PUNE INTERNATIONAL CENTRE

Heat in the City: Investigating Urban Heat Islands, Drivers, and Their Impacts

January 2025

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1. Introduction

Research on the Urban Heat Island (UHI) effect has grown substantially in recent years. India, as the world's most populous country and the fifth-largest economy, has experienced rapid urbanisation over the past decades. According to the World Bank Group, India's urban population is expected to reach 600 million people, or 40% of the total population, by 2036 — an increase from 31% in 2011. This rapid urbanisation has contributed to a 60% increase in warming across Indian cities, with Tier-II cities in the eastern region being the most affected (Sethi & Vinoj, 2024). In addition to the effects of urbanisation, land availability is becoming increasingly scarce due to the rising demand for agricultural production and population growth. The swift transformation of rural areas into urban centres is happening at an unprecedented pace, significantly disrupting ecosystems and altering their natural functions.

Luke Howard is recognised as the first scientist to systematically study the climate of cities, laying the foundation for urban climatology. Through his observations, he discovered that London consistently had higher temperatures than the surrounding countryside, with an average temperature difference of 1.579°F (0.88°C). This made Howard the first to measure what is now known as the UHI effect. Today, organisations like the NOAA National Centers for Environmental Information (NCEI) continue to monitor global temperature changes. Using data from reliable temperature observation datasets, NOAA calculates global temperature anomalies every month. According to their June 2024 Global Climate Report, June 2024 was the warmest June on record in NOAA's 175-year history. The global surface temperature for that month was 1.22°C (2.20°F) above the 20th-century average of 15.5°C (59.9°F) (NOAA, 2024).

History has shown us that progress often comes at a cost, and climate change is no exception. Heat islands represent the temperature differences between urban and rural areas, while climate change refers to the global rise in the Earth's surface temperature. Contrary to common misconceptions, urban heat is not the root cause of climate change. Both urban and rural regions across the globe are experiencing warming due to the increased concentration of greenhouse gases in the atmosphere. However, studies have consistently shown that the UHI effect exacerbates the warming caused by climate change, leaving urban areas particularly vulnerable to extreme heat.

Our idea of **this paper is to analyse and draw insights from existing research on the global UHI effect and the factors driving its growth**. We aim to **explore the body of research conducted worldwide, with a particular focus on studies related to India**.

Additionally, we will identify key research gaps and propose potential solutions to address these challenges effectively.

