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Review

Exploring the Complexities of Urban Forms and Urban Heat Islands: Insights from the Literature, Methodologies, and Current Status in Morocco

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Abstract: The Urban Heat Island phenomenon (UHI), characterized by elevated temperatures in urban areas compared to their rural surroundings, is highly exacerbated by urbanization and climate change. Understanding the complex relationship between UHI effect and urban form is crucial for effective urban planning and climate mitigation strategies. This paper examines the multifaceted connection between UHIs and urban forms, exploring various methods used to study this relationship. Through a review of the existing literature, we analyze the influence of various urban characteristics on the intensity and spatial distribution of UHIs. Furthermore, we discuss the key methods and technologies, such as remote sensing and modeling, used in advancing our understanding of UHI–urban form interactions. This study then delves into the literature on UHIs within the specific context of Morocco, identifying research gaps and emphasizing the need for more comprehensive research to address them. By translating study findings into actionable urban solutions, this paper suggests contextual mitigation strategies based on the research outcomes. Finally, by synthesizing current research findings and methodologies, this paper seeks to provide insights into the complexities of UHI dynamics and their implications for climate resilience, highlighting the potential of research for forging sustainable and climate-conscious planning strategies in Morocco and across the broader MENA region.

Keywords: Urban Heat Island; urban form; research methods; climate change; Morocco

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Citation: Benaomar, K.; Outzourhit, A. Exploring the Complexities of Urban Forms and Urban Heat Islands: Insights from the Literature, Methodologies, and Current Status in Morocco. *Atmosphere* **2024**, *15*, 822. https://doi.org/10.3390/atmos15070822

Academic Editor: Jihui Yuan

Received: 16 May 2024
Revised: 27 June 2024
Accepted: 2 July 2024
Published: 9 July 2024

1. Introduction

Urbanization has transformed the world's landscapes, as more than half of the global population is currently residing in urban areas [1]. With over 80% of the world's GDP generated in cities, urbanization has become an unavoidable and key factor of a country's economic strength. However, urbanization is directly associated with several factors of climate disruption (e.g., high energy and resource consumption, GHG emissions, etc.), mainly manifested through the phenomenon of Urban Heat Islands (UHIs). This phenomenon occurs when urban areas experience higher temperatures than their surrounding rural areas due to a combination of factors, including heat absorption and re-radiation by urban materials, building density, and the release of anthropogenic heat [2,3]. These effects can have significant impacts on the environment and human health, such as increased energy consumption, air pollution, and heat-related illnesses [4,5].

The term Urban Heat Island dates back to the early 20th century; it was first introduced and documented in the 1940s by Balchin and Pye [6]. However, the phenomenon itself has been observed and studied for much longer by researchers such as Luke Howard [7] and Emilien Renou [8], who observed the difference in temperature between urban centers and their rural surroundings in the 19th century. Since the start of the 21st century, the interest in studying Urban Heat Islands has grown significantly(see Figures 1 and 2) given that they associate two of the major issues of the current century, namely urbanization (see Figure 3), driven by population growth, and climate change [9]. In fact, the change in urban climatic conditions caused by urbanization affects the urban thermal environment more directly than global climate change impacts [10,11]. Therefore, understanding how different urban form characteristics can influence the intensity and spatial distribution of a UHI is essential for developing effective mitigation strategies. Investigating this connection can provide valuable insights into the complex interactions between the built environment, microclimate, and urban energy performance. This knowledge can guide researchers and urban planners to identify optimal urban design approaches that can help reduce the negative impacts of UHIs, optimize energy consumption, improve urban air quality, and ultimately foster human health and well-being.

Additionally, in this study, several research gaps were identified regarding Urban Heat Islands in Moroccan cities. These gaps include the limited scope and depth of existing studies (limited long-term studies, a lack of socio-economic perspectives, the limited use of advanced tools, etc.), emphasizing the need for more comprehensive research to fill the existing knowledge voids not only in Morocco but also across the MENA region. By addressing these research gaps within the Moroccan context, this study aims to contribute to the advancement of knowledge on UHIs in Moroccan cities and across the region and inform sustainable urban planning practices tailored to the specific climatic and socio-economic challenges faced in the MENA region.

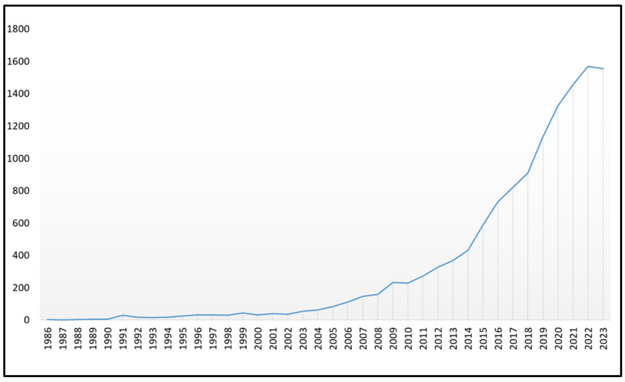

Figure 1. Evolution of research on UHIs, 1986–2023 (source: authors, from Web of Science data).

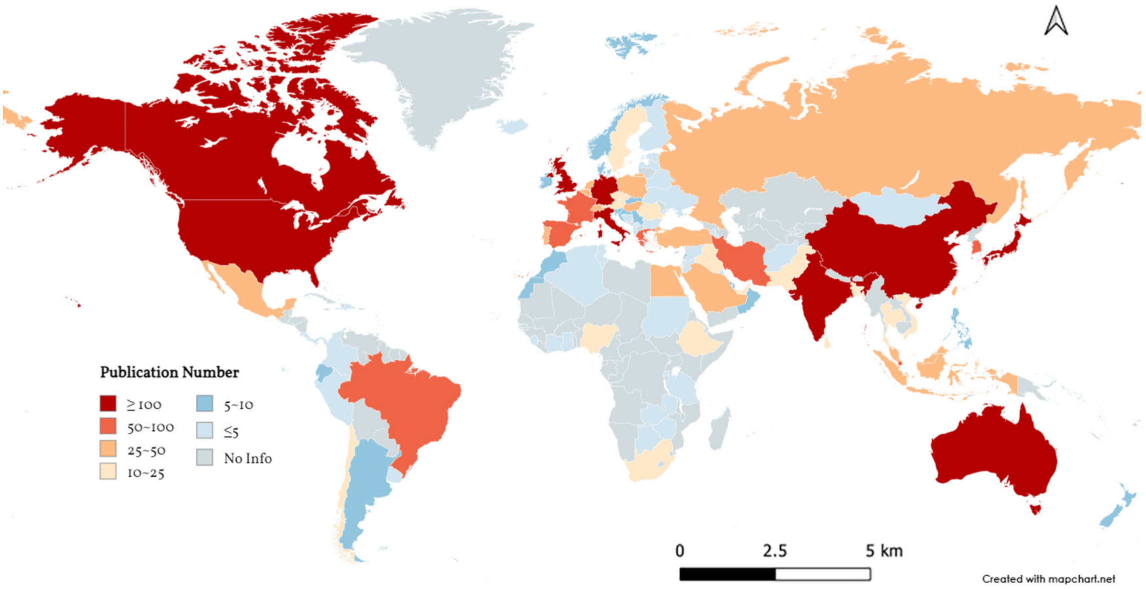

Figure 2. Country distribution of UHI research (source: authors, from Web of Science data).

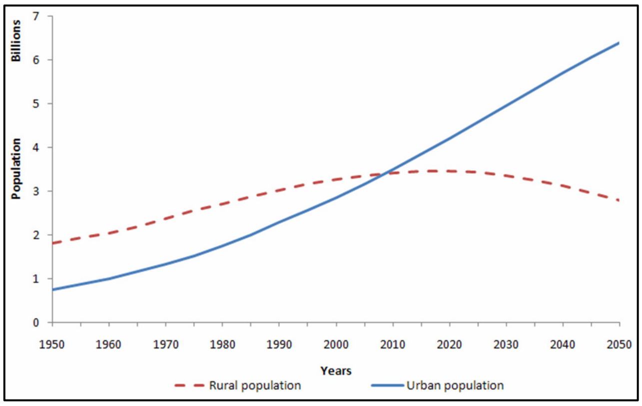

Figure 3. Evolution of urbanization in the world by 2050 (source: [12]).

2. Methodology

In order to explore how various urban forms and characteristics affect the phenomenon of Urban Heat Islands (UHIs), identify the various methods used to study it, and have an overview on the current landscape of UHI research in Morocco, a methodology consisting on three main stages was used. Stage I, “Literature survey and selection”, was conducted in three phases using two search engines, Web of Science and Google Scholar. Its two first phases were conducted in three steps: (i) “General survey”, (ii) “Identification of categories”, and finally (iii), a detailed survey was conducted using specific key words from the identified categories. The first phase of Stage I aimed to understand the phenomenon of Urban Heat Islands and the different urban characteristics leading to their formation and affecting their intensity. This first step (i) consisted of a “General survey” about UHIs using key words such as “Urban Heat Island”, “Urbanization”, “Urban forms”, etc. From this preliminary survey, two categories were identified in phase (ii), namely “Urban Morphology” and “Land Use/Land Cover patterns”. Lastly, a deeper survey was conducted using specific key words from the identified categories such as “Building Density”, “Street Layout”, “Aspect Ratio”, “Impervious/Pervious surfaces”, etc. Similarly, the second phase of Stage I explored the existing methods used to study the UHI phenomenon. The “General survey”, in its step (i), was conducted using key words such as “Urban Heat Island”, “Analysis”, “Study”, “Methods”, “Techniques”, etc. Secondly, three main categories were identified in phase (ii), namely “Remote sensing”, “Modeling”, and “Field measurements”. Finally, a detailed survey was carried out using specific key words from the identified categories such as “Land surface Temperatures”, “Energy balance Models”, “Computational fluid dynamics models”, “Mobile measurements”, etc. Lastly, the third phase of Stage I delved into the existing literature about UHI research in the specific context of Morocco. The findings of this specific survey were then organized following the identified categories from phase (i) and (ii), namely “Urban Morphology” and “Land Use Patterns”, and linked to their corresponding study methods (remote sensing, modeling, field measurement).

In Stage II, the collected data were analyzed and synthesized to identify key information from selected publications, analyze common methods and research trends, and pinpoint potential gaps in the existing literature. Subsequently, our discussion and interpretation (Stage III) contextualized the findings within urban planning, climate change mitigation, and sustainable development, with a focus on Moroccan cities.

Recognizing the risk of potential selection bias in the research process, several measures were implemented to enhance the comprehensiveness of the review. To overcome database limitations, the search was expanded to include multiple databases such as the Web of Science and Google Scholar, and gray literature was also considered. To avoid temporal bias, especially in the introductory sections, seminal works were included regardless of their publication date to provide a historical perspective on the subject of UHIs. As for the sections regarding UHI study methods, recent publications were prioritized to emphasize the latest scientific contributions. The Figure 4 details the steps of the research methodology.

