Discover Cities

Review

Urban heat island effect in India: a review of current status, impact and mitigation strategies

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Received: 20 June 2024 / Accepted: 19 November 2024
Published online: 05 December 2024

Abstract
The Urban Heat Island (UHI) phenomenon significantly affects us by exacerbating heat discomfort, increased energy consumption, and urban air pollution. The severity of UHI associated with heat waves and heat stress-related mortality is now one of the major concerns, particularly in densely populated cities. Therefore, the significance of the UHI has emerged as a crucial issue due to cities' fast growth and urban development, necessitating a comprehensive review of the present status of UHI research, particularly concerning regional comparisons. This paper delineates the characteristics of UHI, focusing on its intensity, impact, determining factors, and potential mitigation strategy. It synthesizes an insight into important aspects of UHI from a comprehensive analysis of over 400 national/international research articles. The findings indicate a lack of UHI research studies in the central and eastern regions of the country, bringing out the need for further investigation in these areas. The observed UHI intensity varies across the country between 2 and 10 °C, with the northwest seeing a more pronounced temperature gradient. Following a detailed review, a few suggestions for future research to minimize the impact of UHI on public health, energy consumption, and the economy are proposed, as are strategies for mitigation. While studies on UHIs in India have primarily relied on observational data, there is still a substantial need for more research on employing numerical model-based and machine-learning approaches. Furthermore, the availability of mitigation research on Indian cities is limited. Additional research is needed to ascertain the intricate mechanisms behind the UHI effect on cities vulnerable to various climatic risks and hazards.

Keywords UHI · Review · Consequences · Mitigation · Future

1 Introduction

Cities worldwide are experiencing rapid urbanisation, marked by both horizontal and vertical expansion, to accommodate the needs of increasing populations [1]. Urbanisation, which modifies land use and land cover (LULC), upsurges absorption of solar radiation primarily due to proliferated artificial dark surfaces and building materials that are characterised by low albedo, higher thermal capacity, and conductivity compared to non-urban areas [2]. Because of this, temperature is elevated over the cities and experience a phenomenon known as Urban Heat Island (UHI), which is delineated by higher near-surface air temperature than their non-urban surroundings, particularly at night [3–12]. The primary factors

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contributing to this phenomenon are the properties of urban infrastructures, reduced sky visibility, decreased relative humidity and latent heat flux, increased sensible heat flux, diminished vegetation coverage, and limited open space in urban environments [13, 14]. Figure 1 illustrates a schematic view of the components that influence the urban heat island phenomena (Adapted from [15], page 2).

Undoubtedly, urbanisation has led to significant advancements in human comfort and the augmentation of quality of life. However, it has also brought along numerous unforeseen adverse effects. Urbanisation, in conjunction with UHI impacts in metropolitan areas, significantly changes local and regional climates, contributing to weather extremes such as higher temperature anomalies, thermal stress, and frequent and protracted heat waves [16–25]. These aspects have a significant impact on energy consumption [26–28], the economy [29], air pollution [30], and society as a whole. The elevated temperatures also cause heat-related illness and mortality, particularly among vulnerable populations [31, 32]. In addition, the increase in UHI dehydrates the land, which could result in water shortages [33, 34]. Given these consequences, it is imperative to comprehensively assess the effects of the UHI phenomenon, considering its social and economic ramifications and the imperative to control the escalating UHI levels.

Numerous studies have proven the specific regional climatic hazards faced by urban regions and the causal association between urban growth and climate change [35, 36]. Due to extensive urbanisation, Southern Asia might have substantial economic and health ramifications [37]. The cumulative effects of rising temperatures in Indian cities are associated with heat stress conditions, which could result from the acceleration of global warming and climate change [38, 39]. Thus, a comprehensive review of the UHI is necessary for scientific communities to understand its status and impact on urban areas, particularly in India, one of the fastest-growing urban countries [40].

According to the 2011 Census data, nearly 31% of India's population resides in urban areas, contributing 63% of the country's gross domestic production. By 2030, approximately 40% of India's population would likely reside in urban areas and contribute 75% of the country's GDP [41, 42]. In recent decades, India has seen tremendous urbanisation and industrial expansion, resulting in weather extremes that have adversely affected the overall quality of life, particularly in urban areas [43–49]. Nevertheless, there needs to be more scientific analysis and study on the changing pattern of UHI and urban growth in India's major cities [50–52].

Few observational-based studies demonstrated the causes of UHI and its impact on cities. Analysis of remote sensing and on-site measurements over India showed that UHI intensity is caused by man-made heat sources and patterns of LULC [53, 54]. Most studies have shown that UHI intensity over various cities tends to peak at night, with intensities ranging from 2.0 to 10.3 °C [23, 55–57]. A detailed account of the research on UHI undertaken in Indian cities based on observational data is presented (Sect. 7.1).

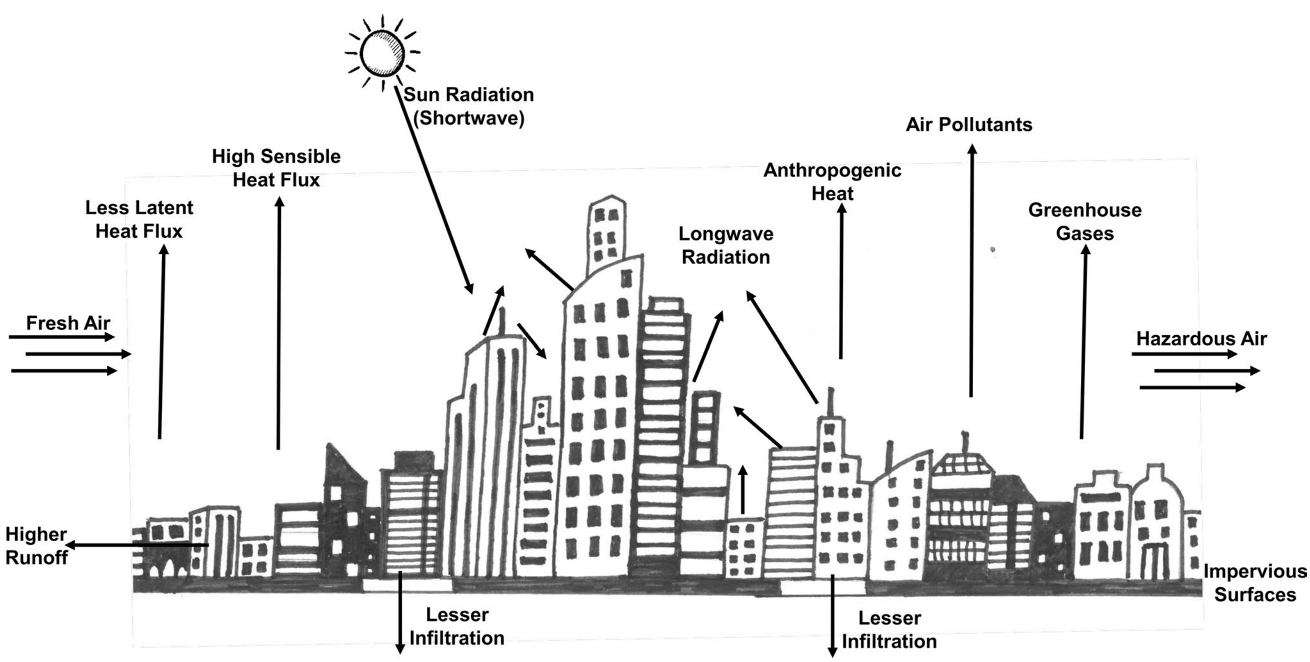


Fig. 1 Schematic representation of the impacts of urbanisation on the environment [15]

Given the Indian government's ongoing development of over a hundred smart cities, research in this domain, specifically in formulating efficient mitigation strategies, must be prioritized [35, 58, 59]. Understanding the present status and future trends of UHI research can help researchers focus on significant concerns and help policymakers develop effective mitigation and adaptation policies. Considering this, the primary objective is to conduct an extensive review of UHI studies in India and an in-depth analytical evaluation of existing and planned future research.

The structure of this review article is as follows: Sect. 2 describes the methodology and techniques used for UHI estimation; Sect. 3 describes the driving factors of UHI; and Sect. 4 discusses the classifications of UHI. Sections 5 and 6 highlight the temporal variability and consequences of UHI, respectively. Section 7 reviews the research on UHI over India that is based on observations and numerical modeling, subsequently the potential mitigation measures are discussed. Section 8 illustrates possible mitigation approaches by emphasizing the significance of addressing UHI effects. The research gaps for UHI are presented in Sect. 9, along with necessary and possible research directions in the future. Finally, Sect. 10 concludes the article, summarising the findings and identifying areas that could benefit further investigation.