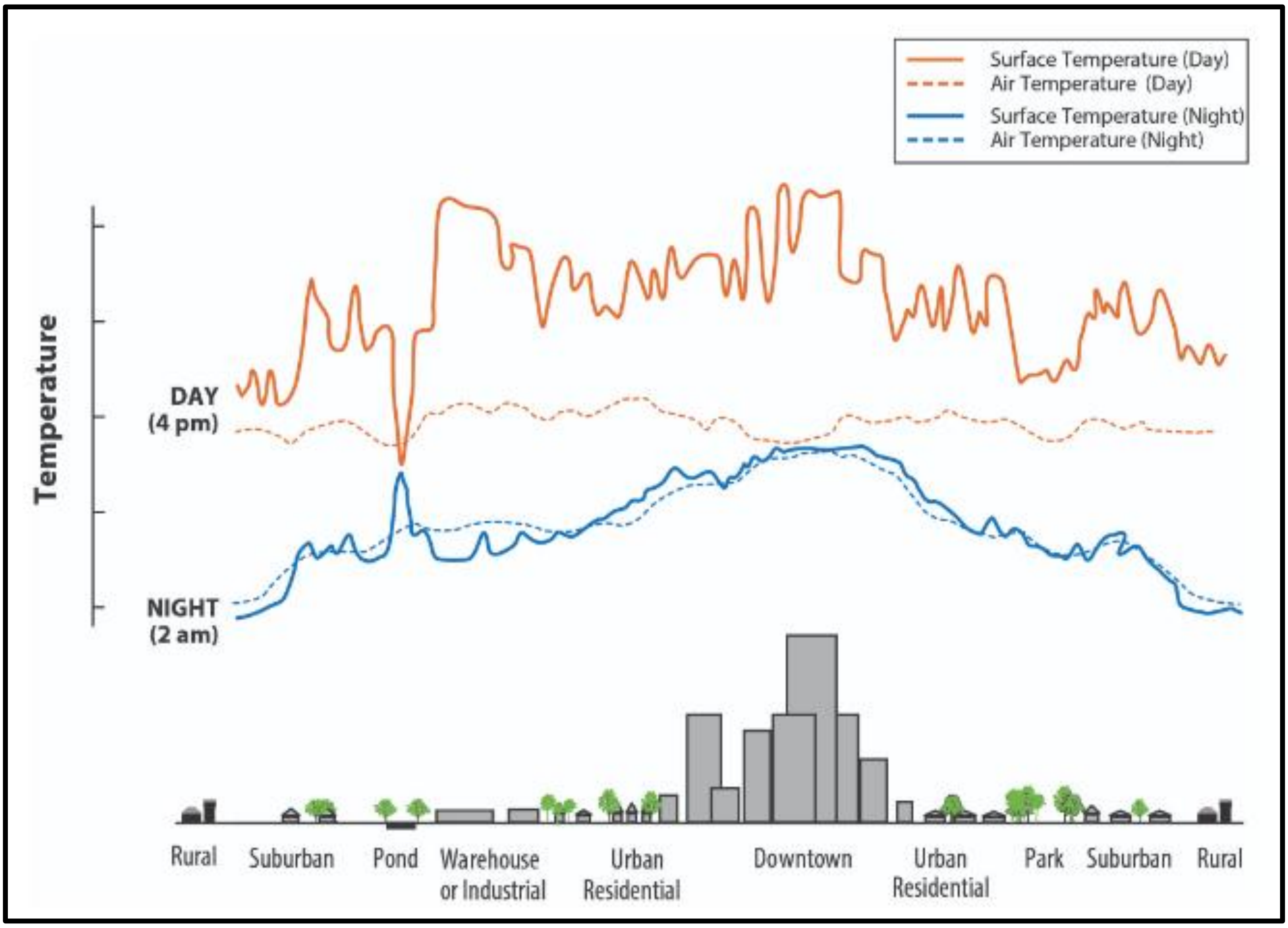
2. About Urban Heat Island Effect

The United States Environmental Protection Agency (US EPA) defines UHIs as areas within cities where air temperatures are significantly higher than in nearby rural areas. According to the US EPA, urbanised areas experience elevated temperatures because buildings, roads, and other infrastructure absorb and retain more heat from the sun compared to natural landscapes like forests or water bodies. The dense concentration of structures and limited greenery in cities creates these "islands" of warmth, where temperatures are noticeably higher than the surrounding regions. In the United States, urban areas are typically 1–7°F warmer during the day and 2–5°F warmer at night than their rural counterparts (US EPA, n.d.).

UHI can be categorised into three types based on where the temperature is measured, each addressing different spatial scales: Surface UHI (SUHI), Canopy UHI (CUHI), and Boundary Layer UHI. SUHI refers to the Land Surface Temperature (LST), typically measured using remote sensing techniques. CUHI focuses on air temperature within the urban canopy, approximately 2 metres above the ground, and is often measured directly at this level. Boundary Layer UHI represents air temperatures within the urban boundary layer, an invisible layer above the cityscape that captures the broader urban temperature dynamics.

Temperature is one of the key factors that shapes plant growth patterns, alongside sunlight and water availability. These factors collectively determine whether an area can sustain dense forests, grasslands, or sparsely vegetated deserts. At the same time, plants influence how hot the land surface becomes. According to the National Aeronautics and Space Administration (NASA), areas with thick vegetation rarely experience land surface temperatures exceeding 35 degrees Celsius. In contrast, barren desert landscapes without plant cover record some of the highest land surface temperatures on Earth (NASA, n.d.).

Temperature differences between the Earth's surface and the atmospheric air above cities give rise to two types of heat islands: surface heat islands and atmospheric heat islands. Surface heat islands occur when urban surfaces, such as roads and rooftops, absorb and release more heat than natural areas. This effect is particularly noticeable during the day when the sun is shining. On the other hand, atmospheric heat islands happen when the air in urban areas is warmer than the air in surrounding rural regions. While these atmospheric heat islands are



generally less intense than surface heat islands, they still contribute to the overall warming effect in cities (Refer to Figure 1).

Figure 1: Heat Island Effect Diagram, Source: US EPA

Figure 1 illustrates that surface temperatures fluctuate more significantly than air temperatures during the day but tend to stabilise and align with air temperatures at night. Temperature variations over pond areas demonstrate how water maintains a more stable temperature throughout the day and night. Unlike buildings or paved surfaces, water does not absorb and retain solar energy in the same way, resulting in less fluctuation in its temperature. Open spaces like parks and water bodies can help in creating cooler spots in a city. In general, temperatures are lower near the edges of suburban and rural areas than in the downtown core. As shown in Figure 2, cities with the highest warming rates are not necessarily those with the greatest urban contribution to overall warming. This highlights the complex interplay of factors influencing urban temperature changes. (Refer to Figure 2)