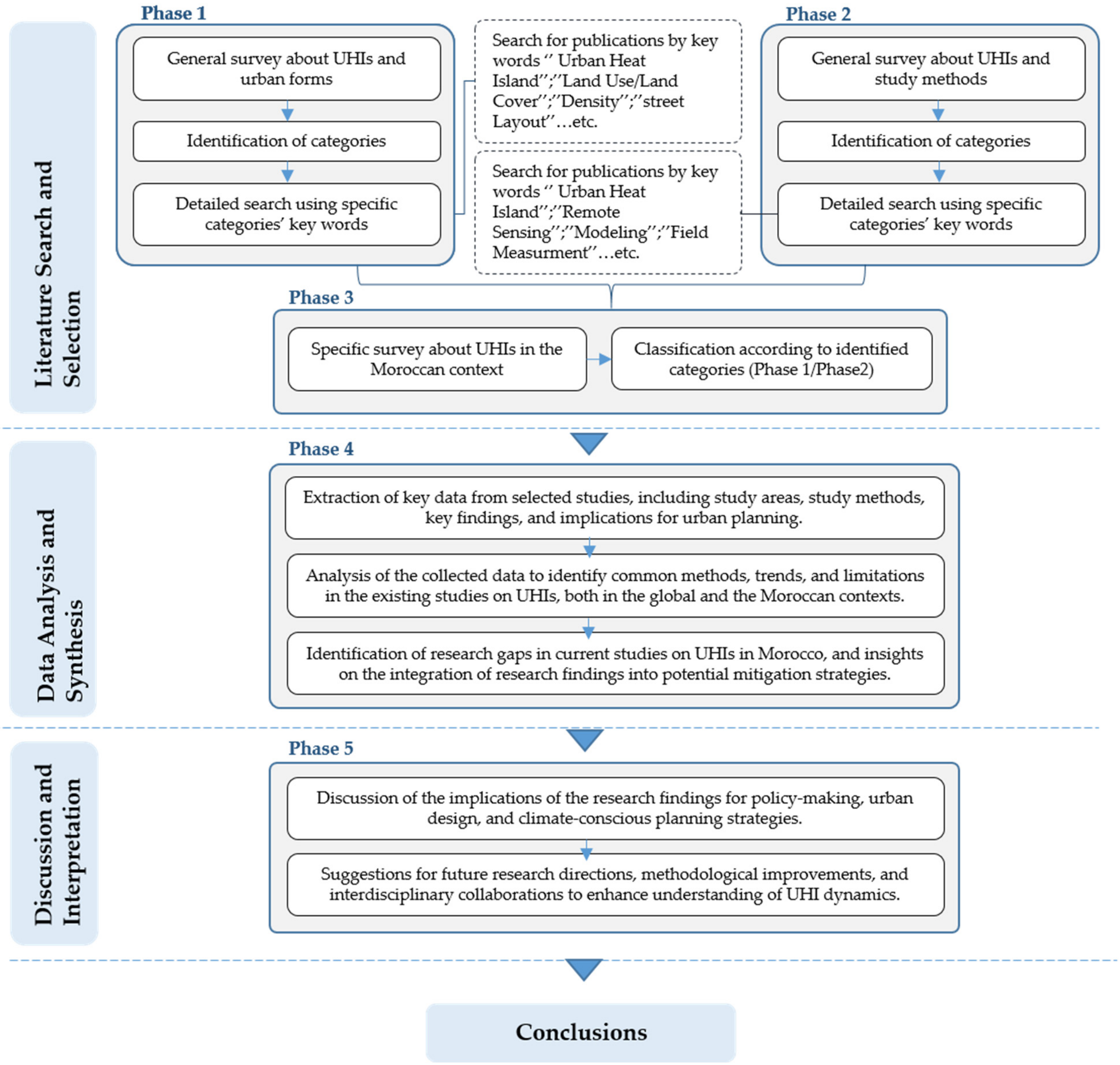

Figure 4. Outline of the study methodology.

3. Urban Heat Islands: Layers and Scales

Urban Heat Islands (UHIs) refer to the phenomenon in which cities and urban areas experience higher temperatures compared to their surrounding rural areas [13]. This temperature gap comes from the interplay of various factors within the urban environment and the atmosphere [2], leading to distinct types of UHIs operating at different scales (see Table 1 and Figure 5). The three primary types of UHIs include the surface layer UHI, the canopy layer UHI, and the boundary layer UHI [13]. Each type is characterized by specific spatial scales and particular heat dynamics (see Table 2), contributing to the overall temperature variations observed within urban landscapes. Analyzing these UHI types necessitates the application of various research methods tailored to capturing nuanced thermal behaviors across different urban scales and contexts.

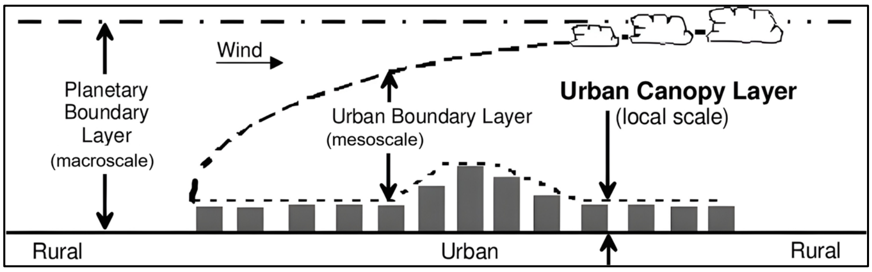

Figure 5. Layers of the urban atmosphere (source: [13,14]).

Table 1. Scales of UHI study (source: [15]).

Scale	Horizontal (m)	Vertical (m)
Microscale	10^{-2} to 10^{2}	10^{-2} to 10^{1}
Local scale	10^{2} to 10^{4}	10^{1} to 10^{3}
Mesoscale	10^{3} to 5×10^{5}	10^{1} to 10^{3}
Mesoscale	2×10^{5} to 5×10^{5}	10^{1} to 10^{5}

Table 2 describes the variations of UHI types across scales and layers.

Table 2. Layers and scales of Urban Heat Islands (source: authors).

UHI Layer	Scale of Study	Description
Surface layer UHI	Microscale to Local Scale	The surface layer is the layer closest to the ground and typically extends up to a height of a few meters [16]. The surface layer is influenced mainly by the thermal properties of urban materials. It is often characterized by an increase in temperature due to the absorption and re-radiation of heat by materials [3,17]. This layer is also affected by factors such as surface moisture and vegetation cover that can mitigate the UHI effect [18]. The heat island effect at this layer, referred to as a surface Urban Heat Island (SUHI), is typically measured through thermal infrared imagery that provides land surface temperatures (LSTs).
Canopy layer UHI	Local Scale to Mesoscale	The urban canopy layer is the layer above the surface layer and it extends from the ground up to the roof of buildings. This layer is influenced by the urban form, which affects sun exposure and airflow and can therefore create trapped "heat pockets" between buildings [19]. At this layer, Urban Heat Islands are typically measured using ground-based methods. This includes mobile measurement throughout cities and their surroundings, or fixed networks of sensors distributed within and around cities [14].
Boundary Layer UHI	Mesoscale to Macroscale	The urban boundary layer UHI sits above the urban canopy layer and varies in thickness, from hundreds of meters at night to over a kilometer during the day [15]. This layer is influenced by anthropogenic heat as well as meteorological conditions; it can trap heat and pollutants, resulting in negative impacts on air quality and public health. Numerical modeling and simulation techniques and weather forecasting models are utilized to analyze this UHI layer [20]. These methods help us to understand the complex interactions between the urban surface, atmospheric dynamics, and anthropogenic heat sources.

4. Influence of Urban Characteristics on Urban Heat Island Intensity

4.1. Urban Morphology

Urban morphology refers to the physical structure, layout, and shape of a city. It plays an important role in influencing the intensity of the UHI effect [21]. Factors such as surface roughness, building form and density, and street layout and orientation are key elements of urban morphology that contribute to creating and exacerbating UHIs [22,23].

i. Building Height and Density

The vertical dimension of urban development, characterized by building heights, plays a major role in shaping the intensity and spatial distribution of the Urban Heat Island effect [24].The height and density of buildings can disrupt the urban energy balance [25] through intensifying solar absorption, shadow casting, and airflow obstruction. Studies have shown that the disruption of this energy balance (see Figure 6) can lead to elevated temperatures and reduced thermal comfort within urban canyons [26]. Additionally, higher building densities tend to exacerbate these effects by restraining natural UHI mitigation mechanisms, such as air circulation and the presence of green spaces. Li et al. employed a regression model based on 3D urban structure data in a study that quantitatively established the relationship between urban morphology, density, and UHI intensity [22]. Their findings indicated that building density significantly influences UHI intensity, with a higher density correlating with increased UHI effects. Additionally, the model showed that sprawling or open developments might create a more favorable thermal environment compared to compact urban clusters, emphasizing the role of building distribution in UHI formation.

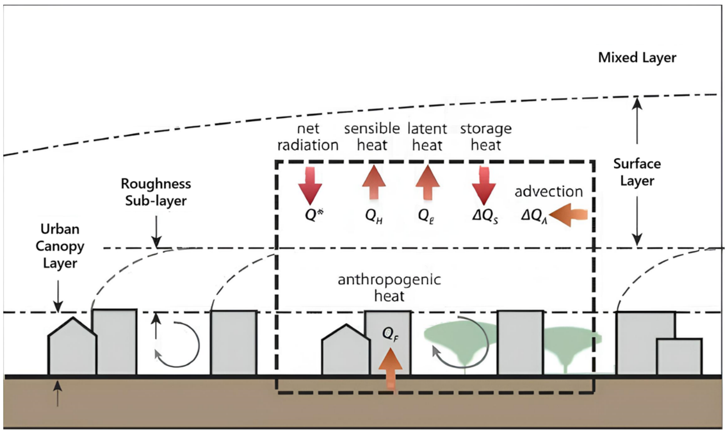

Figure 6. Components of urban surface energy balance (source: [27]).

ii. Street Layout and Orientation

The layout and orientation of streets (see Figure 7) within urban areas influence their exposure to solar radiation and airflow patterns and affect their heat retention capacities, thereby affecting the intensity and spatial variability of the UHI effect [28]. The aspect ratio of street canyons, defined as the height of buildings divided by the width of the street ($AR = H/W$), which correlates negatively with the sky view factor ($SVF = Vsky/Vtotal$), influences UHI dynamics significantly, depending on the region's climate. A study conducted by Bakarman and chang [24] in the hot and arid city of Riyadh, Saudi Arabia, revealed that modern street canyons with lower H/W ratios exhibited a more significant UHI effect than traditional street canyons with higher H/W ratios, with ambient air temperatures rising, respectively, by 15% and 5% compared to rural surroundings. Additionally, the orientation of the streets plays a major role in UHI intensity. For instance, street orientations that align with the prevailing wind directions promote ventilation and heat dispersion, reducing UHI intensity and improving thermal comfort [29].