2 Methodology and techniques

An extensive literature review (more than 300 peer reviewed articles) has been carried out in preparing this manuscript by contextualizing the UHI research activities, describing its scientific methodologies, the plan for further research, the issues and potential areas for mitigation improvement, and future directions. The review study used web-based search engines for academic materials and scholarly publications.

a. We screened the research articles to identify studies related to UHI. A variety of search phrases, including "impact of urbanisation," "effect of urban heat island," "effect of UHI and heatwave in India," "relationship between UHI and heatwave," and "UHI review in India," were used to identify a substantial number of scholarly articles and research materials. The criteria are then applied to the reviewed articles: peer-reviewed publications in English; the impact of UHI intensity; the UHI and heatwave relationship; observational research on UHI; and UHI modeling research.
b. We sorted through these publications to find articles relevant to the UHI issue, utilizing information from the titles, abstracts, methodologies, and results to create a helpful database pertinent to the topic.

Our study primarily examined recently published articles to gain insights into the latest research results on the UHI phenomenon. This review study carefully examines the existing literature on the causes, effects, and ways to improve UHIs to find the most relevant findings, present the topic clearly and concisely, and suggest possible areas for further research.

3 Driving factors of UHI

The processes and factors contributing to the formation and intensification of the UHI phenomenon are one of the thrust research areas [60, 61]. UHI's intensity is affected by factors such as LULC pattern, local climatic variations, city location, city structure, urban growth, and cities' geometric and topographical attributes. When tall urban canyons and dark surfaces with low reflectivity soak up sunlight, it raises the surface and atmospheric temperatures and enhances heat retention across a metropolitan area [8]. Human activity, including releasing waste heat from air conditioning systems, vehicles, and industrial processes, substantially impacts the proliferation of urban heat islands. Numerous factors may contribute to the UHI phenomenon; however, the following elements are the most significant contributors to the UHI effect:

3.1 Influence of geolocation

The UHI phenomenon in a specific region arises from a confluence of local climatic and topographical attributes, including urban density, latitude, elevation, and atmospheric stability [62, 63]. The contribution of local terrain to the formation of heat islands becomes increasingly significant when larger-scale influences, such as prevailing wind patterns, are relatively weak. In addition, proximate mountain ranges may obstruct wind flow toward a city or generate wind patterns that traverse an urban area [64]. The intensity of the UHI is directly related to the size of the urban region and arid atmospheric conditions, among others [65–67]. When these conditions prevail, urban surfaces receive the maximum solar radiation in clear sky conditions and emit negligible surface heat, leading to elevated temperatures, particularly over flat terrain. Thus, the presence of hills and the land surface characteristics can impact the formation of urban heat islands. However, this effect diminishes gradually throughout the day in regions characterized by elevated terrain or hilly areas, primarily due to the equilibrium between surface energy and solar radiation [3, 68]. Depending on the size of the city and the geographic features in its surroundings, the UHI effect on rainfall may also be enhanced [69, 70] or initiated [71]. Therefore, the association between precipitation and urbanisation exhibits variation contingent upon the physical location of the urban area.

The degree of the UHI intensity fluctuates depending on whether the city of interest is inland or near the coast. For example, the presence of oceans, seas, or lakes can regulate temperature variability and induce the formation of breezes that carry heat away from urban areas. It is to be noted that sea breezes exhibit significant variations across different locations due to the diverse underlying surface conditions. One way to study the variability of UHI influence in highly developed cities on the coast is to analyse the relationship between urbanization and humid weather [72]. However, the complex thermodynamics of urban regions pose challenges in measuring the influence of sea breeze on UHI fluctuation in coastal cities such as Mumbai, Chennai, and Kolkata in India [73]. It is worth mentioning that the urban areas surrounded by humid rural regions may experience beneficial natural cooling effects during sweltering and humid conditions [74].

3.2 Dimensions of urban area

The vertical and horizontal dimensions, building density, heat-absorbing capacity of urban structures, and city geometry mostly dictate the severity of the UHI effect. Oke [65] presented empirical findings regarding the correlation between UHI intensity and city size (as measured by population). This study provided evidence that the intensity of the UHI is inversely proportional to regional windspeed and logarithmically proportional to population size when clouds are absent. Research on the UHI effect in Gothenburg City, Sweden, identified urban geometry as the primary determinant of temperature variations within cities [75]. The city growth characterized by the construction of high-rise structures exacerbates the UHI effect by blocking or reducing the natural wind flow and raising the surrounding temperature [9, 28]. Reduced wind speed hinders the movement of heat from the surface to the surrounding air, resulting in an increase in heat retention. Another study has shown that the city's size has the most significant impact on UHI, followed by the city's compactness and the degree to which the cities grow [76]. They also examined the complicated relationship among UHI intensity, city size, fractality, and anisometry. The UHI intensity rises with city size and fractal dimension but decreases with anisometry.

3.3 Anthropogenic activities

Anthropogenic activities, such as building development, vehicle production, and industrial system operation, have multidimensional sources and are responsible for heat islands within metropolitan areas [77]. Heat islands are characterized by excessive energy consumption and the resulting creation of surplus heat, contributing to an elevation in local temperatures. A study found that human-generated heat and material properties such as albedo substantially influenced urban air temperatures [78]. The generation of local ambient heat is mainly due to residential appliances, heating and cooling systems in buildings, and various manufacturing processes [9]. Therefore, the heat emitted from anthropogenic sources significantly influences the formation of UHI, especially in denser urban areas [79].

3.4 Weather conditions

It is widely known that radiation, clouds, and the wind are the most significant meteorological parameters that play a vital role in developing heat islands [80]. When the weather is bright and quiet, heat island intensities are at their peak since this is when a significant amount of sunlight strikes urban areas, and the least amount of heat is lost by convection [74]. When the outside air temperature is moderate, the air within buildings has a greater capacity to retain heat for extended periods. Contrarily, the impact of heat islands is reduced when there is an increase in brisk wind and cloud cover [64, 79].

4 Classifications of UHI

There are a few distinct variants of UHI occurrences, and the methods of approach and measurement determine these variations. Some of the important types of UHIs are discussed below.

4.1 Surface UHI

The UHI is referred to as Surface UHI (SUHI) when the UHI intensities are calculated using the surface temperature, as shown in Fig. 2. The main factor influencing SUHI is the disparity in daytime radiative surface heating between urban and rural areas caused by oscillations in solar radiation intensity, local meteorological conditions, and ground cover. Therefore, this variability and the SUHIs are frequently the highest during the summer [9, 74]. Urban surfaces, including structures, roads, pavements, open spaces, water bodies, and vegetation covers, contribute to the development of the SUHI [81]. It may also be noted that urban expansion, geographical location, urban materials, seasons, and the duration of day and night play essential roles in modulating SUHIs [82]. The SUHI is the most popular approach for studying the urban thermal environment because of the availability of various remote sensing data [83], such as thermal satellite images and GIS techniques [84]. Remote sensing technology, thermal imaging, and field observations have been used to assess the intensity of the SUHI in metropolitan areas. SUHIs refer to the land surface temperature (LST) differentials between neighbouring regions within a metropolis or core city and its immediate surrounding rural areas and are the most prominent during the daytime [85, 86]. LST is "how hot the Earth's surface would feel to the touch in a certain place" [87]. To calculate SUHI, one may utilise the Eq. (1):

$$SUHI = LST_{City} - LST_{Rural}, \tag{1}$$

where LST_{City} is computed inside urban and built-up environments, while LST_{Rural} is estimated within rural areas, such as waterbodies and vegetation areas.

It is vital to accurately discern between the urbanised built-up area and the rural vegetation surroundings. A densely populated urban built-up region typically defines an urban area. Alternatively, one can select rural areas by considering NDVI values that exceed 0.5, which should be at least 5 km from the urban build-up areas [88]. The rural area should be sufficiently far from any dominant water bodies. Based on these criteria [88], we have determined that urban and rural areas (Fig. 2) exhibit a temperature difference of 0.5 °C to 3 °C, with urban areas consistently experiencing greater temperatures than the surrounding rural areas.

Figure 2 is an example of Pune City, India and five rural locations identified following the aforementioned criteria used for UHI calculation. Empirical findings indicate that despite identical NDVI values across five identified rural locations, there are noticeable variations in the corresponding UHI values. Additional research would be necessary to determine the exact reason for these differences, however, it could be related to local meteorological conditions.