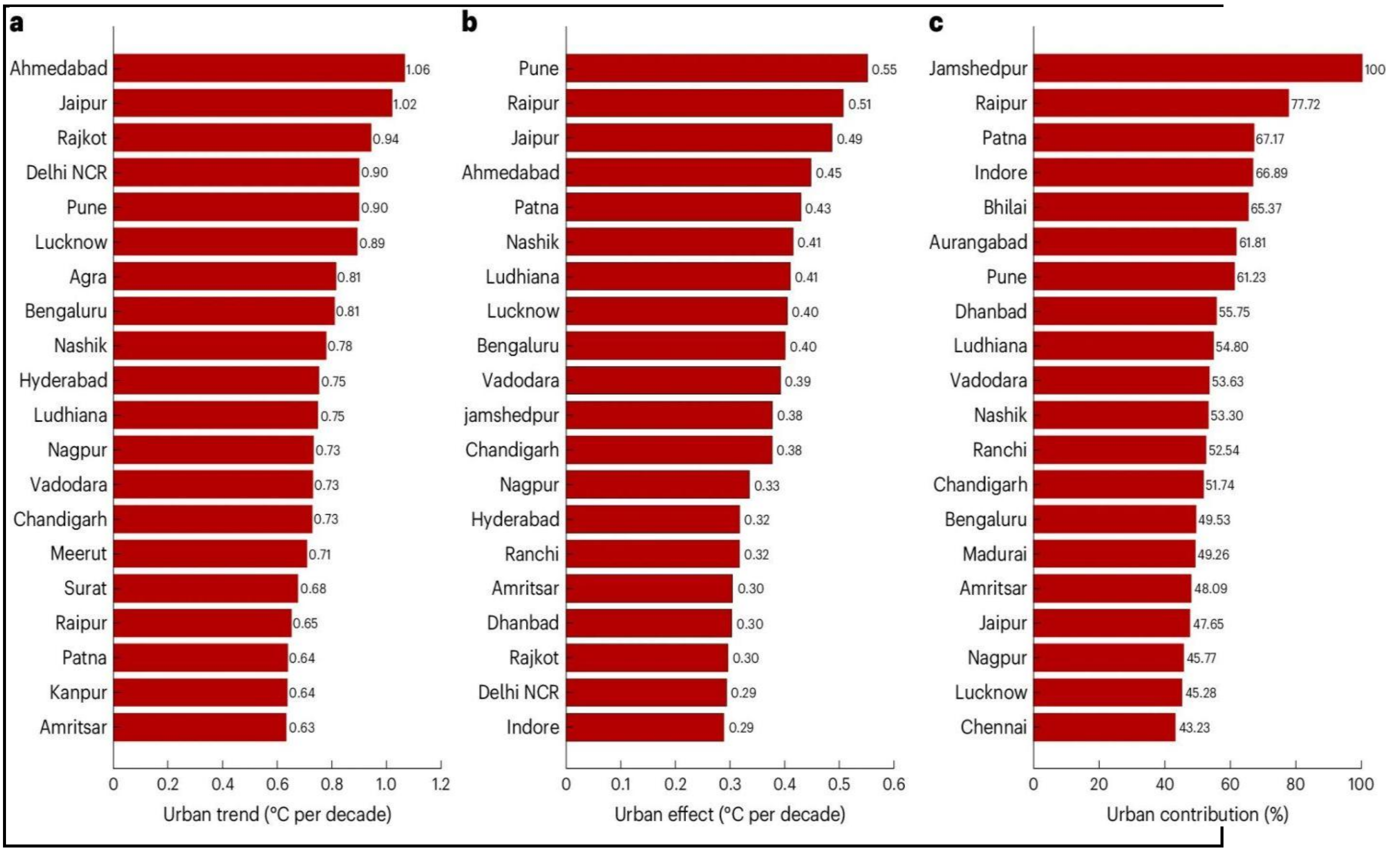


Figure 2: Ranking of the Top 20 Warming Indian Cities.

Adapted from Sethi and Vinoj (2024), this figure provides a ranking of the top 20 warming Indian cities, considering the following factors:

- **(a–c)**: Urban Normalised Land Surface Temperature (NLST) trends.
- **Urban effect:** The absolute impact of urbanisation-driven warming.
- **Urban contribution:** The relative impact of urbanisation-driven warming.

The rankings are based on cities with populations exceeding one million, according to the 2011 Census, and include urban NLST trends that are statistically significant at the 95% confidence level (Sethi & Vinoj, 2024).