In an experimental study, Hang and Chen [30] investigated how different aspect ratios (H/W = 1, 2, 3, and 6) impact the urban microclimates in street canyons. The results revealed that higher aspect ratios led to reduced convective ventilation, as indicated by a decrease in the velocity ratio $V0.25H/V2H$, reflecting lower airflow efficiency. Additionally, higher aspect ratios increased the trapping of radiation, with a decrease in urban canyon albedo and higher net all-wave radiation values. The surface temperature exhibited a negative correlation with the aspect ratio during the day, suggesting lower temperatures due to shading effects, and a positive correlation at night, indicating higher temperatures due to increased heat trapping. The findings of these studies highlight the significant influence of canyon aspect ratio and orientation on the dynamics of urban microclimates.

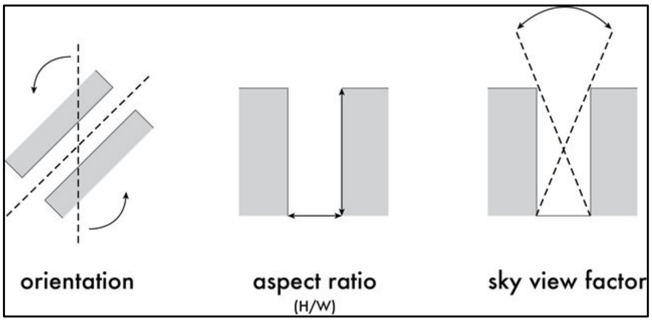

Figure 7. Aspects of urban canyon geometry: orientation, aspect ratio, and sky view factor (source: [31]).

4.2. Land Use/Land Cover Patterns

Several studies have demonstrated the impact of land use/land cover (LULC) patterns on UHI intensity due to the distribution of surfaces that absorb, reflect, or emit heat within urban areas [32,33]. This connection between land use/land cover and UHI intensity is closely tied to the ratio of impervious to pervious surfaces and the spatial arrangement of land use patterns within urban environments.

i. Impervious vs. pervious surfaces

With the rise of urbanization, pervious surfaces (e.g., green spaces, soil) are continuously being replaced with impervious surfaces (e.g., concrete, asphalt); these surfaces, characterized by low Albedo (see Table 3), absorb more incident radiation, trapping heat and reducing evapotranspiration [34,35]. A study conducted by Henits et al. [34] in Szeged (Hungary) provides insights into how land use/land cover changes influence urban temperature patterns. The study monitored UHI patterns over the years from 1987 to 2011. It observed significant increases in impervious surface ratios in industrial areas (5.7–9.1%) and inner residential areas (2.5–4.8%) over this period. These changes in impervious surface ratios directly affected UHI intensity, with higher UHI values observed in areas with increased impervious surfaces. Similarly, Li et al. [36] suggested a new method for quantifying Surface Urban Heat Island intensity (SUHII) in the Berlin region based on the relationship between land surface temperature (LST) and Impervious Surface Areas (ISAs) using Kernel Density Estimation. The results reflected that LST and ISA values showed a strong positive correlation, indicating that impervious surfaces significantly influence local temperature patterns and contribute to the intensity of the Urban Heat Island effect. Moreover, the spatial patterns of impervious surfaces, including their density, distribution, and aggregation play a crucial role in UHI intensity. Studies have shown that a higher density and aggregation of impervious surfaces tends to exacerbate the UHI [37,38].

Table 3. Albedo of typical urban materials (source: [39]).

Material	Albedo
Asphalt	0.05–0.20
Concrete	0.10–0.35
Grass	0.25–0.30
Trees	0.15–0.18
Pavers	0.07–0.35

In contrast, the presence of pervious surfaces in urban areas contributes to the mitigation of UHIs [40,41]. Pervious surfaces, such as vegetation, soil, and water bodies contribute to higher evapotranspiration, which provides a cooling effect in the atmosphere and a reduction in surface temperatures through shading, the interception of solar radiation, and thermal buffering.

ii. Spatial patterns of land use/land cover

The spatial distribution of land use patterns plays a role in UHI dynamics by influencing key parameters in UHI formation such heat fluxes and anthropogenic heat emissions. Urban areas integrating efficiently mixed land use patterns (residential, commercial, industrial, and recreational) can minimize heat buildup [42]. The juxtaposition of mixed patterns of land use can contribute to a balanced distribution of heat-absorbing surfaces, heat-generating activities, and cooling elements like vegetation. In contrast, single-use land patterns can lead to localized heat accumulation in areas dominated by a single land use type characterized by a high proportion of impervious surfaces [38]. Additionally, the disconnection of land uses can lead to reliance on transportation, particularly private vehicles [43]. This increased car usage and its associated anthropogenic heat generation can exacerbate the UHI effect [44,45].

5. Analyzing Urban Heat Islands: Methods and Limitations

The study of Urban Heat Islands requires using various methods that operate at different scales and target different characteristics of UHIs. Methods like remote sensing provide large-scale spatial data, allowing for a broad-scale analysis of UHI patterns. Modeling approaches, including numerical simulations and computer models, enable researchers to simulate and predict UHI dynamics under different scenarios. Field measurements involve on-site data collection using instruments like temperature sensors and thermal imaging cameras, providing detailed information on local UHI characteristics and validating remote sensing and modeling results. Each method has its advantages and limitations depending on the targeted aspects of UHI behavior and the spatial and temporal scales of the study.

5.1. Remote Sensing Methods

Remote sensing plays a crucial role in studying the connection between urban forms and the UHI phenomenon. By providing data on urban morphology, land cover, surface temperatures, and atmospheric conditions, remote sensing enables researchers to quantify the key urban form parameters influencing UHI intensity and spatial patterns. Remote sensing methods can be classified into two main types:

i. Passive remote sensing

Passive remote sensing involves sensors that detect and record the radiation emitted by the Earth’s surface or atmosphere in various spectral bands. Passive remote sensing is widely employed in UHI studies as it allows researchers to analyze the spatiotemporal changes in LST, used as a proxy for SUHI, and LULC patterns to investigate UHI intensity in relation to urban development and planning trends.

- Surface Temperature Mapping

Advancements in satellite remote sensing technologies have fostered the study of surface Urban Heat Islands (SUHIs) by providing improved spatial and temporal resolutions (see Figure 8). The main sensors used to study SUHIs include the Landsat series, MODIS (Terra/Aqua Moderate Resolution Imaging Spectroradiometer), and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). Several algorithms are employed in retrieving land surface temperatures (LSTs) such as the Split-Window Algorithm (SWA), Mono-Window Algorithm (MWA), and Radiative Transfer Equation (RTE) [41]. The Split-Window Algorithm (SWA) is frequently utilized, particularly with sensors like Landsat and MODIS [46,47], given its improved accuracy, which is achieved through leveraging the differential absorption of thermal infrared radiation, with reduced sensitivity to atmospheric effects and universal applicability across sensors and platforms while maintaining the consistency of LST values [48].

The significant use of the Landsat series in remote sensing studies (see Table 4) is largely due to its long-term imagery, dating back to its first launch in 1972, and the fact that it is freely available, providing researchers with valuable and consistent data over the past fifty years.

Table 4. Proportion of SUHI studies using various satellite images (source: [49]).

Sensor	Landsat Series	MODIS	ASTER	Multiple Sensors	AVHRR	Others [1]
Proportion	53%	25%	7%	6%	4%	5%

[1] SEVIRI, GOES, HCMM, HJ-1B, AATSR, ITOS-1, COMS, FY-2F, AMSR-E, AMSR2.

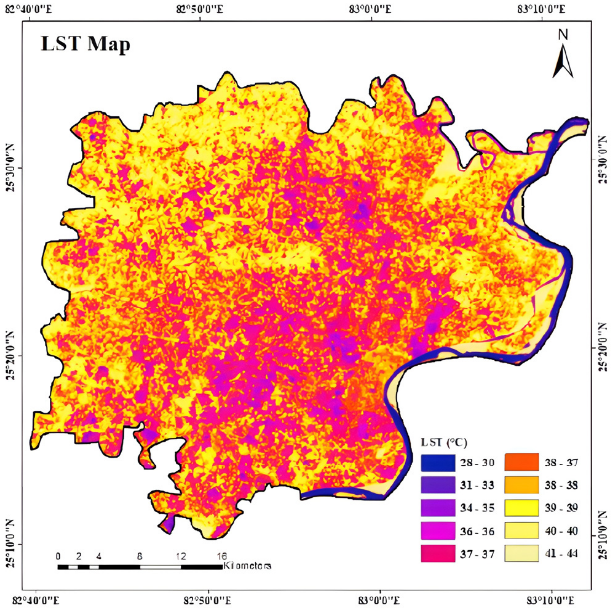

Figure 8. Land surface temperature (LST) map of Varanasi developed using Landsat 8 imagery (source: [50]).

- Land Cover Classification

Passive sensors capture reflected solar radiation across various spectral bands, facilitating the classification of land cover types and monitoring their dynamics. Analyzing land cover composition (impervious surfaces, vegetation, water, etc.) and spatiotemporal changes within urban areas is essential for understanding UHI dynamics. Various algorithms are employed to retrieve LULC data through supervised and unsupervised classifications. The widely used algorithms for supervised classification are the Maximum Likelihood Classifier (MLC) and Support Vector Machine (SVM) [51,52], while unsupervised classifications use algorithms like K-Means clustering [53,54] and Fuzzy C-Means (FCM) clustering [55,56].

In recent years, advances in machine learning have revolutionized unsupervised LULC classifications [57]. Machine learning models such as Convolutional Neural Networks (CNNs), Self-Organizing Maps (SOMs) and Artificial Neural Networks (ANNs) excel at identifying complex patterns and spatial structures by enabling automatic feature extraction, pattern recognition, and cluster analysis from remote sensing data without the need for manual supervision [57]. Thus, they are highly useful when applied to LULC classification.

ii. Active Remote Sensing

Active remote sensing relies on the transmission of electromagnetic radiation from a sensor or instrument towards a target, with the sensor then receiving and analyzing the reflected radiation. Active remote sensing techniques like LiDAR (Light Detection and Ranging) can generate high-resolution 3D maps of urban terrain and structures and, therefore, are useful for studying Urban Heat Islands as they provide detailed information about surface characteristics, building morphology, and temperature distributions.