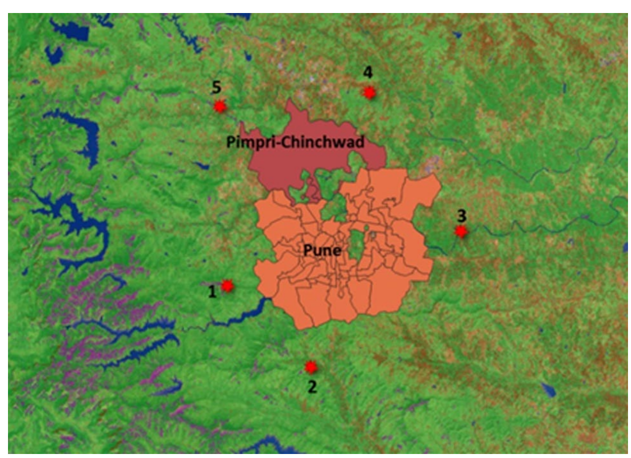


Fig. 2 Urban and Rural area identification

4.2 Atmospheric UHI

The atmospheric UHI (AUHI) is estimated from the difference in measured air temperature over urban and adjacent rural areas. The effects of AUHI tend to be negligible in the late morning and throughout the day. In contrast, the impact becomes more noticeable in the evening due to the prolonged dissipation of heat from urban infrastructure [89]. AUHIs are primarily responsible for the differential in cooling rates between urban regions and their rural or non-urban surroundings. This difference in cooling rates is especially noticeable on clear, calm nights [90] and on days when rural locations may cool more rapidly than urban ones. AUHIs can be subdivided into the canopy and boundary layer UHI based on the altitude at which their effects are detected [91, 92]. The Canopy layer UHI (CUHI) is computed from the ground surface to the average building height, depicted in Fig. 3 [93]. The inhabited zone of the urban environment is where the UHI effect from the canopy layer is seen to be the most substantial. The CUHI, a microscale to mesoscale atmospheric warming impact linked to cities, is measured by comparing near-surface air temperatures in urban and non-urban locations, typically at 1.5 m AGL [94]. An evaluation of CUHI is best suited for a study conducted at a micro-scale and is often calculated using data from meteorological stations [95]. However, the BLUHI extends above the canopy layer and is often used to study the UHI phenomenon at the mesoscale, as measured by radiosondes [96]. It may grow up to a height of about 1 km during the day and a few hundred meters or even less at night [3]. Canopy and boundary layers are responsible for the complex surface-to-above-ground meteorological interactions [97]. Due to this, surface UHI and canopy layer UHI have the most significant impact on human comfort. Researchers have used several datasets to study the UHI phenomena in all its facets. AUHIs are conventionally measured and quantified through meteorological station observations; in contrast, SUHIs are ascertained through satellite remote sensing data [89, 98]. Figure 3 depicts the schematics of SUHI, CUHI, and BLUHI over a typical urban location [89].

4.3 Micro UHI

The micro-urban heat island (MUHI) is a localized climatic phenomenon in which certain urban areas exhibit higher surface temperatures than their surrounding urban regions. According to the definition provided by Aniello et al. [99], a MUHI is any region in which the surface temperature is greater than the maximum surface temperature attained by the tree canopy. MUHIs refer to urban hot spots as poorly vegetated parking lots, non-reflective roofs, and asphalt roads with too little vegetation. Since microclimate circumstances significantly impact micro-urban heat

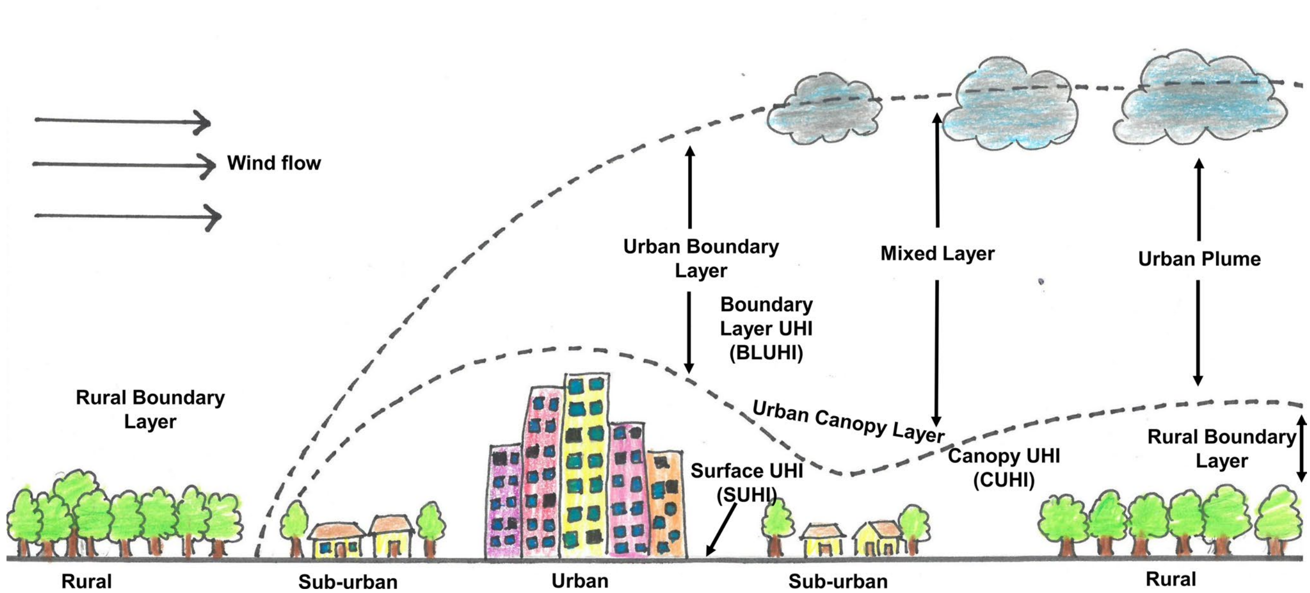


Fig. 3 Types of UHI and the main components of the urban atmosphere [89]

islands, remote sensing data is more effective than atmospheric data in identifying MUHI hot spots [100]. An analysis conducted in Chennai, India, revealed that dark surfaces, built-up areas, cars, and industries generate micro UHIs [101]. In addition, street width, the distance between buildings, and building heights influence urban ventilation, ultimately affecting MUHI [102].

5 Temporal variability of UHI

The temporal variability of the UHI refers to how the intensity of UHI change over different timescales, such as daily (diurnal) and seasonal variations. Understanding these variations is important for developing strategies to mitigate the adverse effects of UHI. Variations in temperature during the day and across the seasons impact the consequences of UHI [103]. The oscillations in solar radiation and meteorological conditions region are the factors that affect the seasonal variations in UHI levels in a specific area. In temperate locations, the UHI impact is defined depending on summer and winter seasons, whereas in tropical climates, it is categorized based on dry or wet seasons [104]. The diurnal UHI effect is the daily temperature difference between urban and rural regions. Although the temperature difference varies significantly throughout the year due to the severity of the UHI effect, the disparity is often more pronounced during winter. A study [105] showed that the intensity of UHI varied between Indian cities, and the different climatic factors influenced UHI's daily and seasonal patterns in various climatic zones.

To summarise the classifications mentioned above, each location's distinctive urban infrastructure and vegetation attributes shape the emergence of distinct urban heat islands. Due to surface variability, the AUHI phenomenon is usually minimal or insignificant during the daytime but becomes more prominent at nighttime and in the winter [106]. The delayed heat release from the urban infrastructures makes the effect more noticeable. Conversely, the season and weather conditions, along with the characteristics of rural and urban surfaces, dictate the timing of this peak. However, SUHI exhibits diurnal and nocturnal patterns, displaying fluctuating intensity levels. While examining the intensity of UHI, it is clear that the AUHI has less spatial variability, whereas SUHI has higher geographical and temporal variation.

6 Consequences of UHI

The UHI phenomenon poses a worldwide concern that jeopardizes the operation and liveability of cities and urban ecosystems [8]. The proliferation of UHI may give rise to many detrimental consequences, the severity of which would be exacerbated by the escalating urbanization trend and concurrent economic expansion. The UHI can have significant implications for public health, industrial pollution, increasing need for energy to power-based cooling systems, and air and water quality degradation. Rapid urbanization leads to substantial alterations in the soil cover, accompanied by rising soil surface temperature. The fast expansion of urban infrastructure in Indian cities due to the implementation of smart city development plans might potentially enhance the occurrence of the UHI phenomenon. Understanding the ecological impacts of urban expansion on our well-being would be intriguing. The following paragraphs delineate the preeminent impacts of UHI on the environment, public health, energy consumption, air pollution, and water resources.

UHI-induced higher temperatures may cause discomfort, dehydration, exhaustion, respiratory problems, heatstroke, and perhaps increased mortality rates due to heatstroke among urban people [107–109]. Skin issues and even higher death rates might result from the UHI effect's elevated urban temperature [79, 110]. Many people in cities are now facing the repercussions of the UHI phenomenon and heat waves, which have adversely affected biodiversity and human well-being [111, 112]. According to a study [113], residents of urban areas experiencing UHI have a higher prevalence of digestive system disorders, such as decreased appetite and dyspepsia. In addition, research has demonstrated that residents of UHI-vulnerable regions might suffer from neurological diseases characterised by symptoms such as sleep disturbances, mood changes, depressive symptoms, and cognitive decline [114]. Furthermore, rises in temperatures increase surface ozone concentrations, which may worsen respiratory disorders such as pneumonia, bronchitis, and irreversible lung damage [15, 115]. With the growing intensity of UHI in India, there has been a rise in heatwave conditions, resulting in increased mortality [116–118].