3. Research Methodology

This paper adopts a qualitative approach, focusing on synthesising insights from secondary data sources to explore the UHI effect, its drivers, and impacts. The methodology revolves around reviewing a wide array of scientific literature, reports, and datasets to develop a nuanced understanding of the UHI phenomenon and propose strategies for mitigation. The data sources were drawn from a variety of credible and widely recognised platforms; digital libraries and repositories such as Elsevier, ResearchGate, Google Scholar, SpringerLink, and PubMed were extensively utilised. Additionally, we referred to datasets and reports from authoritative organisations like NASA's Earth Observatory, NOAA's National Centers for Environmental Information, and the United States Environmental Protection Agency (USEPA). These platforms were chosen for their reliability, relevance, and depth of information on climate-related research.

The timeframe covers over three decades of research, with foundational studies from the late 20th century. A significant concentration of studies appears between 2017 and 2024. This period was selected because it encapsulates recent technological advancements, urbanisation trends, and global climate action efforts. Additionally, it aligns with significant advancements in research tools, increasing global awareness of urbanisation's impacts, and the development of heat action plans, particularly in India.

A systematic search strategy was employed to identify relevant studies. Specific keywords and phrases included: "Urban heat island (UHI)," "urbanisation and temperature variations," "anthropogenic heat impacts on cities," "land surface temperature trends in India," "mitigation of urban heat effects," "heat action plans and urban cooling strategies." These keywords were selected to capture the multifaceted aspects of UHIs, including their causes, consequences, and possible solutions. Boolean operators (e.g., AND, OR) were used to combine terms, ensuring a comprehensive search. The selected keywords reflect a deliberate effort to address the study's objectives comprehensively, focusing on UHI phenomena and actionable recommendations. The inclusion criteria for selecting literature were as follows:

a. Articles and reports focusing on urban heat dynamics and mitigation measures.
a. Publications relevant to the Indian context, alongside global perspectives for comparative analysis.
b. Studies offering empirical data or modelling approaches related to UHIs.

Conversely, the exclusion criteria ensured the elimination of:

a. Non-English publications to maintain accessibility and uniformity.
b. Articles published before 2017, except for seminal works cited in multiple sources.
c. Materials lacking credible data or peer review.

4. Literature Review

Recent data from the Copernicus Climate Change Service (C3S) highlights a worrying trend in global temperatures. On July 22, 2024, the Earth recorded its highest daily global average temperature in the ERA5 dataset at 17.16°C. This broke the previous record of 17.09°C set just one day earlier, on July 21, 2024, and surpassed the 17.08°C record from July 6, 2023 (C3S, 2024). These rising temperatures underscore the growing evidence of the causes and impacts of climate change. While densely populated urban and coastal areas are at significant risk, rural regions are also feeling the strain due to ongoing anthropogenic activities, widespread loss of vegetation, and rapid urbanisation. **Projections suggest that India could face a temperature increase of 1.1–5.1 °C by 2100, emphasising the urgent need for comprehensive strategies to address these challenges** (Kumar, Kuttippurath, Gopikrishnan, et al., 2023).

The Census of India (2011) reports that over 1.7 million people in the country are homeless, with 938,384 of them residing in urban areas. This makes India one of the nations with the largest homeless populations globally, leaving many citizens highly vulnerable to various risks and challenges (Census of India, 2011). This highlights the serious need to address heat-related disparities. According to a recent study by Anna University in India (2024), urbanisation in terms of rapid expansion in residential, commercial, and industrial areas in the Chennai Metropolitan Area (CMA) has resulted in major changes in land use—agricultural lands decreased from 42.2% in 1988 to 19.6% in 2017, while forestland shrank from 15% to 6.1%, which led to the conversion of vegetation, fallow land, and water bodies into built-up areas, thus intensifying the urban heat island effect.

The study by Mohan et al. (2012) assessed and compared UHI intensities and hotspots in India's Delhi using in situ measurements and remote sensing observations. It addresses the research gaps, such as the lack of field campaigns on UHI intensities in India in the past few decades and the need to further explore the relationship between maximum UHI and population data and compare it with other countries. The main findings are that UHI effects were most dominant in areas with dense built-up infrastructure and commercial centres; the three locations with the highest UHI were in commercial and/or densely populated areas. We observed a higher UHI during both afternoon and nighttime hours, peaking at 8.3°C. The study's flaws were pointed out by the researchers, who said that the remote sensing data might not fully show the effects of UHI, especially during the day, and that the comparison between measurements made in the field and data from remote sensing was not as good during the day (Mohan, Kikegawa, Gurjar, Bhati, Kandya, & Ogawa, 2012)

