cover change and land surface temperature. ISPRS Journal of Photogrammetry and Remote Sensing. 124, 119–132.

[82] Santamouris, M., 2014. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy. 103, 682–703.

[83] Barker, A., Garcia-Blanco, G., Garcia, I., et al., 2024. The role of strategic planning in nature-based solutions (NBS) transformation: An evaluation of the Green Cities Framework in mainstreaming NBS in 6 European countries. Nature-Based Solutions. 6, 100157.

[84] Mansouri, A., Erfani, A., 2025. Machine learning prediction of urban heat island severity in the Midwestern United States. Sustainability. 17(13), 6193.

[85] Wang, Q., Chen, C., Xu, H., et al., 2025. The graded heat-health risk forecast and early warning with full-season coverage across China: A predicting model development and evaluation study. The Lancet Regional Health–Western Pacific. 54, 101266.

[86] Sahani, J., 2023. Mortality Risk Assessment, Vulnerability Mapping and Perception of Heatwaves towards Their Management via Nature-Based Solutions [PhD Thesis]. University of Surrey: Guildford, UK.

[87] Almashhour, R., Kolo, J., Beheiry, S., 2024. Critical reflections on strategies for mitigating and adapting to urban heat islands. International Journal of Urban Sustainable Development. 16(1), 144–162.

[88] Anser, M.K., Nassani, A.A., Al-Aiban, K.M., et al., 2025. Sustainable urbanization strategies: Mitigating urban heat islands through synergy between economic choices, renewable energy consumption, and environmental interventions. Problemy Ekorozwoju. 20(2), 86–100.

[89] Singh, N., Singh, S., Mall, R., 2020. Urban ecology and human health: Implications of urban heat island, air pollution and climate change nexus. In: Verma, P., Singh, P., Singh, R., et al. (Eds.). Urban Ecology: Emerging Patterns and Social-Ecological Systems. Elsevier: Amsterdam, Netherlands. pp. 317–334.

[90] Leal Filho, W., Echevarria Icaza, L., Neht, A., et al., 2018. Coping with the impacts of urban heat islands—A literature based study on understanding urban heat vulnerability and the need for resilience in

cities in a global climate change context. Journal of Cleaner Production. 171, 1140–1149.

[91] Trihamdani, A.R., 2017. Urban Climate Challenges in Growing Cities of Southeast Asia: Urban Heat Islands and Global Warming [PhD Thesis]. Hiroshima University: Higashihiroshima, Japan.

[92] Musco, F., 2016. Counteracting Urban Heat Island Effects in a Global Climate Change Scenario. Springer Nature: Cham, Switzerland.

[93] Siddiqui, A.R., Khan, R., Akhtar, M.N., 2025. Sustainable concrete solutions for green infrastructure development: A review. Journal of Sustainable Construction Materials and Technologies. 10(1), 108–141.

[94] Calovi, M., 2018. Healthcare and Disaster Management: A Geographical Approach [PhD Thesis]. Sant'Anna School of Advanced Studies and Specialization: Pisa, Italy.

[95] Weng, Q., 2012. Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. Remote Sensing of Environment. 117, 34–49.

[96] Botkin, D.B., Beveridge, C.E., 1997. Cities as environments. Urban Ecosystems. 1(1), 3–19.

[97] Tariq, A., Mumtaz, F., 2023. Modeling spatio-temporal assessment of land use land cover of Lahore and its impact on land surface temperature using multi-spectral remote sensing data. Environmental Science and Pollution Research. 30(9), 23908–23924.

[98] Kafy, A.-A., Islam, M., Sikdar, S., et al., 2021. Remote sensing-based approach to identify the influence of land use/land cover change on the urban thermal environment: A case study in Chattogram City, Bangladesh. In: Singh, R. (Ed.). Re-envisioning Remote Sensing Applications. CRC Press: Boca Raton, FL, USA. pp. 217–240.

[99] Govender, T., Dube, T., Shoko, C., 2022. Remote sensing of land use-land cover change and climate variability on hydrological processes in Sub-Saharan Africa: Key scientific strides and challenges. Geocarto International. 37(25), 10925–10949.

[100] Ghorbany, S., Hu, M., Yao, S., et al., 2024. Towards a sustainable urban future: A comprehensive review of urban heat island research technologies and machine learning approaches. Sustainability. 16(11), 4609.

[101] Veisi, O., Tehrani, A.Z., Gharaei, B., et al., 2024. Using Artificial Intelligence for Predicting Universal Thermal Climate Index Based on Different Urban Conditions: A Comparative Study of Machine Learning Models. Preprint. DOI: https://dx.doi.org/10.2139/ssrn.4840700

[102] Yu, M., Xu, F., Hu, W., et al., 2021. Using long short-term memory (LSTM) and Internet of Things (IoT) for localized surface temperature forecasting in an urban environment. IEEE Access. 9, 137406–137418.

[103] Yang, J., 2021. Fine-Scaled IoT Temperature Filling and Urban Heat Predictions with Deep Learning. George Mason University: Fairfax, VA, USA.

[104] Kim, E.S., Bae, C., Ko, S.Y., et al., 2024. Enhancing the effectiveness of heat adaptation strategies through citizen science-based outdoor thermal comfort. Heliyon. 10(21), e39413.

[105] Lv, Y., Sarker, M.N.I., 2024. Integrative approaches to urban resilience: Evaluating the efficacy of resilience strategies in mitigating climate change vulnerabilities. Heliyon. 10(6), e28191.

[106] Mabon, L., Shih, W.-Y., 2019. Mapping the socio-political landscape of heat mitigation through urban greenspaces: The case of Taipei Metropolis. Environment and Urbanization. 31(2), 552–574.

[107] Sharifi, A., Khavarian-Garmsir, A.R., 2022. Urban Climate Adaptation and Mitigation. Elsevier: Amsterdam, Netherlands.

[108] Lam, W., 2005. Barriers to e-government integration. Journal of Enterprise Information Management. 18(5), 511–530.