Heat islands increase the requirement for air conditioning to maintain the coolness of buildings. It is well-established that UHI disturbs the city's overall energy equilibrium. The urban warming caused by UHI in the summer months causes an increase in energy use for cooling, generating heat from air conditioners, leading to an even relatively high rise in the ambient temperature [119]. Research shows that for every degree Celsius that temperatures rise in urban areas, electricity consumption increases by 0.45% to 4.6% [120]. As a result, the increased temperatures, compounded by heat islands, lead to an escalation in energy use as cooling appliances such as air conditioners are utilized more often [121, 122].

Another environmental consequence of the UHI phenomenon is the deterioration of air quality [123, 124]. Rising pollution levels in urban areas may amplify the UHI effect because of the radiative impacts of various atmospheric pollutants. The escalated utilization of fossil fuels worsens heat islands, leading to a rise in the power demand for air conditioning and air pollution due to the industrial emissions of carbon dioxide and other harmful pollutants like sulphur and nitrogen oxides [125, 126]. These greenhouse gases contribute to a warmer temperature by trapping some of the Earth's outgoing energy, thus retaining heat within the atmosphere. In addition to acting as a positive catalyst for global warming, air pollutants harm human health and contribute to smog formation and sometimes acid rain, which are complex air quality concerns [79].

Elevated water temperatures caused by urban heat islands may affect water's chemical and biological processes. Cities in dry and semiarid regions might need help with water shortages and quality. Guhathakurta and Gober [127] investigated the impact of urban heat islands on water use and reported a significant increase (3.8%) in water use with the rise of UHI. Muller et al. [128] investigated the influence of UHI on underground water and its potential effects on water quality. They observed a subsurface UHI intensity of 9 K between the urban city center and a rural area. For example, impermeable urban surface runoff has a greater concentration of contaminants and worse water quality, prompting more extensive water treatment needs [129]. The excessive heat from hot pavement and rooftop surfaces is transferred to stormwater, causing an increase in water temperature that may harm aquatic ecosystems.

Figure 4 below provides a concise visual representation of the aspects and consequences associated with the UHI phenomenon [130, 131]. UHIs may significantly affect local weather, altering wind patterns, changing humidity levels, generating clouds and fog, changing humidity levels, and impacting rainfall patterns. Furthermore, the UHI may generate a localized low-pressure system during the day, causing the convergence of relatively humid air from the surrounding rural areas. This convergence may result in more conducive conditions for the development of clouds [132].

7 An overview of the research on UHI

Over the last 3–4 decades, urbanisation in several parts of India has led to notable changes in the local atmosphere, accompanied by an increase in surface temperature relative to the adjoining rural regions [133–136]. UHI, a localized climatic phenomenon, has garnered significant attention in India since the 2000s, and it has received more attention recently in science, economics, urban planning, and society. This section presents a comprehensive literature analysis of UHI research undertaken in various cities in India over the last few years. UHIs have been investigated through

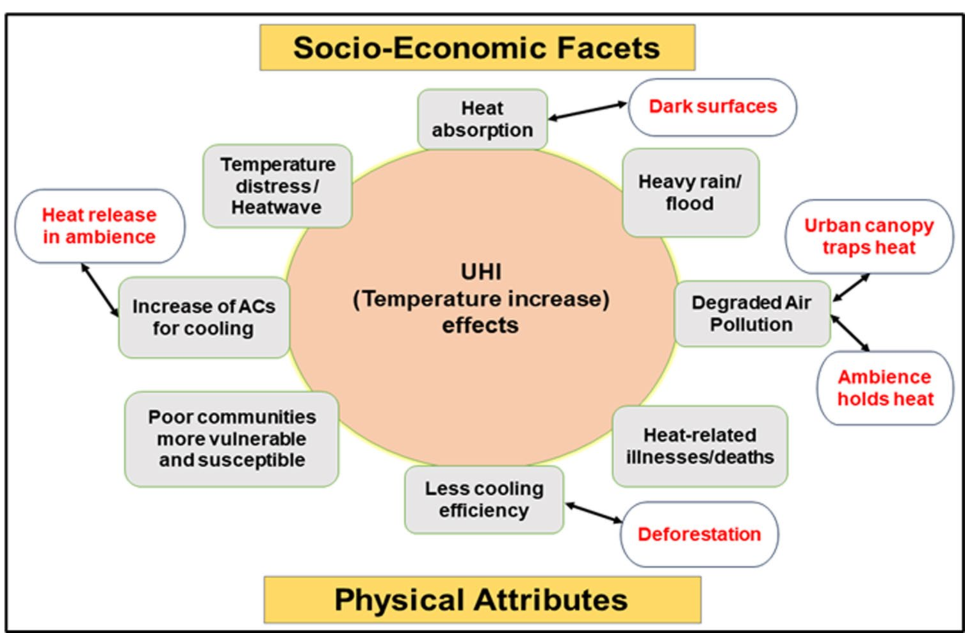


Fig. 4 Sketch illustrating the impact of UHI [130]

observations (Sect. 7.1) and numerical modeling (Sect. 7.2) approaches. In this review, we assess and examine both of these methodologies.

7.1 Observations based studies

The way to proceed with UHI research is to gather observed data, but the biggest problem is deciding on observational methods [137]. Investigations that are based on observational data may primarily be placed into one of the three methods: (a) measurements taken in the field (also known as "in-situ" observations), (b) measurements carried out using mobile devices, or (c) through satellite or remote sensing technologies. High temporal resolution but inadequate spatial resolution and coverage are characteristics of in-situ (weather) stations. Even though data from remote sensing technologies cover a large geographic region and offer various spatio-temporal resolutions, they are associated with quality uncertainties [138, 139]. Determining the UHI, therefore, necessitates a densely distributed and continuous dataset [140].

Over the past few years, many observations have become available to researchers in heat island studies and other related domains [141]. Some have argued that observational research on UHIs provides more trustworthy findings in understanding the characteristics of urban heat wave and its impact on the society [142, 143]. The following subsections are divided into 'in-situ observations' and 'satellite/remote sensing' based on the data obtained from different categories/types of instruments and utilized for UHI research. This categorization is based on the distinct ways each data measurement is performed, with each category possessing its own set of benefits and drawbacks.

7.1.1 Satellite/remote sensing

Recent developments in sensor technology have made it possible to conduct thermal remote monitoring of UHI from satellite, aerial, and airplane platforms [144]. Using ASTER and Landsat data, Mallick et al. [145] estimated that variations in LULC, human activity, and vegetation fractions contributed to a 4 °C higher LST in Delhi's commercial and industrial zones compared to the suburbs. In another study in Delhi, Yadav and Sharma [146] found that intra-city UHI values fluctuated throughout the day, with the highest levels recorded in the evening. Singh et al. [147] used satellite data to examine the spatial changes in important biophysical parameters of the Delhi city area from 2000 to 2020. They found that NDVI, NDBI, and LULC changes are the primary drivers of UHI in the city. Recent studies [55, 148, 149] have found an increasing trend of UHI leading to heat stress and shown the impact of UHI over various parts of the Indian urban regions using remote sensing data. An analysis of 89 cities in India shows a significant relationship between the UHI-induced heatwave and the area of impermeable surfaces in the city [150]. Sussman et al. [151] studied the LULC changes in Bangalore between 2003 and 2018 and found a strong association between the growth of urban areas and the occurrence of the UHI effect. Using MODIS LST data from 2003 to 2013, Raj et al. [152] studied the UHI impact over 44 cities in India, demonstrated a rise in nighttime surface UHI intensity, and highlighted its importance in city planning and management. Siddiqui et al. [153] assessed the diurnal (day/night), seasonal, and annual variations and trends in LST and surface UHI for three Indian cities over the last two decades. They observed an increasing trend in UHI intensity in all the cities. Barat et al. [154] studied SUHI intra-seasonal variability over Gangetic plain regions and found that the SUHI increased during the night. [105] used MODIS data from 2003 to 2018 to quantify the diurnal, seasonal, and interannual variation of SUHI intensity (SUHII) over 150 prominent Indian cities in different climatic zones. They found clear evidence of a positive UHI urban heat island regardless of the local climate. In another study [155], it was examined the climatic variability of LST to analyze the weather variability inside Chandigarh city and the UHI phenomena to find urban hotspots. The table (Table 1) below summarizes other studies conducted using data obtained from remote sensing.