- Urban Morphology Mapping

LIDAR is widely used to assess the urban morphology features (see Figure 9), such as building height, density, and spatial arrangement [58], influencing UHI intensity and spatial patterns. A study by Park et al. [59] utilized LiDAR technology to create accurate 3D representations of urban surfaces, estimate building heights, and generate 3D tree canopy models, in order to conduct a comprehensive analysis of the influence of trees and buildings on UHI intensity. Through LiDAR data integrated with building and tree information, the study investigated how urban shades affect land surface temperatures (LSTs). Their findings highlighted the cooling effects of vegetation and the adverse effects of larger building footprints on local warming.

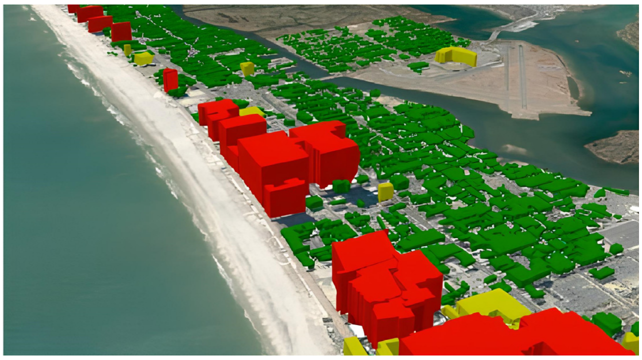

Figure 9. Three-dimensional depiction of the building structures derived from LiDAR data (Buildings are classified as high-rise (red—54.9 meters and above), mid-rise (yellow—54.9–29.3 meters), and low-rise (green—29.3 meters and below). (source: [60]).

- Surface Roughness Characterization

LiDAR data can provide detailed information on surface roughness by capturing variations in terrain elevation and structure heights. These variations are indicative of the presence of buildings, vegetation, roads, and other urban features which contribute to the overall roughness of the urban landscape. LiDAR data are commonly applied when studying urban surface materials' features and performance [61,62].

5.2. Modeling Methods

Modeling methods rely on numerical or computer simulations to predict UHI effects. These simulations can foresee different scenarios of UHIs by integrating several factors such as land use, land cover, urban form and density, and meteorological conditions. Therefore, modeling helps researchers to analyze and test different scenarios of UHIs in a controlled environment. The modeling methods applied to analyze UHIs include the following:

i. Energy Balance Models

Energy balance models use physical equations to simulate the energy exchanges between various components of the urban environment, considering incoming and outgoing radiation, heat storage, and other variables (see Figure 10). These models are typically employed to investigate the surface energy balance and UHI intensity under different urban configurations and meteorological conditions. By comparing the energy balance of urban and rural areas, researchers can identify areas experiencing higher temperatures due to the UHI effect [63]. For rural areas, the energy balance is defined at the evaporating surface and quantifies the partition of net radiation Q^* between soil heat flux Q_g, sensible heat flux Q_h, and latent heat flux: $Q^* = Q_h + Q_g + Q_e$ [64]. However, in urban areas, it considers anthropogenic heat flux Q_f and replaces Q_g with storage heat flux ΔQ_s: $Q^* + Q_f = Q_h + Q_g + \Delta Q_s$) [64].

A study by Dudorova and Belan [65] developed a quantitative energy model to investigate the formation and intensity of the Urban Heat Island effect in Tomsk (Russia) and its seasonal and diurnal variations. The equation [65] describing the radiation flux Q_{UHI}, which contributes to the temperature rise in a UHI, is

$$Q_{UHI} = Q_F + \Delta Q_{sur} + \Delta Q_a + \Delta Q_E - \Delta Q_H^{UHI}$$

where

- Q_F: the anthropogenic heat flux in the city;
- $\Delta Q_{sur} = \Delta Q_{sur}^{SR} + \Delta Q_{sur}^{LR}$: the difference between the shortwave ($\Delta Q_{sur}^{SR} = \Delta Q_{urb.sur}^{SR} + \Delta Q_{rur.sur}^{SR}$) and longwave ($\Delta Q_{sur} = \Delta Q_{urb.sur}^{LR} + \Delta Q_{rur.sur}^{LR}$) radiation fluxes absorbed by the urban $Q_{urb.sur}$ and rural $Q_{rur.sur}$ underlying surface;
- $\Delta Q_a = \Delta Q_a^{SR} + \Delta Q_a^{LR}$: the difference between the shortwave ($\Delta Q_a^{SR} = \Delta Q_{urb.a}^{SR} + \Delta Q_{rur.a}^{SR}$) and longwave ($\Delta Q_a^{SR} = \Delta Q_{urb.a}^{LR} + \Delta Q_{rur.a}^{LR}$) radiation fluxes absorbed by the urban and rural atmosphere;
- ΔQ_E: the difference in urban and rural heat consumption for evaporation;
- $\Delta Q_H^{UHI} = Q_H^{urb} - Q_H^{rur}$: the difference in urban and rural turbulent heat fluxes.

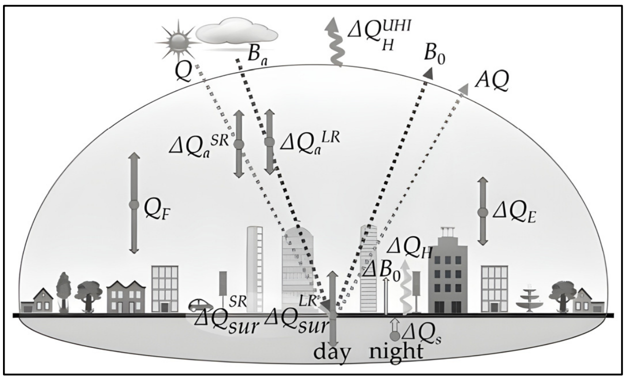

Figure 10. Main changes in the heat and radiation fluxes that cause UHI formation (source: [65]).

The findings revealed that the main contributors to UHI formation were anthropogenic heat emissions and the absorption of shortwave radiation by the urban underlying surface. Specifically, anthropogenic heat emissions accounted for 80–90% of the UHI effect in winter and 40–50% in summer, while the absorption of shortwave radiation amounted to 5–15% in winter and 40–50% in summer. The study also highlighted the role of turbulent heat fluxes in dissipating absorbed energy, with 40–50% released in summer and 20–30% in winter.

A popular model used in UHI analyses is TEB (Town Energy Balance), a sophisticated model developed by Victor Masson [66] from the Centre National de Recherches Météorologiques (CNRM) that calculates surface temperatures, heat fluxes, and other urban climate variables by considering various urban characteristics such as building geometry, surface materials, and anthropogenic heat fluxes. SUEWS (Surface Urban Energy and Water Balance Scheme) is another widely used model that estimates surface temperatures, heat fluxes, and microclimate variables by accounting for urban morphology, vegetation cover, and anthropogenic heat fluxes [67,68].

ii. Computational Fluid Dynamics (CFD) Models

CFD models simulate the flow of air and heat transfer within and around urban structures at a fine spatial resolution. These simulations are used to study microscale phenomena such as street canyon effects, building-induced airflow, and localized temperature variations, offering detailed insights into UHI dynamics at the neighborhood or street level (see Figure 11). Several modeling tools are commonly used to simulate Urban Heat Islands, such as ANSYS Fluent [69,70] or ENVI-met [71,72]. Various studies have used these tools to analyze different urban layouts and predict their microclimate scenarios at early design stages, which is useful for developing efficient mitigation strategies. For instance, a study by Ambrosini et al. [71] evaluated UHI mitigation effects in a historical small center (Teramo, Italy) using the ENVI-Met Climate Model. By using this model, the researchers were able to simulate the interactions between buildings, the atmosphere, and vegetation, and evaluate the effectiveness of mitigation strategies such as cool and green roofs in reducing the impact of UHIs. Their simulations revealed significant microclimate alterations, with thermal gradients of up to 8K during the hottest hours and over 3K at night between built-up areas and vegetated open spaces within a few hundred meters of each other. The analysis highlighted the potential formation of a fully developed UHI in the city, emphasizing the crucial role of urban geometry in shaping local microclimates.

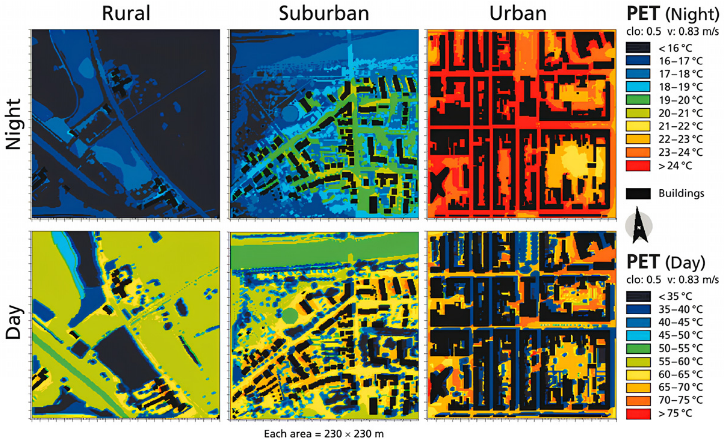

Figure 11. ENVI-met simulation results: the Physiologically Equivalent Temperature (PET) state of three planned areas (rural, suburban, and urban), with a comparison of day and night conditions in the city of Oberhausen (source: [73]).

iii. Statistical Models

Statistical modeling techniques help analyze the relationship between UHIs and various factors such as land cover, meteorological conditions, and demographic and socioeconomic data (see Figure 12). Through statistical models, researchers can analyze and predict different UHI scenarios. Multiple Linear Regression (MLR) models are often employed for this purpose, allowing researchers to identify significant predictors of UHI intensity and estimate their individual contributions. For example, researchers may use MLR to analyze how land use composition, building density, vegetation cover, and other urban form variables influence UHI intensity across different neighborhoods or cities [74].

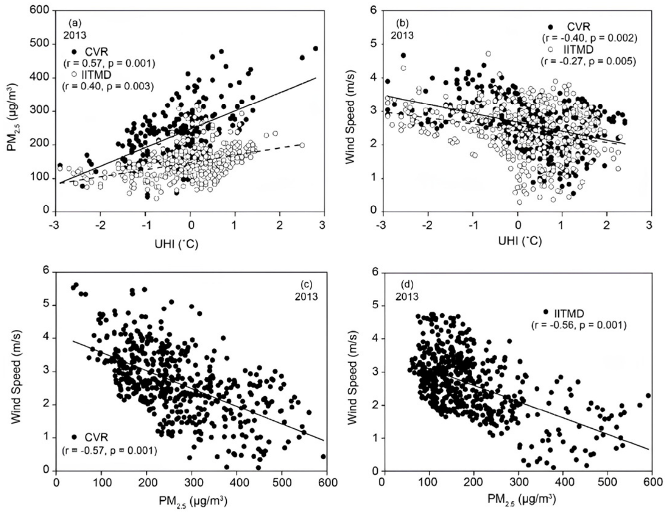

Figure 12. Regression analysis to explore the correlation between the UHI in New Delhi and two possible dependent variables during a specific period (**a**) PM2.5 concentration and (**b**) Wind speed, and regression between the PM2.5 concentration and Wind speed at (**c**) CVR site and (**d**) IITMD stations. The solid and dashed lines in represent the regression lines) (source: [75]).