7.1.2 In-situ

High-frequency and accurate in-situ observations are essential to UHI research. They provide detailed data on temperature variations at specific locations and times, allowing researchers to capture the fine-scale spatial variability of temperatures within different parts of a city, which is crucial for understanding the UHI effect in detail. Moreover, if available, long-term in-situ observations are crucial in analyzing daily, seasonal, and even long-term trends in UHI intensity, helping scientists understand how the UHI effect varies throughout the day and across different weather conditions and its changing pattern. The following table (Table 2) provides a concise overview of in-situ observations data-based research conducted on urban heat islands in several cities in India. The Table 2 succinctly illustrates urbanization's influence on UHI, its spatiotemporal variability, and its connection with LULC and meteorological variables affecting UHI

Table 1 UHI studies using remote sensing data

Study city	Focus of the study [references]
Chandigarh	Assess the relationship between LST fluctuations and UHI intensity [155]
Shimla and Dehradun	Demonstration of the impact of urbanisation on LST [156]
Tiruchirappalli	Investigation of the spatio-temporal variations in the effects of UHI [157]
Bengaluru	Identification of surface urban heat variability [158]
Chandannagar	Study the spatiotemporal patterns of urban heat and its link with LULC [159]
Delhi and Mumbai	Assess the spatial–temporal structure of UHI and its interactions with land use pattern [160]
Jaipur	Evaluation of the decadal changes in the LULC pattern with UHI [161]
Jaipur	Comparison of urban heat stress and heat waves [162]
Delhi region	Exploration of spatial changes in LULC for the development of UHI [147]
Ahmedabad	Understand the variability in LST and UHI [105]
Chennai	Determination of relationship between dynamic landscape and LST [163]
Chennai	Assess the severity of heat islands and determine their influence on microclimate parameters [164]
Visakhapatnam	Assess the local temperature variability and UHI changes [165]
Urban Agglomerations east India	Examination of the relationship between LULC and LST [166]
Mumbai	Impact of urban green spaces in controlling the UHI intensity [167]
Kolkata Metropolitan	Identification of factors influencing the UHI intensity [168]
Delhi	Assess the impact of LULC and LST on UHI [169]
Kolkata	Study the impact of urbanisation on UHI intensity over urban and suburban regions [170]
Ludhiana	Study the problem of urban development on UHI, air quality and health [51]
Durgapur	Analyse the development of a heat island in terms of LULC change [171]
Lucknow	Evaluate the adverse impacts of urbanisation and its influence on the growing temperature [54]
Ahmedabad	Assessment of UHI effect surrounding Ahmedabad [55]
Chandigarh	Determination of surface UHI seasonal fluctuation [172]
Noida	Assess of the temporal changes in rising trends of UHI [173]
Kolkata	Investigation on LST and biophysical aspects in rapidly urbanising areas [174]
Delhi	Assess urban heat fluxes and their effects on anthropogenic heat [175]
Mumbai and Delhi	Comparison of UHI intensity due to LULC changes [176]
Jaipur	Quantification of LST and UHI changes in context of LULC changes [177]
Delhi	Quantification of the UHI intensity [178]
Delhi	Study the behavior of UHI with respect to spatial pattern and its intensity [90]

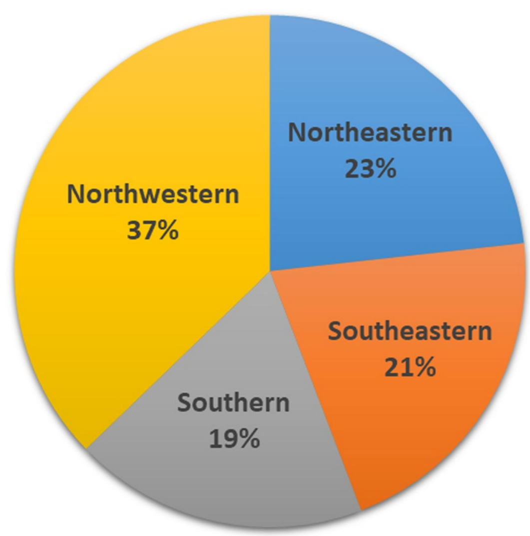
intensity. The main emphasis of these studies is to examine the impact of urbanisation on the formation of UHI and its negative consequences. It also showed the microclimatic consequences of urbanisation and the role of green areas in managing UHI intensity. This study also summarises the connections between heat waves and stress to pinpoint UHI hotspots and heat sinks. The findings of these earlier studies support the notion that the UHI phenomenon is intensifying. Jain [179] studied seasonal, annual, and decadal nighttime surface UHI intensities from 2001 to 2020 for nine major populated cities in India and observed the most substantial surface UHI intensity development during the pre-monsoon and winter months. These studies should have emphasized research focusing on specific climatic zones and considering regional climate characteristics. These studies also emphasized the critical need for dense observation stations. These observations would enhance our understanding of the dynamics and variability of the UHI phenomenon and identify various thermal hotspots within the city boundary. Furthermore, these investigations have provided limited solutions for efficiently mitigating the intensity of the UHI impact. Rajagopal et al. [180] investigated the impacts of several environmental metrics on UHI and proposed various mitigation measures to meet the goal of sustainable development. Nisar et al. [181] suggested conducting more profound research across India's climatic zones and developing a zone-specific mitigation and adaptation strategy to mitigate its effects.

By leveraging the abundance of these observational studies, the percentage of research conducted in various Indian locales has been estimated. Figure 5 depicts the approximate percentage breakdown of the total number of research articles conducted for different regions of India as per our database considered during the review (more than 300 research articles excluding book chapters, technical notes, media reports, etc.). Our review study shows

Table 2 UHI studies using in-situ data

Study city	Focus of the study (references)
Jaipur	Examination the effect of urbanisation on UHI in relation to LST [56, 182]
Bhubaneswar	Understand the extent of UHI and the variations [183]
Mumbai Metropolitan area and others	Exploration of microclimatic effects of urbanisation [184]
Angul-Talcher industrial area	Examination of the UHI impact due to industry [149]
Bengaluru	Evaluation of changes in Enhanced LULC and its impact on UHI development [151]
Nagpur	Identification of UHI affected critical areas based on local climate zone (LCZ) to curb heat island [185]
Mumbai	Examine the relationship between slum housing and surface UHI [186]
Chennai Metropolitan Area	Study the distribution of heat intensity due the changes of land use and green cover [187]
Chennai Metropolitan Area	Assess the impact of urbanisation on UHI intensity [78]
Nagpur	Investigate on the effect of LULC and population density to identify UHI hotspots and heat sinks [188]
Guwahati	Impact of UHI effect over the urban core and the periphery [189]
Delhi	Analysis of annual and seasonal temperature changes and anomalies owing to urbanisation [190]
Delhi	Understand the intensity and dynamics of heat-island in Delhi [191]
Chennai	Assess UHII effect in Chennai and its relationship to urban factors [192]
Pune	Investigation of horizontal structure of the heat and moisture islands [193]
Thiruvananthapuram	Quantification of urban heat island intensity [194]
Madras (now Chennai)	Assess heat island characteristics [195]
Mumbai	Studied UHIs in the interiors of Mumbai city [196]

Fig. 5 Proportion (in %) of UHI research conducted in India



that the majority of observation-based research is concentrated in the western region of India, while very limited study was found for Central and Eastern regions of India.

The literature review indicates that most research relies on data from meteorological stations and remote sensing techniques. However, the restricted number of monitoring stations can only partially represent the UHI's geographical distribution. Another crucial aspect is that remote sensing data cannot precisely quantify the magnitude of local UHI variations due to susceptibility to atmospheric and cloud cover influence. Alternatively, a numerical model may provide a broader range of information in terms of spatial and temporal scales when compared to in-situ and remote sensing data. Nevertheless, it necessitates a substantial volume of computational resources.

7.2 Numerical modeling studies

Employing numerical simulation as a research technique helps to thoroughly understand the non-linear mechanisms underlying a phenomenon in particular study areas. In addition, numerical studies offer a significant benefit over observational research, allowing for comparison analysis based on multiple parameters/scenarios [197]. Also, unlike observational assessments, numerical simulations can generate results for any pertinent variable across the entire area of interest. Using modeling tools, researchers can evaluate the mechanisms that underlie UHI's effects on meteorological variables, assess the significance of various cause-and-effect relationships related to the phenomenon, and develop viable scientific solutions [7, 61, 94].

Studying the UHI effect at different scales requires the use of physics-based numerical models that consider many aspects, including thermal convection, solar radiation exchanges, and urban infrastructure such as roads and buildings [7]. These factors that occur on a city-scale level may be influenced by mesoscale environmental changes and human activities resulting from urbanization [198]. In order to achieve an accurate depiction and examination of weather phenomena at the city level, computational numerical approaches must include concurrent and coherent small-scale processes. According to Oke et al. [199], numerical models can effectively represent real-world events by solving equations related to different aspects of urban climate and may replicate meteorological fields regardless of place or time. Modeling studies can also evaluate several scenarios or hypotheses and provide estimates of probable consequences [12]. Hayes et al. [200] recommended using regional models to downscale Global Climate Models (GCMs) to include urban processes contributing to the UHI effect. The modeling-based research has been widely used to study UHI-induced events like heat waves [201], future scenarios [202], and the consequences of urbanization [203]. Morris et al. [204] used the WRF model to evaluate the UHI effect in the Malaysian city of Putrajaya and emphasized that urban vegetation significantly impacts nighttime temperatures. The WRF model, in combination with an Urban Canopy Model (UCM), has been utilized in several kinds of research to investigate a wide range of UHI-related topics. A UCM describes the energy and momentum transfer between the atmosphere and the urban surface, which are crucial characteristics for modeling UHI investigations [205, 206]. Several studies have investigated the impact of UHI using the integrated WRF and UCM models to simulate changes in meteorological conditions in different urban regions [207–209]. Hence, by employing numerical models to simulate and forecast UHI processes, urban planners and decision-makers would obtain significant data that would empower them to address UHI concerns effectively.

Notably, most modeling research on UHIs has focused on North American, European, and East Asian regions. India's limited research in numerical modeling may be attributed to the absence of considerable computing demands for UHI modeling and simulation. Several researches conducted with a comprehensive approach using observational data to examine the impact of urbanization on land surface in Indian cities [183, 210–212]. Veena et al. [48] reported that although observational studies provided a significant amount of information in India, there is a need for a stronger focus on numerical modeling research, highlighting the significance of understanding the implications of urbanisation. To assess UHI intensity, Bhati and Mohan [213] used the WRF model coupled with UCM to investigate the impact of LULC. They found that urban areas exhibited a heat index around 1.5–2 °C higher than non-urban regions. By utilizing the WRF model to quantify the impact of LULC on UHI intensity across the northern regions, Kedia et al. [23] showed a significant increase in surface temperature and stressed the need for further study on the UHI effect under various urban expansion scenarios. Naveena et al. [214] analysed the heatwave during May 2013 over Andhra Pradesh and Telangana using the WRF model and showed that it could accurately simulate the temperature rise. The WRF model has been utilized in previous research in India to demonstrate the profound impact of land cover change and UCMs on UHIs [23, 149, 215, 216]. Sultana and Satyanarayana [217] examined the capacity of WRF and WRF-UCM models to simulate UHI over Delhi, Kolkata, and Hyderabad using WRF and WRF-UCM models and found that WRF-UCM outperformed WRF. The existing modeling studies conducted in India primarily focused on examining the effects of urbanization on rainfall and flooding [216, 218–222]. Possibly as a result of limited computing resources, these studies primarily employed the coarser resolution model and overlooked city-specific urban parameters. Sussman et al. [223] studied local diurnal weather fluctuations during both the dry and wet seasons over Bangalore City using the high-resolution WRF model and highlighted the significance of surface fluxes for UHI study. Because there has been limited study on urbanisation modeling in India, particularly on how well models perform and how sensitive they are to different types of urban canopy models, further analysis is needed. Thus, there is an opportunity to (i) evaluate UCM schemes across all climatic zones in India and (ii) apply the most effective UCM schemes to gain an understanding of UHI processes and use appropriate mitigation tactics [222].

It is crucial to acknowledge that modeling and simulation approaches have inherent limitations in their capacity to include the complex scientific physical principles that govern or approximate the processes of urban micro-climates or other atmospheric phenomena, resulting in oversimplification. Hence, it is essential to carry out and evaluate the model simulations rigorously.

A growing variety of modeling techniques are now available to simulate the micro-weather systems of urban areas [141]. The below-mentioned modeling tools, briefly introduced here, might be utilised to study the UHI estimation and its consequences.

7.2.1 Weather research and forecasting model

The Weather Research and Forecasting (WRF) model can satisfactorily represent the lower atmosphere's wind, temperature, and humidity. The model also accounts for the combined impacts of these factors on mesoscale motions. The use of the WRF model in conjunction with the UCM model has shown to be very advantageous in real-time weather prediction inside urban areas [224]. Using the WRF-UCM makes it feasible to modify land use and physical parameter specifications, including urban morphology, heat capacity, building surface albedo, and anthropogenic heat [225]. Thus, the WRF model is a potential model that can represent finer-scale land surface characteristics with variable properties of urban areas and their physical interactions with the atmosphere. Research on urban modeling often uses the expanded version of WRF called WRF-Chem, which couples meteorology with atmospheric chemistry to represent the atmosphere over an urban area accurately. The details are available at https://www.mmm.ucar.edu/models/wrf.

7.2.2 SURFEX combined with town energy model

Meteo-SURFEX France's (Surface Externalisée) is a surface modeling tool that computes averaged momentum, sensible heat fluxes, and latent heat fluxes [226]. It combines the ISBA land-surface system [227] with the Town Energy Balance (TEB) UCM [228, 229]. The TEB model calculates the energy balance of a city using the concept of a canyon, where a city is represented by a roof, a road, and two opposing walls, which are crucial in estimating the city's energy budget. Specifically, the model accounts for the canyon's capture of some of the incoming solar and infrared radiation. The TEB UCM model replicates the impact of important urban physical features on the local climate, with the capability to include the influence of vegetation and water bodies. Further details of the model are available at (https://www.umr-cnrm.fr/surfex/).

7.2.3 Charles university large eddy microscale model

This Charles University Large Eddy Microscale Model (CLMM) is a numerical model that describes turbulence and is designed to simulate turbulent flow and dispersion in the planetary boundary layer. The foundation of this model primarily lies in computational fluid dynamics (CFD), a tool utilized for microscale flow modeling involving intricate terrain or structures that solve problems through large eddy simulation (LES) [230]. It incorporates transport equations for scalars such as temperature, humidity, and passive contaminants in addition to flow equations. The usefulness of the CFD technique in assessing cities' thermal microclimate has been demonstrated by [231] and [232].

7.2.4 Computational fluid dynamics model

Exploring urban heat islands presents a significant challenge in modeling multi-scale urban wind patterns within a city [233]. It is crucial to model the airflow around each specific structure strategically throughout the urban area, and it necessitates accurately assessing the complex flows encompassing a structure. To achieve this, one must solve the governing Navier-Stokes equations using Computational Fluid Dynamics (CFD) to model the fluid flow [234].

Modeling micro-weather conditions in urban areas is becoming an increasingly popular application of CFD [197, 235]. To investigate the thermal environment by integrating velocity and temperature fields, CFD can be an effective technique; however, it requires a model with an extremely high resolution, knowledge of pertinent boundary conditions, and adequate computer resources for simulations [197, 236]. Making meso-micro scale modeling is possible by scaling up CFD models, which can help predict and plan multi-scale urban airflows around complex building flows [237]. Miao et al. [238] integrated a CFD software program with the WRF model to investigate the movement and spread of pollutants in a complicated urban region in Beijing. Assessments of wind velocity [239], thermal flux analyses [240], and simulations of the drag effect of urban trees [241] are examples of recent CFD-based research. CFD software that is widely utilized, including CFX, ANSYS, Phoenics, and OpenFOAM, can generate airflow details at a resolution of 50 m or less over an area.

7.2.5 ENVI-met

The ENVI-met [242] is a well-known CFD microclimate simulation model. It is a high-resolution 3D modeling program that correctly simulates complicated microclimatic phenomena. It gives in-depth insights into how environmental elements influence urban design, allowing for better decision-making in urban management. The model is intended for microscale study, with a resolution of 5 m or less. This resolution enables the investigation of even small-scale interactions between individual urban structures, surfaces, and vegetation. The further reading is available at https://www.envi-met.com/.

7.3 Data-driven methods

Data-driven models are based on statistical approaches and machine learning methods, which can capture intricate non-linear patterns from extensive past weather and climate data, improving prediction skills. These techniques can identify concealed patterns and correlations in extensive datasets to acquire insights into weather and climate dynamics [243]. The following sections briefly describe here.

7.3.1 Statistical downscaling approach

Finding statistical correlations between large-scale meteorological variables (i.e., predictors) and local ones (predictands) is the objective of statistical downscaling (SD) techniques [244]. Establishing a statistical relationship between small-scale and large-scale variables is necessary to implement statistical downscaling [245]. Statistical downscaling has effectively been used to examine variations in the intensity of the UHI [246]. However, it is difficult to get the geographical distribution of the UHI using the statistical approach, mainly when observational data is scarce. This method's primary benefit is that it requires little computing resources while yielding valuable results.

7.3.2 Machine learning techniques

Everyday meteorological data is collected/generated through "real-time observation sensors" and "model simulation." This vast amount of spatial data is available in structured and unstructured formats. Processing these data to get relevant scientific insights is an enormous undertaking for scientists. Because of the datasets' volume, variety, veracity, and hybrid forms, processing, analysing, and visualizing them require machine learning-based approaches [247].

While prior studies have employed observations and numerical models to investigate the UHI effect, scientists now focus on developing data-driven models that can anticipate UHI effects using machine/deep learning (ML/DL) techniques [248]. These approaches have grown in popularity among researchers all around the globe because data-driven procedures have a less expensive computing overhead than numerical simulations. Also, accurately depicting intricate urban structures via analytical modeling requires substantial urban-specific information, which may not be readily accessible to the average user or challenging to acquire [249]. Standard methodologies employed in developing UHI-predictive data driven models comprise traditional regression techniques. In addition, sophisticated non-linear analytic methods, such as Artificial Neural Networks (ANNs), may be used to investigate the UHI phenomenon. Random Forests (RF), boosted decision trees (DTs), and Support vector machines (SVM) have been identified as very successful approaches [250].