Researchers often utilize specialized techniques like Stepwise Multiple Linear Regression (SMLR) to study the interaction of urban forms and the UHI phenomena. SMLR is a variant of MLR that automatically selects the most relevant subset of predictor variables from a larger pool of potential predictors based on their statistical significance [76]. This approach is particularly useful when dealing with a large number of potential predictor variables, as it helps to streamline the model selection process and identify the most influential factors driving UHI intensity. Other relevant models used for this purpose include Geographically Weighted Regression (GWR), which accounts for spatial variations in the relationships between urban form and temperature [77].

5.3. Field Measurement Methods

Field measurements and sensor networks play a crucial role in quantifying and understanding the Urban Heat Island phenomenon by providing detailed spatial and temporal data on temperature variations within urban environments. To study UHI patterns, field measurements can be conducted either through mobile measurements using mobile sensors or through fixed measurements using sensor networks across the study area.

i. Mobile field measurements

Mobile measurements involve using portable sensors like handheld temperature sensors, thermal imaging cameras, or infrared thermometers to collect temperature data while moving through urban areas (see Figure 13). These methods provide researchers the flexibility to assess temperature gradients and variability across different microenvironments. Researchers conduct transect surveys by walking or driving predefined routes to collect temperature measurements, allowing for the systematic sampling of temperature gradients and the identification of UHI hotspots. Some studies also monitored CO_2 and PM_{10} concentrations to provide a comprehensive analysis of the impact of urban morphology and anthropogenic activities on microclimate variables [78]. The measurements can be conducted at various times to capture diurnal variations and over extended periods to assess seasonal changes in temperature gradients and microclimate conditions. The gathered data are integrated with geographic information systems (GIS) to enable the visualization of temperature distributions and correlations with urban features. For instance, Liu et al. [79] relied on an integrated method combining mobile measurements along a designated route and GIS-based spatial interpolation to analyze local-scale Urban Heat Island characteristics in the Shenzhen Overseas Chinese Town (OCT) area. The study found significant relationships between influential urban pattern indicators and local-scale Urban Heat Island intensity (LUHII) in the Shenzhen Overseas Chinese Town (OCT) area. The results revealed that building density (BD) exhibited a strong positive correlation with LUHII in August, while building height (H) and ecological coverage rate (ECR) showed negative correlations. Specifically, the BD had a Pearson's r of 0.778 in August, H had a Pearson's r of -0.472, and ECR had a Pearson's r of -0.694, indicating their respective impacts on LUHII [79].

Figure 13. Equipment used for UHI study conducted by mobile measurement bicycle (source: [80]).

ii. Fixed Measurement Networks

Fixed measurement networks consist of stationary sensors strategically positioned across urban areas to monitor temperature changes over time, providing the continuous data collection crucial for understanding diurnal and seasonal fluctuations in UHI intensity. Sensors are placed at various locations within the urban canopy layer, such as parks, streets, and green spaces, and at different heights above the ground (see Figure 14) to capture spatial temperature variations and assess temperature gradients [81,82]. Connected to data loggers, these sensors record temperature data at regular intervals, enabling a detailed temporal analysis of UHI dynamics. A study by Lyu et al. [83] suggested an advanced method for UHI prediction with high spatiotemporal granularity by integrating satellite remote sensing data and urban sensor network data within a cyberGIS and machine learning framework. The researchers employed various machine learning models, with Random Forest showing a superior performance in predicting UHI. Their temporal analysis revealed that the UHI cluster in the downtown area peaked around 3 p.m. and dissipated by 8 p.m., while, spatially, one major UHI cluster was centered around East Village, Chicago, with a minor heat island detected in the north part near Evanston [83]. This cyberGIS framework allowed for the detection of these UHI clusters at a detailed spatiotemporal scale, providing insights into the localized variations of UHI within the city.

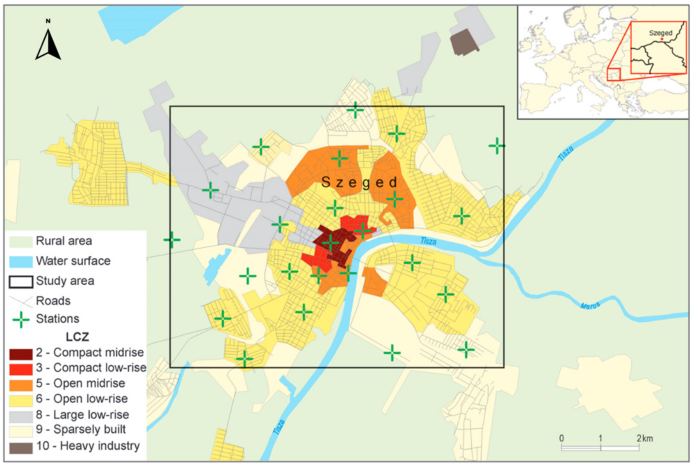

Figure 14. Monitoring network in Szeged, distributed across local climate zones (source: [81]).

6. Advantages, Limitations, and Combinations of UHI Research Methods

The various methods for analyzing Urban Heat Islands each have their distinct advantages and limitations, influenced by the scale and pattern of the studied UHIs (see Table 5). While remote sensing offers a broad perspective by capturing temperature variations across large urban areas, providing valuable insights into spatial patterns and trends over time, it may lack the fine-scale detail necessary to understand localized UHI effects. Modeling approaches, on the other hand, enable researchers to simulate complex urban microclimates and assess the impacts of different variables on UHI intensity. Yet, model accuracy depends heavily on the quality of the input data and assumptions made, potentially limiting their reliability. Field measurements offer ground-truth validation and capture detailed information at specific locations, but they may be time-consuming and costly to conduct over large areas.

Combining these methods can enhance the comprehensiveness of UHI studies. For instance, integrating remote sensing data with field measurements allows for the validation and calibration of satellite-derived temperature values. Similarly, coupling modeling with field measurements enables model refinement and validation against real-world conditions, improving accuracy and reliability. By leveraging the strengths of each method and integrating them into comprehensive research frameworks, scientists can gain a more holistic understanding of UHI dynamics across different scales and patterns, facilitating informed decision-making in urban planning and climate mitigation efforts.

Table 5. Summary of main UHI research methods and their advantages and limitations.

Method	Corresponding Layer	Advantages	Limitations
Remote Sensing	Surface UHI	Passive Remote Sensing utilizes electromagnetic radiation emitted or reflected by the Earth's surface and atmosphere, allowing for the continuous monitoring of UHI intensity and spatial distribution.	Limited temporal resolution, as satellite imagery may not capture short-term UHI fluctuations; data availability and accuracy can be affected during cloudy periods.
		Active Remote Sensing employs active sensors (e.g., radar, LiDAR) to provide detailed information on surface characteristics and elevation.	Involves higher operational costs due to complex instrumentation and data processing requirements.
Modeling	Canopy UHI	Urban Energy Balance Models simulate surface energy balance and heat exchange processes within urban environments, providing insights into the drivers of UHI formation.	Requires extensive input data (e.g., land use/land cover, building characteristics), which may be challenging to obtain and validate.
		Computational Fluid Dynamics (CFD) Models simulate fluid flow and heat transfer within urban environments, allowing for a detailed analysis of airflow patterns, temperature distributions, and UHI dynamics.	Model uncertainties and assumptions may introduce biases and inaccuracies into UHI simulations, which require validation against field measurements or remote sensing data.
	Boundary Layer UHI	Statistical Models analyze historical temperature data and correlate them with urban characteristics and meteorological parameters to identify UHI patterns and predict future trends.	Limited ability to capture spatial variability and microscale UHI variations compared to physical models.
Field Measurements	Canopy UHI	Fixed Sensor Networks allow us to continuously monitor temperature variations associated with vegetation and built structures, facilitating the assessment of canopy UHI effects on local microclimates.	Limited ability to capture spatial variability and intricate patterns of heat distribution in cases of sparse coverage.
		Mobile Monitoring utilizes portable sensors to collect temperature data while moving through the urban environment, enabling targeted surveys of temperature gradients and microclimate variability within the urban canopy layer.	May be affected by sensor calibration errors, instrument drift, and environmental factors (e.g., shading, wind effects), leading to potential measurement biases.
	Boundary Layer UHI	Fixed Sensor Networks measure vertical temperature profiles and boundary layer characteristics to clarify the vertical extent and intensity of UHI effects on atmospheric stability and turbulence.	Requires specialized instrumentation (e.g., radiosondes, tethered balloons) and expertise in atmospheric boundary layer dynamics for accurate measurements and data interpretation.

The table below summarizes the main research methods used for UHI analyses, their corresponding UHI layers, and their advantages and limitations.

To address the presented limitations and achieve a more comprehensive understanding of UHI effects, researchers can rely on the combination of these methods. This integrated approach allows us to compensate for the weaknesses of a method with the strengths of the others, ensuring more robust and accurate UHI studies. For instance, combining field measurements with remote sensing and modeling data allows for cross-validation, which enhances the accuracy and reliability of the data.

The Table 6 outlines the key aspects of each method, their integration with other methods, and the importance of this integration for UHI research.

Research Gaps in Urban Heat Island Studies Amid Global Urbanization and Climate Change Challenges

Despite the significant advancements in understanding the relationship between Urban Heat Islands (UHIs) and urban forms, several research gaps persist, particularly within the context of rapid urbanization and climate change.

Table 6. Combinations of UHI study methods.

Method	Description	Combination with Other Methods	Advantages of the Combination
Field Measurements	Provides ground-level data on temperature, humidity, wind speed, etc.	Crosschecking, validating, and calibrating remote sensing data to ensure its accuracy. Providing real-time, location-specific data to refine and validate the outputs of model simulations.	Enhancing the accuracy of remote sensing data by providing the ground truth for calibration. Improving model reliability by offering precise, location-specific data for validation. Ensuring and facilitating comprehensive studies by confirming results from other methods.
Remote Sensing	Provides extensive spatial and temporal data on land surface temperature (LST) and land use/land cover (LULC).	Providing comprehensive data for modeling inputs while covering a large spatial range, even inaccessible areas. Calibrating satellite-derived LST data with ground truth data to ensure the accuracy of the study.	Offering a broad spatial and temporal perspective that complements detailed field data. Enhancing model simulations by providing extensive datasets for input and validation.
Modeling	Simulates UHI dynamics under various scenarios.	Calibrating and validating model outputs using real-world data from both field measurements and remote sensing data.	Using accurate real-world input data to provide predictive simulations and test scenarios about UHI dynamics.