8 Mitigation approaches

The combination of rapid urbanization, the UHI effect, intense heat waves, and population growth in arid urban areas poses significant challenges for authorities in managing the impacts on energy, water, and public health [251]. Research suggests that suitable UHI mitigation methods lowered yearly energy costs by $4–15 million over five cities in the USA [252]. According to a study [253], mitigating the effects of UHI in the United States required an estimated 3–8% of annual electricity consumption. The rise in UHI impacts and resulting more frequent and intense heat waves highlight the need to effectively manage and reduce the effects of UHI [81, 254, 255]. Given the prevailing urban distress, developing efficient solutions and constructing a comprehensive assessment approach to mitigate the UHI phenomenon is essential.

Various techniques have been developed to alleviate the consequences associated with the UHI. Few studies [256, 257] have attempted to quantify the extent to which vegetation and albedo can reduce the UHI intensity of a city using WRF-UCM. Integrating green spaces, such as parks, street trees, permeable pavements, reflective materials, and plant growth, can alleviate the negative consequences of UHI [258–260]. Another research analysed UHI by changing city-specific architectural elements and local climatic zone (LCZ) data to establish their sensitivity to reduce its effect and increase climate-resilience adaptability [185]. Haddad et al. [261] showed that implementing heat mitigation strategies in Riyadh could decrease cooling energy use by about 16%. Nevertheless, these studies have assessed mitigation measures but have considered city-specific data that determines the severity of the UHI phenomenon. Furthermore, it is crucial to apprehend the microscale processes at the street level to formulate more accurate measures for mitigating the UHI effect. Taking corrective measures at the ward or city level to minimize the impact is vital to designing optimum mitigation plans to alleviate the harmful impacts of UHI [262, 263]. Consequently, it is critical to develop a very high-resolution modeling framework that quantifies the extent to which leading factors can affect the intensity of UHI so that urban planners can formulate the most effective mitigation strategy.

India is now the most populous country in the world, surpassing China, resulting in a surge in urban population. This population rise would inevitably result in significant alterations in LULC and a corresponding escalation in human-caused heat emissions. Consequently, these surface alterations might lead to the UHI effect on cities, resulting in urban discomfort due to heat [55]. Mallick et al. [145] examined the influence of Delhi's LULC on the UHI effect and proposed that strategic urban design might reduce the impact of UHI. While developed countries have conducted extensive studies and have developed good policies for sustainable city development, Sharma et al. [52] pointed out that India is still in the early stages of its efforts to mitigate UHI. Exploratory research was conducted to address the issue of urban heat mitigation in Indian cities by implementing three separate methods: covered parking, roofs, and non-roof interventions [264]. Additionally, some mitigation strategies, e.g., green spaces, have been proposed by researchers for Indian cities to lower surface temperatures [265, 266]. While strategizing city development to mitigate the repercussions of urbanisation, urban planners and administrators encounter formidable challenges that have necessitated them to acquire knowledge of the UHI mechanism. It is relevant to bring out that there is now a rising interest among Indian researchers, city administrators, stakeholders, insurers, and the real estate sectors in implementing effective mitigation solutions to reduce the harmful effects of UHI.

The below examples represent a few of the often-used techniques towards mitigation.

8.1 Vegetation/green spaces

Urban areas have water-resistant surfaces and little vegetation, thus reducing surface cooling from plants and soil [267]. Enhancing plant cover is recommended to mitigate the escalating temperatures in urban regions. Enhancing urban green areas like parks, street trees, and green roofs may reduce UHI [268]. Green spaces must be carefully constructed for city planning to benefit the environment, society, and economy while enhancing climate resilience [269]. The development of green infrastructure may have a cooling influence, although this impact may also be felt outside of the area of interest [270]. The greenery creates a canopy that protects the region below from the sun [271]. Shade and evapotranspiration from plans decrease surface air temperatures, making it a practical UHI mitigation approach. The incorporation of urban green spaces has been proven to result in a reduction in surface temperatures [272].

8.2 Green roofs

"Green roof" refers to a roofing system in which vegetation is integral to the design. Urban expansion reduces green space due to the rise in impermeable surfaces and buildings with dark roofs that absorb solar heat. Excessive heat retention in buildings undermines the thermal comfort of occupants and necessitates excessive energy use for cooling purposes. This phenomenon entails discharging more heat from buildings directly via air conditioning operations and indirectly through power plants. This heat is then released into the air at night, making it even hotter [273]. Therefore, eliminating heat from the roofs and walls of buildings can reduce the temperature of cities [274, 275]. Green roof vegetation, much like other types of trees and plants, has the potential to offer shade and help cool the surrounding air via the process of evapotranspiration [276]. Therefore, it is an effective strategy for minimising the UHI effect since it may substantially lower roof surface temperatures [277].

Moreover, green roofs reduce heat transfer to the atmosphere above a building, which might help cities maintain a more comfortable temperature. Few research studies have shown that placing plants on roofs reduces the energy needed to chill buildings because the building is shielded from solar radiation and reflected radiation from the environment [102, 278]. As a result, green roofs reduce the heat transmitted from the rooftop to the interior of the building due to evaporation and the shade created by the plants [264]. Dwivedi and Mohan [279] examined the UHI phenomenon and the use of green roofs for mitigation. They utilised ENVI-met software and suggested using dense urban vertical cover or forests as effective measures to alleviate the impact of the UHI effect.

There are three types of green roofs: intensive, semi-intensive, and extensive [280]. Parks, gardens, and urban farming belong to the "intensive" category. In contrast, semi-intensive consist of green roof gardens, and extensive green roofs have a thin veneer of minimally maintained vegetation.

Figure 6 schematically demonstrates how urban green spaces contribute to reducing the UHI effect [131]. Concurrently, a few mitigating techniques may significantly affect temperatures and the amount of energy required to cool metropolitan infrastructure. Implementing these measures could reduce greenhouse gas emissions associated with electricity generation [281].

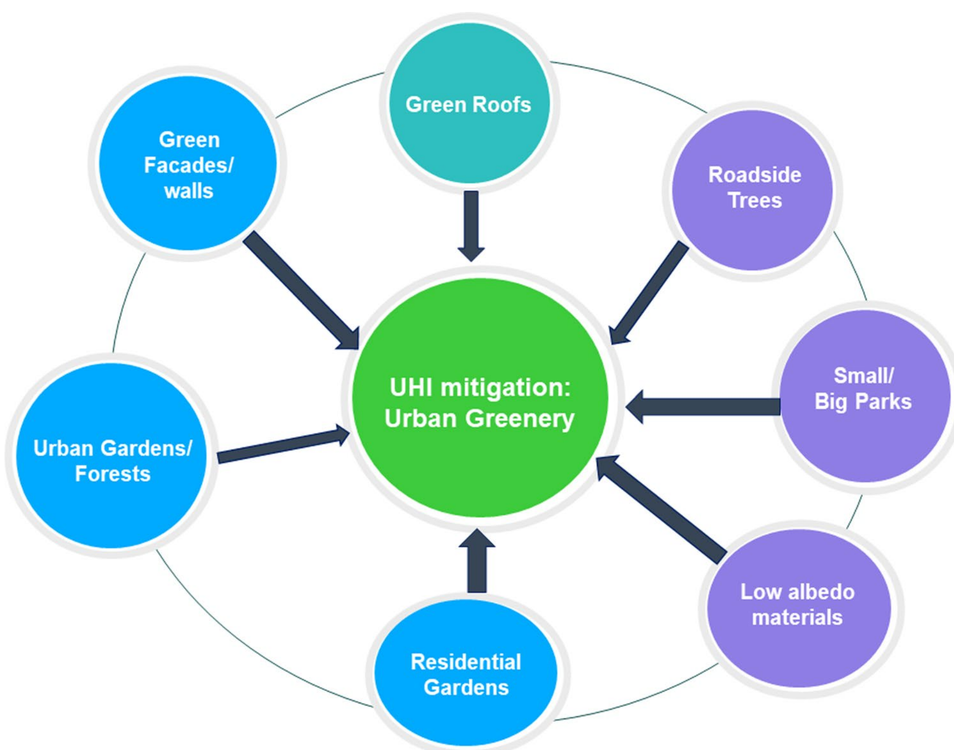
8.3 Cool roofs

The primary objective of a "cool roof" design is to maximize solar radiation and heat energy reflection while minimizing absorption [264, 282]. Cool roofs can augment solar reflectance, which subsequently leads to reduced heat absorption and lowered temperatures within the building's structural system [283]. This is accomplished through the increase of roof albedo. Therefore, a building's roof could be designed using highly reflective paint, sheets, or tiles, which is vital for lowering the UHI impact [27]. Zeeshan and Ali [284] showed that integrating cool roof materials into urban areas alleviates heat stress. Integrating cool and green roofs may effectively minimize heat transmission to the surrounding environment.