A critical area that deserves further exploration is the prediction of the impact of rapid urbanization on UHI dynamics. With global urbanization accelerating, there is a growing need for comprehensive studies linking the effects of urban expansion, population growth, and fast land use changes on UHI intensity and its future patterns. Additionally, there is a limited availability of longitudinal studies tracking UHI trends over long-term periods in urbanizing areas. For instance, long-term data can help assess the effectiveness of mitigation measures and project future UHI scenarios under different urbanization and climate change scenarios.

Another essential research direction involves the interactions between UHIs and climate change. Climate change adds another layer of complexity to the UHI phenomenon by exacerbating heat-related risks and affecting urban resilience. Research should explore how future climatic scenarios can interact with UHIs; this can help planners and policymakers to develop adaptive strategies for mitigating heat stress in urban areas at early design stages. Comprehensive comparative analyses across diverse urban contexts are also crucial. By examining UHI patterns in cities with varying climatic conditions, development trajectories, and urban morphologies, researchers can identify common trends, unique challenges, and the best practices for mitigating UHI effects globally.

Additionally, interdisciplinary collaboration and data sharing are essential for addressing the current gaps in UHI research, especially in the context of developing countries. Collaborative efforts between urban planners, climatologists, architects, and policymakers can enrich research methodologies, enhance data interpretation, and facilitate the translation of research findings into actionable mitigation recommendations.

7. UHI Research in Morocco: Methods, Limitations, and Future Prospects

7.1. Urbanization and Climate Challenges in Morocco and the Broader MENA Region

The rapid upward trend in urbanization that Morocco is undergoing is significantly reshaping its landscapes and presenting new challenges concerning climate and energy dynamics. Moroccan cities are expected to be significantly impacted by climate change, particularly as they continue to experience rapid population growth and urbanization. Rising temperatures, water scarcity, and socio-economic challenges are among the most significant impacts of climate change on Moroccan cities [84]. Morocco is particularly vulnerable to climate change impacts as its economy relies heavily on the agricultural sector [84]. This challenge is aggravated by fast urbanization, leading to the continuous consumption of arable lands by new urban settlements. These climate challenges may exacerbate existing social and economic inequalities in cities, particularly in dense suburban slums and informal settlements, where residents are, in addition to having low access to essential services, more vulnerable to extreme weather events.

This situation is illustrative of the broader trends across the Middle East and North Africa (MENA) region, which shares the same dominant climate types, according to Köppen–Geiger climate classifications: desert climates (BWh) and Mediterranean climates (Csa) (see Figure 15). Additionally, MENA countries face common challenges related to rapid urbanization and climate change. The region was identified as a climate change "Hot-Spot" according to the Regional Climate Change Index (RCCI)) [77]. In fact, despite contributing little to climate change historically, the region's heat levels are projected to rise at almost twice the global average rate in the coming years [85]. The Intergovernmental Panel on Climate Change (IPCC) predicts that, by 2050, the MENA region will experience more frequent and severe droughts, heat waves, and extreme weather events [86]. Additionally, the region experiences some of the highest rates of population growth in the world, with a significant concentration in cities [87]. Within this context, the Urban Heat Island effect is becoming a major concern, as the growing concentration of heat-retaining buildings, roads, and urban infrastructure tends to make cities significantly warmer.

Moreover, the rise in urban populations amplifies energy demands, especially for the residential sector, which imposes new challenges in meeting this growing need while mitigating carbon emissions. A study by Haouraji et al. [88] predicted that the total electricity demand for residential energy consumption (REC) in Morocco will reach 1937 ktoe by 2030, with an average consumption increase of around 115.18%. Therefore, with cities becoming focal areas for economic activity and population growth, the need for sustainable and resilient urban planning practices becomes vital. The country has made notable efforts in water management, renewable energy development, and urban resilience, which serve as valuable examples for other developing nations with similar climate challenges in the MENA region and beyond. Morocco's investments in solar and wind power, alongside improvements in its public transportation and green spaces, provide a model for sustainable urban development. However, despite these efforts, there is still a lack of evidence-based strategies grounded in actual research and collaboration, and the global impact of climate change on cities is still understudied.

Therefore, in order to forge efficient strategies, Morocco must foster scientific research in this field and encourage collaborations between researchers, planners, and policymakers. Scientific research can provide valuable insights into the complex interactions between urban development, environmental sustainability, and societal needs in order to implement urban solutions tailored to the specific context of the Moroccan territory.

7.2. Exploring the Impact of Urban Form on Urban Heat Islands in the Moroccan Context

Various studies have addressed the impact of urban form on Urban Heat Islands in Morocco. Researchers have employed mostly remote sensing data, field measurements, and modeling techniques to understand how urban design influences temperature variations and thermal comfort within cities.

i. The impact of urban morphology/street layouts on UHIs
    - Methods: Field Measurements/Modeling

The research on Urban Heat Islands in Morocco dates back to 2006, when it was first introduced through a collaboration between LPEE (Laboratoire public d'essais et d'études) and the University of Lund (Sweden) in the city of Fez [89]. This study, conducted by Erik Johansson [90] in Fez, relied on field measurements to compare deep and shallow street canyons and assess their impact on outdoor thermal conditions and human comfort. The results showed significant temperature disparities, with the deep canyon being notably cooler than the shallow canyon during the hot summer season, with a maximum temperature difference averaging around 6 °C and reaching up to 10 °C on the hottest days.

Thermal comfort assessments using the Physiologically Equivalent Temperature (PET) index revealed that the deep canyon provided a comfortable environment in summer, while the shallow canyon was considered extremely uncomfortable, with PET values exceeding 40 °C during some peak hours. Conversely, during the winter period, the shallow canyon was found to be more comfortable in winter compared to the deep canyon due to the possibility of solar access.

Another study was conducted in the same city (Fez) in 2016 by Jihad and Tahiri [91]. The objective was to investigate the influence of urban canyon geometry, particularly the aspect ratio, on the Urban Heat Island effect and the consequent energy demand of residential buildings. The research employed modeling techniques to simulate the energy consumption of three types of residential buildings under varying aspect ratios. In addition to simulation models, field measurements from two distinct street canyons in Fez were utilized to validate the accuracy of the simulations. The findings highlighted that the aspect ratio significantly influences canyon ventilation efficiency, affecting pollutant dispersion, building thermal loads, and energy needs. Overall, the annual energy demand was higher than expected, by 17.7% on average, due to the UHI effect. To ensure minimal energy needs, the study recommended aspect ratios of 1.85, 2.14, and 1.93 for the Economic Villa, Economic building, and Medium Class building, respectively.

Similarly, Lachir et Nia [92] investigated the impact of urban design on local climates, specifically focusing on the UHI effect, and analyzed how these urban design factors influence building energy demands in various Moroccan cities with different climate types (Ifrane, Marrakesh, Fes, Tangier, Errachidia, and Agadir). The study relied on energy simulation models and incorporated the Urban Weather Generator (UWG) to assess the UHI effect by generating synthetic meteorological data for different urban contexts and climates. The UWG model was evaluated against field measurements to validate its accuracy. The findings indicated that the intensity of the UHI effect varied notably among the studied cities, with the hourly UHI intensity fluctuating between 11 °C and −5 °C. The highest average annual UHI intensity was observed in Ifrane, Marrakesh, and Fes.

ii. Impact of land use patterns on UHIs (land use/land cover and pervious/impervious surfaces)

   - Methods: Remote Sensing/Modeling

While several Moroccan cities have been subject to UHI research, Casablanca, the largest city in Morocco, with more than 3.5 million inhabitants [93], has been the case study for the majority of this research work. A study conducted by Bahi et al. [94] examined the spatial distribution of surface Urban Heat Island (SUHI) patterns in the Casablanca region, focusing on the effects of urbanization and seasonal cycles. The intensity of UHIs was analyzed using remote sensing data. The researchers employed the Normalized Difference Vegetation Index (NDVI) and the Land Surface Temperature (LST) derived from Landsat 8 imagery to assess the UHI effect. The study revealed significant seasonal variations, with a winter intensification of SUHII in residential and industrial areas, while summer showed contrasting effects, with heat islands in rural regions and cool islands in urban areas. Additionally, urbanization effects, such as built-up density and land surface modifications, were identified as key factors contributing to SUHI development, particularly in industrial zones. Two similar studies by Rhinane et al. [95] and El Ghazouani et al. [96] have relied on remote sensing data to analyze the key factors of UHI formation and seasonal variations in the city of Casablanca.

To understand the influence of land use patterns on UHI formation, some studies conducted comparative analyzes of various Moroccan cities with varying climates and urban characteristics. For instance, El Ghazouani et al. [97] studied the impact of land cover on the Urban Heat Island (UHI) and urban heat sink (UHS) in five Moroccan cities (Tangier, Casablanca, Ifrane, Marrakesh, and Smara). In Tangier, a sub-humid city, the analysis focused on understanding the spatial distribution of temperature and defining the UHI amplitude. Casablanca exhibited significant UHIs, with the city center being notably warmer than coastal areas, emphasizing the role of land cover properties and ambient climate in temperature variations. Ifrane, a mountainous city, showed a moderate UHI amplitude, while Marrakech and Smara displayed distinct UHSs, with temperatures lower by 9 °C to 12 °C, indicating the cooling effects in these arid and hyper-arid cities, respectively.

Due to its fast urban growth, coupled with rising climate concerns, the hot semi-arid city of Marrakesh has also been a focal area for different UHI studies in Morocco. Lachir et al. [98] evaluated the impact of urbanization on the SUHI in Marrakech using remote sensing data (Landsat and MODIS) with the SiB2 model. The study aimed to analyze surface carbon, energy, and water exchanges; assess the Urban Heat Island effect; and investigate the role of vegetation in mitigating urban warming and energy consumption. The results revealed significant temperature variations between urban areas and other cover types, with daytime warming ranging from 1.6 °C to 6.0 °C and nighttime warming from 0.7 °C to 1.1 °C. The expansion of urban areas led to a loss of green spaces, affecting the city's climate. Similarly, Gourfi et al. [99] combined field measurements with remote sensing methods to investigate the relationship between land cover types and the surface Urban Heat Island (SUHI) in Marrakesh. The study identified the significant role of bare ground in influencing the SUHI effect, with bare areas showing the highest correlation with temperature. Changes in vegetation cover over time were found to affect SUHI dynamics, with decreasing correlations between the vegetation index (NDVI) and SUHI due to urban planning policy changes and growth. Moreover, LST variations were observed across the different city neighborhoods (with a maximum mean LST difference of 3.98 °C). This highlighted the influence of urban structures on temperatures, with traditional dense urban layouts contributing to cooler microclimates compared to newer developments.

The literature on UHI research in Morocco shows that the majority of studies relied on remote sensing methods (see Figures 16 and 17) to retrieve LST and LULC data to analyze the relationship between urban forms and UHI patterns. However, a recent study by Derdouri et al. [90] highlighted an existing research gap in these studies. This research gap in UHI studies in Morocco stems from the limited consideration of crucial factors such as terrain characteristics, the limited periods of study, and the underutilization of advanced analytical methods like machine learning (ML) [100]. To address this research gap, Derdouri et al. suggested incorporating advanced ML models with remote sensing data, specifically XGBoost and LightGBM algorithms, in order to analyze LST trends in multiple Moroccan cities over a 30-year period. These ML algorithms are known for their ability to handle the complex and non-linear relationships between variables, capture spatial autocorrelation, and address the issues of heteroscedasticity and multicollinearity commonly encountered in LST research. The findings revealed consistent increases in LSTs over time, with inland cities experiencing higher temperature rises compared to coastal cities. Urban Heat Sink (UHS) features in coastal areas have been diminishing due to urbanization and vegetation cover degradation, while built-up areas, particularly industrial zones, significantly contributed to rising temperatures. Green–blue spaces were found to have a cooling effect on LSTs, emphasizing their importance in urban planning strategies. The Table 7 summarizes the methods and key findings of the other studies on UHIs in Morocco.

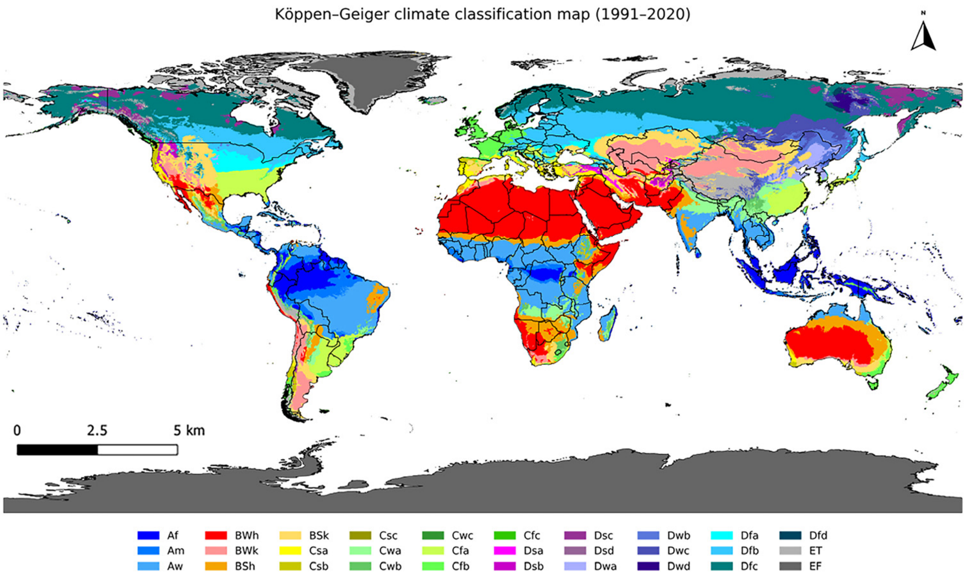

Figure 15. Köppen–Geiger climate classification map (1991–2020). (source: [101]).

Table 7. Summary of studies on UHIs in Morocco (source: authors).

Study	Study Area(s)	Method(s)	Key Findings
[102]	Morocco (24 selected cities representing the 12 regions)	Remote sensing	- UHIs prominent in cities built within vegetated lands, warmer than rural fringe by 1.51 °C during the daytime. - Urban Heat Sink (UHS) observed in cities built within arid regions. - Daytime UHI and UHS amplitudes higher than nighttime; UHI amplitude increases with urban area size.
[103]	Meknes	Remote sensing	- Significant increase in UHI over the last 30 years. - Strong correlation between green surfaces, built-up areas, and SUHI, with a temperature difference of 3.98 °C in different areas of the city.
[104]	Martil	Remote Sensing	- Variations in outdoor comfort levels in different urban areas during summer, influenced by urban morphology, greening, and water elements. - Average temperature difference of 4: 1.8 °C and 3: 0.8 °C between the different areas. - Average difference in aerosol density values: 0.24 mol/m^2 for axis 1 and 0.026 mol/m^2 for axis 2.
[105]	Benguerir	Remote Sensing	- Strong correlation between specific LCZs and surface temperature. - Inversion effect of the surface Urban Heat Island observed. - Urban classes like open low-rise and compact low-rise showed a significant decrease in surface temperature over two decades.
[106]	Benguerir	Modeling	- UTCI values without green spaces: 36 °C. - UTCI values with green spaces: 29 °C. - Reduction in UTCI values by 7 °C thanks to green spaces, improving outdoor thermal comfort and mitigating UHIs.

7.3. Comparative Insights from the Broader MENA Region

The research conducted in Moroccan cities has clarified the complex dynamics between urban forms and characteristics and UHI patterns. Comparing these findings with similar studies in the broader MENA region with comparable climates reveals both similarities and some differences in UHI dynamics and mitigation strategies. For instance, in Egypt, where the literature on UHI studies is larger compared to other countries in the region, several studies have demonstrated how UHIs are significantly influenced by the dense urban fabric and limited green spaces, similar to findings in Moroccan cities. As an example, a study in

Cairo [107] revealed that random urban growth has led to a notable increase in temperatures, with a documented rise of 6 °C in unplanned areas compared to a 2 °C increase in planned areas from the early 1990s to 2015. This significant temperature difference underscores the great impact of urban planning on thermal conditions. Moreover, the study highlighted the effectiveness of green spaces in mitigating the urban heat island effect, with the Maadi area, characterized by approximately 50% green coverage, demonstrating lower temperature increases compared to areas with less vegetation. Additionally, this study underscored the role of street networks and urban density in influencing thermal behavior, with narrow streets shown to aid in temperature regulation and harmful gas reduction (similar to study [91] in Fez), while high urban density exacerbates the urban heat island effect.

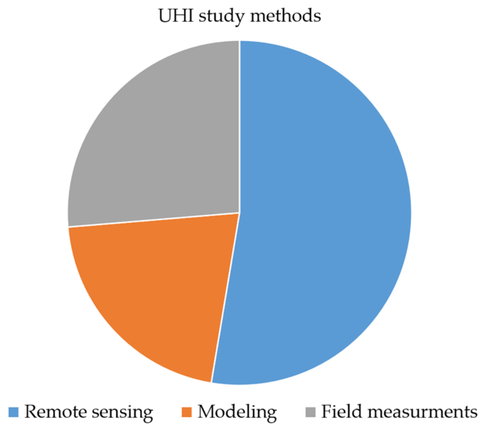

Figure 16. Research methods used for UHI research in Morocco (source: authors).

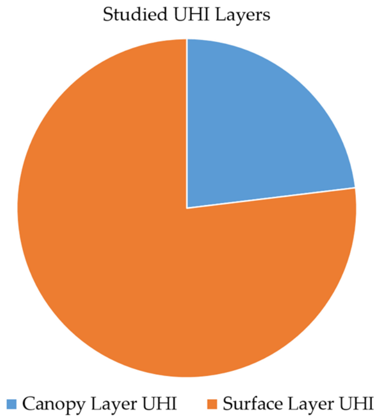

Figure 17. Layers of UHIs studied in Moroccan cities (source: authors).

However, the intensity and spatial distribution of Urban Heat Islands in Cairo are also affected by factors such as higher air pollution [108] and sprawling informal settlements [109], which may present unique and more complex challenges compared to Moroccan contexts.

Another study [110] observed the formation of UHIs in eight cities from the Gulf region (Doha, Abu Dhabi, Dubai, Riyadh, Jeddah, Muscat, Kuwait, and Manamah). Similarly to the study conducted in Marrakech [99], the findings of this study revealed that bare areas had the highest mean LST values compared to urban and green areas. The temperature variations between bare areas and urban areas ranged from 1 to 2 °C, between bare areas and green areas ranged from 1 to 7 °C, and between urban areas and green areas ranged from 1 to 5 °C. However, Gulf cities have unique characteristics that differ from Moroccan cities and therefore may affect their UHI patterns differently. For instance, with arid desert climates and rapid urbanization driven by economic growth, most Gulf cities feature dense high-rise developments and extensive infrastructure, which further intensifies the formation of UHIs due to large areas of heat-retaining materials. Additionally, higher levels of air pollution from industrialization in Gulf cities and limited green spaces due to arid conditions further exacerbate UHI intensities.

These comparative studies underscore the importance of context-specific strategies for UHI mitigation. For instance, while the general mitigation principles of increasing vegetation and optimizing urban design are applicable across different regions, their specific implementation must consider local urban forms, socio-economic conditions, and climatic characteristics.

7.4. Research Gaps of UHI Studies in the Moroccan Context

Despite the growing body of literature on UHIs globally, several research gaps in understanding UHI dynamics still persist in the Moroccan research landscape. Although existing studies on Morocco have provided valuable insights into the spatial distribution of UHI patterns and the influence of urban characteristics on their intensity, these studies are still limited in scope and depth, stressing the need for more comprehensive research to fill the existing gaps.

One of the key research gaps in studying UHIs and urban form in Morocco is the lack of long-term monitoring and an analysis of UHI trends. While some studies have highlighted the immediate impacts of UHIs in specific cities like Casablanca and Marrakesh, there is a need for continuous monitoring to assess how UHI dynamics evolve over time and space. Longitudinal studies can provide valuable insights into the temporal variability of UHIs, the impact of seasonal variations, and the effectiveness of mitigation measures in different urban contexts.

Furthermore, there is a research gap in exploring the socio-economic implications of UHIs for vulnerable populations in Moroccan cities. In fact, in Morocco, like most developing countries, low-income populations tend to live in highly dense urban areas and informal settlements. These urban forms, as shown in the literature, are more vulnerable to the growing impacts of climate change, notably UHIs. Research including the social dimensions of UHIs can inform targeted interventions to enhance the resilience of urban communities and reduce heat-related health risks.

Another research gap concerns the integration of advanced analytical methods and innovative technologies in studying UHIs in Morocco. While some studies have started to leverage remote sensing data, some modeling approaches, and introduced machine learning algorithms, there is a need for further advancements in research methodologies and the combination of methods. Integrating these advanced technologies can enhance the accuracy of UHI assessments, improve the predictive modeling of UHI dynamics, and support evidence-based decision-making for mitigation strategies.

i. Constraints and Difficulties of UHI Research in Morocco

Despite the importance of studying UHIs, researchers in Morocco face several constraints and difficulties in conducting research in this field. For instance, the lack of comprehensive datasets and infrastructure for monitoring microclimatic conditions within urban areas poses a challenge in accurately assessing UHI characteristics and validating research findings. Furthermore, the complexity of urban systems and the dynamic nature of UHI dynamics require interdisciplinary collaboration and expertise, which may be limited in the current research landscape.