8.4 Cool pavement

Traditional pavements such as concrete and asphalt heat up during summer due to increased solar radiation absorption [74]. These surfaces can hold the heat generated during the daytime and then emit it at night, exacerbating the already elevated temperatures in urban regions. The phrase "cool pavements" comprises a range of materials that can reduce surface temperatures and minimise heat absorption by pavements. Santamouris [285] presented a comprehensive examination of the primary technical breakthroughs associated with cool pavements, which have the potential to

Fig. 6 Schematic depiction of sustainable approach for UHI mitigation [131]



mitigate surface temperatures and minimise heat absorption via the reflection of solar radiation. Cool pavement's design incorporates the pavement's permeability, facilitating the infiltration of air, water, and water vapor into the underlying soil [285]. Implementing strategies such as planting trees along streets and establishing city gardens may enhance green space and create cooler pavements, minimizing the UHI impact [8]. This option is popular owing to its cost-effectiveness and ease of application. Sen et al. [286] conducted a study on paving techniques and observed a drop in temperature upon applying a reflective coating to the building walls and roofs.

The preferred choice to design cool pavement is a sun-reflecting coating composed of an asphalt matrix and materials [36]. A recent study comprehensively examined a few pavement technologies, carefully considering the possible challenges and opportunities for future progress [287]. A comprehensive examination of the latest advancements in cool pavements has highlighted the capacity of such pavements to alleviate heightened temperatures inside urban settings [288].

9 Gaps and future scope in India

The literature review shows that the UHI effect is prevalent in Indian cities. However, research on this phenomenon is in its emerging phase. In addition to analyzing and identifying the phenomenon, Indian scholars should now actively address the challenges associated with UHI. The inclusion of stakeholders is also crucial when attempting to resolve the issue.

Concerning the applied research on UHI in India, much work is required to comprehend its development, detection, and significance for public life. While a few studies undertaken in a particular city in India have revealed viable methods for mitigating the effects of UHI, more studies are necessary to evaluate the overall effectiveness of these solutions across several cities nationwide. Compared to its international standing, across India, there is a lack of studies on UHIs, limited strategies to mitigate UHI, and insufficient efforts to detect UHI [52]. Currently, most research investigations have heavily depended on remote sensing data, fieldwork, and weather stations. Moreover, there has been a lack of research utilizing numerical modeling in Indian cities, underscoring the need for more comprehensive investigations on UHI that employ high-resolution urban models. Therefore, researchers in India need to expand the range of their studies and strive to apply preventive and mitigating measures. On top of that, it is essential to conduct research relevant to each city, considering local surface characteristics, to understand the origins, impacts, and strategies for mitigating the UHI issue [289].

Also, there is a scarcity of research publications addressing the link between climate change and the UHI impact across the Indian subcontinent. Understanding the influence of various geographical elements on temperature in different climatic zones and seasons in Indian cities is of utmost importance, especially in the context of the climate change scenario [290]. It would be intriguing to investigate and isolate the specific contribution of the UHI phenomenon in exacerbating cities' susceptibility to climate change.

The following might be major considerations for future research:

a. The rising tendency of heatwaves in India is expected to intensify further, resulting in property losses and human casualties [291–293]. So, as described in Sect. 7.2, the impact of UHIs on heatwaves in Indian cities must be evaluated at a sub-kilometer scale.
b. In addition to studying UHI during summer, wintertime UHI and its urban implications still need to be studied, particularly during episodes of above-average temperatures in cities such as Bengaluru and Pune.
c. Analyzing circulation patterns ranging from the mesoscale to the microscale is critical to comprehending the complex interconnections among UHI events, water bodies, and surface morphology [154]. By applying a simulation model at the meso or microscale, it is possible to enhance the investigation of these connections. Efficiently promoting the development of diverse urban microclimates at different dimensions requires the creation of region-specific or city-specific detailed models, considering the unique urban characteristics of the regions or cities.
d. Before implementing mitigation strategies for the UHI phenomenon, empirical validation and verification are additional critical factors in research. These criteria allow cities to create customized heat stress mitigation plans to tackle UHI implications at the local or municipal level [179]. It would enable the timely application of appropriate adaptation measures from the start of the urban design and execution phase.
e. Examining the synergistic impacts of urbanisation, the UHI effect, and climate change over Indian cities would be an essential study given the state of climate change today [294]. Understanding the impact of climate change resulting from urbanization on diverse urban ecosystem services is crucial for urban planners to devise long-term mitigation strategies effectively. One probable approach to evaluate the impact of UHI and, consequently, its influence on

climate extremes is to analyze various land use characteristics and anthropogenic activities [289, 295]. It would be possible to do this study under various climate change scenarios.

f. Underscoring the anticipated increase in severe heat exposure and subsequent heat illnesses [296, 297], it would be intriguing to do empirical studies on the effects of urban climate change on human health.
g. There is a pressing need for awareness programs on the consequences of UHI and related concerns. Academics, scientists, stakeholders, and municipal authorities must actively participate in fostering a collaborative strategy to address it and promote sustainable urban living [89, 298].

10 Summary and conclusion

Urbanisation promotes the expansion of socioeconomic variety and generates many job opportunities for people from all walks of life, but it comes at the expense of physical landscape changes. Urbanisation, although having several beneficial impacts, is also linked to specific detrimental environmental concerns, including weather extremes, heat strokes, heat cramps, heat-related deaths, air pollution, and respiratory ailments [180]. The expansion of urban structures and development substantially affects the urban environment and the local climatic characteristics of the region, resulting in urban heat island phenomena. Metropolitan areas with high population density are now more vulnerable to the UHI effect than rural areas. This literature review concisely summarizes the research on UHI's genesis, need, assessment, effect, and mitigation. The study sheds light on the importance of UHI assessment and impact analysis in improving our environment and the well-being of future generations.

Upon thoroughly examining the existing literature, it becomes evident that studies on the UHI phenomenon in India still need to be developed. Some researchers are now trying to diagnose the causes of the UHI phenomenon, while others are studying its effects. Several observational data-based studies have been conducted on UHI in India, revealing that the rate of warming is increasing faster in India's urban centers than in its rural regions.

This review article highlights the extensive research conducted on observations in the western region of India. It shows that the severity of the UHI varies from city to city in India, ranging from 2 to 10 °C. The northwest region, in particular, tends to have higher temperatures.

Additionally, these studies have proposed measures to minimize the effect of UHI. However, these studies have yet to consider a city's surface characteristics, highlighting the need for more research to investigate the superficial elements of the urban environment. Only a few research studies have used computational models with a high degree of intricacy to understand better the implications of urban heat islands in metropolitan parts of India.

On the other hand, several researchers indicated drying conditions over central northeast India during the past few decades due to the shift of monsoonal rainfall towards the northwest, and the region has witnessed a warmer climate. The probable increase in UHI over this region and its consequence is significant due to its population density and agro-economic importance [299, 300]. In addition, although high-resolution (~ 4 km) soil temperature and soil moisture data are available over India for extended periods [301], it accounted for more observational data during the summer monsoon seasons. Thus, gathering more comprehensive network data during the pre-monsoon (warmer season) is essential to enhance our understanding of the UHI phenomenon.

The decline of green space in urban contexts is a widespread factor contributing to the impacts of urban heat islands. Local administrators should implement measures to enhance awareness among local inhabitants and devise appropriate tactics to mitigate the UHI's repercussions. Thus, to create sustainable cities with optimum thermal comfort, one must comprehend the UHI effect and its implications on urban environments [302]. In order to alleviate the adverse consequences of the UHI phenomenon, it is critical to give precedence to addressing the requirements of the inhabitants of densely populated urban areas. Diversified city-based research studies and further analyses are needed to evaluate population vulnerabilities and urban hazards and reduce the adverse effects of UHI [303, 304]. As low-income urban inhabitants are more likely to suffer from heat stress, there is a need to identify vulnerable populations and regions to implement suitable mitigation plans [305]. Hence, comprehending the influence of UHI is vital to formulating new urban areas that can effectively address the long-term demands of their inhabitants via mitigation strategies. For our conceptual understanding, this review concentrated solely on a few potential strategies for mitigating the issues brought on by metropolitan heat. We recommend that the city administrator use a systematic tool to evaluate the available mitigation strategies and choose the optimal sets based on the area of interest. We must develop appropriate standard operating procedures (SOP) for planning and policy execution to regulate urban heat effectively and guide sustainable urban expansion. In addition, implementing sustainable urban design strategies may effectively facilitate compact development, contributing to preserving and conserving natural ecosystems [306]. Policymakers and urban planners need to accord high priority to climate resilience within their mitigation measures, taking into account the susceptibility of urban regions to the adverse consequences of the UHI effect and climate change [137]. This approach would guarantee appropriate measures to maintain a healthy environment for the city's people. This review article serves as a reference for anyone intending to deepen their understanding of the UHI effect and its ramifications, encompassing practical applications and scientific research.

Acknowledgements We acknowledge with gratitude the Centre for Development of Advanced Computing (C-DAC) Pune and Department of Atmospheric and Space Sciences, Savitribai Phule Pune University for the support during the entire manuscript preparation.

Author contributions S.I. has conceptualized and written the paper; A.K., R.B., P.S., S.K and M.K., have reviewed the paper contents and suggested applicable changes. All authors are contributed to edit the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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