Moreover, the need for continuous data collection and long-term monitoring to capture temporal variations in UHI patterns present logistical challenges for researchers. Additionally, funding opportunities for UHI studies are often limited, which can hinder the implementation of advanced research methodologies and data collection techniques. Overcoming these constraints and difficulties in UHI research in Morocco requires strategic partnerships and investment in research infrastructure to advance scientific knowledge and inform sustainable urban planning practices, especially under the growing concerns of climate change in Morocco and its broader region.

7.5. Future Research Prospects: Advancing and Linking Research to Practice for Contextual Mitigation Strategies

i. Towards comprehensive studies in Moroccan Cities: Closing the Research Gap

To address the identified gaps in the Moroccan context, several solutions, inspired by the global literature and global initiatives, can be suggested to support future research endeavors. First, as implemented in many cities across the world (Singapore [111], Barcelona [112], Chicago [113], etc.), establishing a comprehensive and continuous monitoring system for UHI dynamics in Moroccan cities is essential. This system includes permanent monitoring sensors to collect real-time data on temperature variations and other parameters of urban microclimates. For instance, large cities like Casablanca and Marrakech could benefit from installing temperature, humidity, and air quality sensors on buildings and in public areas. These long-term datasets will provide valuable insights into UHI patterns and climate change impacts, while also being made publicly available to facilitate further research and community awareness. Moreover, integrating socioeconomic dimensions into UHI studies is important for understanding disparities in vulnerability and resilience among different population groups. Researchers can link social indicators such as income levels, housing conditions, and access to green spaces with different urban fabrics in order to assess the impact of UHIs on vulnerable communities. Such studies will help evaluate UHIs' effects on residents' health, energy costs, and overall quality of life. Additionally, this can inform targeted interventions and policy recommendations, prioritizing the most vulnerable communities. Another key to advancing UHI research in Morocco is embracing innovative technologies and analytical methods, such as remote sensing, geographic information systems (GISs), and machine learning tools. By leveraging these advanced tools, researchers can improve the spatial mapping of UHI hotspots, model future UHI scenarios under different climate change projections, and identify effective mitigation strategies tailored to specific urban contexts. For example, using high-resolution satellite imagery and GISs, researchers can create detailed heat maps of cities to identify UHI hotspots, while machine learning algorithms can predict how changes in land use or vegetation cover might influence their intensity.

Finally, multidisciplinary collaboration must absolutely be encouraged in order to address effectively the multifaceted challenges posed by UHIs. Researchers from diverse backgrounds, such as urban planning, climatology, social sciences, and public health, can address complex research questions, integrate diverse perspectives, and develop holistic solutions to mitigate UHI effects. For instance, urban planners and architects can collaborate with climatologists to incorporate climate projections and microclimatic data into urban design plans to ensure the development of climate-resilient and sustainable urban environments. Public health experts and social scientists can cooperate with policymakers to identify vulnerable populations at risk of heat-related health issues and implement targeted interventions to enhance community resilience. Additionally, engineers can contribute their expertise in developing advanced technologies and smart urban solutions, either to monitor or mitigate UHIs, such as solutions to reduce urban temperatures and improve energy efficiency.

ii. Bridging Research and Practice for Sustainable Urban Planning

The research conducted in Moroccan cities, particularly focusing on large cities like Casablanca and Marrakesh, has clarified the complex dynamics between urban forms and characteristics and UHI patterns. Through remote sensing methods and field measurements, these studies have revealed the spatial distribution of surface Urban Heat Islands (SUHIs) and their intensity, the influence of land cover on temperature variations, and the role of urban design in mitigating or exacerbating UHI effects. Furthermore, recent research has identified gaps in existing studies and proposed advanced analytical methods, such as machine learning algorithms, to enhance our understanding of UHI dynamics over time and space.

Therefore, fostering research in this field is crucial for forging future strategies of climate mitigation and sustainable planning for Moroccan cities. By bridging the gap between researchers, planners, and policymakers, scientific research can contribute to evidence-based decision-making and facilitate the implementation of urban solutions tailored to the specific context of Morocco. As cities continue to be focal areas of economic activity and population growth, addressing the challenges posed by UHIs and climate change requires interdisciplinary collaboration and continuous scientific inquiry to ensure the resilience and well-being of urban communities in Morocco.

To illustrate how research can be linked to practice, the Table 8 suggests some UHI mitigation strategies deduced from the findings of the existing studies in the Moroccan context.

Table 8. Potential UHI mitigation strategies for Moroccan cities.

UHI Mitigation Strategy	Description	Evidence/Studies	Implementation
Optimizing Urban Morphology and Street Layouts	Design urban canyons with optimized aspect ratios to enhance thermal comfort and reduce UHI effects.	Deep canyons are cooler than shallow canyons during summer, with temperature differences up to 10 °C (Study [90]). - Recommended aspect ratios to minimize energy demand (Study [91]).	- Integrate optimal aspect ratios into urban planning and zoning regulations. - Retrofit existing urban layouts to improve air circulation and reduce heat accumulation.
Enhancing Green Infrastructure	Increase the presence of green spaces, such as parks, green roofs, and urban forests, to mitigate UHI effects and improve thermal comfort.	- UTCI values reduced by 7 °C in areas with green spaces in Benguerir (Study [106]). - Green spaces reduce SUHI effects in Marrakesh (Study [99]).	- Implement extensive urban greening programs, prioritizing high-intensity UHI areas. - Promote the installation of green roofs and walls in new and existing buildings.
Incorporating Water Features	Integrate water features such as fountains, ponds, and urban lakes to cool urban environments through evapotranspiration and provide thermal comfort.	- Water elements influence outdoor comfort levels in Martil, with significant cooling effects (Study [104]).	- Incorporate water features into urban design plans for new developments and public spaces. - Ensure the maintenance of existing water features, especially in heat-prone areas.
Utilizing Reflective and Permeable Materials	Use reflective and permeable materials in urban surfaces to reduce heat absorption and enhance cooling.	- Built-up density and land surface modifications significantly influence SUHI development (Study [94]).	- Implement cool roofing materials and reflective pavements in urban infrastructure projects. - Promote the use of permeable materials for sidewalks, parking lots, and other paved areas.
Strategic Land Use Planning	Develop land use plans that balance urban development with natural landscapes and vegetation cover.	- Urbanization and land cover properties significantly contribute to UHI formation (Study [97]).	- Implement zoning regulations to protect green spaces and limit the expansion of impervious surfaces. - Monitor and control urban sprawl to ensure sustainable development practices prioritizing the conservation of natural spaces.

8. Discussion

By synthesizing the existing literature and analyzing the various research methods used in UHI studies, this review explored the complexities of UHI dynamics and their implications for urban planning and climate resilience strategies.

One key aspect highlighted in this study is the prominence of remote sensing methods in quantifying UHI intensities and spatial patterns. Remote sensing technologies provide researchers with large-scale spatial data, enabling the analysis of UHI variations across different urban areas and their surrounding regions. Through remote sensing data, researchers can identify the key urban form parameters that influence UHI intensity, such as land cover properties, surface temperatures, and atmospheric conditions.

Additionally, this review explored the advancements of modeling approaches, such as numerical simulations and computer models, and their significant role in simulating and predicting UHI dynamics under different scenarios and at early design stages. These modeling techniques allow researchers to explore the impact of urban design elements, such as building configurations and street layouts, on UHI formation and intensity. Moreover, the study revealed the importance of field measurements in validating remote sensing and modeling results, providing detailed insights into local UHI characteristics and thermal profiles. By conducting on-site data collection, researchers can better understand the real-world microclimatic conditions within urban areas and assess the effectiveness of UHI mitigation strategies.

Overall, this review of UHI studies highlights the importance of employing a combination of research methods and technologies to conduct studies that are more comprehensive and achieve accurate more results. By integrating remote sensing, field measurements, and modeling approaches, researchers can develop evidence-based strategies to mitigate UHI effects, enhance outdoor thermal comfort, and optimize energy use.

Subsequently, the results regarding the various study methods used to understand the connection between urban form patterns and UHI intensity were reviewed within the context of Morocco, providing an example for similar developing nations in the MENA region. This overview of the Moroccan context revealed important insights into the spatial distribution of UHI patterns, the influence of urban characteristics on UHI dynamics, and the effectiveness of mitigation strategies such as green spaces in reducing UHI intensity. Studies in rapidly growing Moroccan cities like Casablanca and Marrakesh have highlighted the complexities of UHI effects and emphasized the need for advanced modeling and analytical methods, including machine learning, to enhance our understanding of UHI dynamics over time and space and predict future scenarios.

However, it is important to note that studies on UHIs in Morocco are still limited, underscoring the need to foster further research in this area. Additionally, Morocco is yet to develop comprehensive mitigation strategies to address the challenges posed by UHI effects, highlighting the importance of advancing scientific inquiry and interdisciplinary collaboration to ensure the resilience and well-being of urban communities in the country.

The research insights on how urban morphology, land cover characteristics, and building layouts influence UHI dynamics provide a valuable framework for policymakers to create climate-conscious policies and design plans tailored to the specific context of Moroccan cities. These tailored solutions not only mitigate the Urban Heat Island effect but also contribute to energy efficiency, improved air quality, and enhanced urban comfort.

By translating study findings into actionable urban solutions, Moroccan cities can address UHI challenges, promote urban resilience, and create livable spaces that ensure the well-being of residents and respect for the environment.

9. Conclusions

Understanding and addressing the complexities of UHI dynamics are crucial for sustainable urban development and climate resilience. The insights deduced from the literature, methodologies, and research advancements in Morocco highlight the significant impact of urbanization and climate change on UHI intensity and spatial distribution. By examining the various research methods and technologies employed in UHI studies, such as remote sensing, field measurements, and modeling techniques, ths study sheds light on the complexities of urban forms and UHI dynamics and their implications for thermal comfort and energy use.

The utilization of advanced analytical methods, including machine learning algorithms and remote sensing data analysis, has revolutionized the study and understanding of UHI dynamics. These methods have allowed researchers to identify key factors influencing UHI intensity, such as land cover properties and urban design, providing valuable insights for mitigating UHI effects, improving outdoor thermal comfort, and optimizing urban energy use.

While existing research has provided valuable insights into the spatial distribution of UHI patterns and the influence of urban characteristics on their intensity, several gaps are still to be addressed. Key research gaps include the lack of long-term monitoring and analyses of UHI trends, the limited exploration of the socio-economic implications of UHIs and climate change on vulnerable populations, and the need for integrating advanced analytical methods and innovative technologies.

Moving forward, it is essential to continue fostering research in this field to inform sustainable planning strategies and climate-conscious policies for Moroccan cities and cities across the MENA region characterized by similar climate specificities and challenges. By bridging the gap between research findings and practical urban solutions, informed by scientific inquiry, sustainable planning strategies can be developed to enhance urban areas' adaptive capacity in the face of ongoing urbanization and climate change challenges.

Author Contributions: Conceptualization, Review and Analysis, Writing—Original draft, K.B.; Review and Validation, A.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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