Recent studies on the UHI effect in India reveal complex patterns influenced by various factors. Contrary to expectations, many Indian urban areas experience daytime Urban Cool Island (UCI) effects, particularly during pre-monsoon summers, due to a lack of vegetation and moisture in surrounding non-urban areas (Kumar et al., 2017; Shastri et al., 2017). Agriculture, irrigation, and atmospheric aerosols largely control this phenomenon (Kumar et al., 2017). However, night-time UHI warming is observed across most Indian cities (Kumar et al., 2017; Shastri et al., 2017). Research approaches in India primarily utilise mobile observations and remote sensing techniques (More et al., 2015). While UHI studies in India have progressed, there is a need for more numerical modelling studies to align with global research trends (Veena et al., 2020). These findings highlight the importance of considering regional factors in urban climate studies and their implications for heat stress mitigation and urban planning in rapidly urbanising India (Kumar et al., 2017; Shastri et al., 2017; More et al., 2015; Veena et al., 2020).

The study by Kumar et al. (2017) shows that agriculture and irrigation are the dominant factors in controlling the UHI and UCI effects in India. The research tries to find the drivers of the UCI effect, which is observed in more than 60% of Indian urban areas. The researchers used satellite data and Community Land Model (CLM) to study how irrigation affects the UCI effect. The study examined how farming practices, particularly irrigation and atmospheric particles, influence temperature differences between urban and rural areas. One of the key findings revealed that over 60% of Indian urban areas experience a daytime Urban Cool Island (UCI) effect, where urban areas are cooler than surrounding rural regions. This phenomenon is attributed to a lack of vegetation and moisture in rural areas compared to cities. However, in urban regions with extensive irrigation, a positive Urban Heat Island (UHI) effect was observed, making urban areas warmer than their rural counterparts.

The study also addressed two major research gaps: understanding the causes of the UCI effect in India and the role of land-use decisions and aerosols in shaping, altering, and sometimes reversing the expected temperature differences between urban and rural areas. Despite its findings, the study acknowledged limitations, noting that the drivers of the UCI effect remain "poorly constrained," and further research is necessary to fully understand these dynamics. It highlighted the importance of considering both land-use decisions and aerosols as critical factors, suggesting that these aspects were not comprehensively explored in the research (Kumar et al., 2017).

The 2017 review paper by Shastri et al. gives an overview of the UHI phenomenon, including what causes it, how it affects people, and why cities need to come up with their own plans to reduce it. These plans should include things like green building codes, energy efficiency, controlling air pollution, and planning for cities across the country. The researchers found that, during the pre-monsoon summer, SUHII is more negative than expected in most urban areas. However, at night, SUHII is positive, showing stronger heat effects. In winter, daytime SUHII becomes positive in the Indo-Gangetic Plain. Interestingly, non-urban areas have higher LST than urban areas during pre-monsoon summer days, leading to more intense heat waves outside cities, challenging past assumptions. Since this is the first study to look at the daily and seasonal patterns of SUHII in India, there is a need for more research to fully understand the phenomenon. Also, there is a need to reassess SUHII in India to better understand climate adaptation, heat stress management and urban micro-climate analysis (Shastri, Barik, Ghosh, et al., 2017).

The study conducted by Tyagi et al. (2017) emphasises the need for city-specific studies to develop effective mitigation strategies, establish high-resolution UHI monitoring and forecasting systems, and align UHI-related policies across various government levels. The researchers identified UHI as a phenomenon where city centres experience higher temperatures compared to surrounding areas, leading to negative impacts on energy consumption, public health, the economy, and climate change. Key drivers of UHI include rapid urbanisation, economic growth, and changing climate conditions. The intensity of UHI is influenced by several factors, such as local climate, population density, anthropogenic heat emissions, green cover, land use practices, and the layout of urban areas (Tyagi et al., 2017).

Raj et al. (2020) examined UHI effect across 44 major cities in India and found that anthropogenic forcing is exacerbating the UHI with positive daytime surface UHI intensity and increasing night-time UHI intensity. Using satellite temperature data collected from 2000 to 2017, researchers observed that the average daytime SUHII was positive, reaching up to 2°C in most of the 44 major cities studied across India. The analysis revealed that SUHII trends were generally positive during the monsoon and post-monsoon seasons, while winter and summer showed negative trends. However, these seasonal variations were not statistically significant. In contrast, night-time SUHII consistently increased across all seasons in most cities, reflecting a steady rise in urban temperatures driven by rapid urbanisation and the impact of human activities (Raj, Paul, Chakraborty, & Kuttippurath, 2020).

To understand the extent and characteristics of the UHI effect in Ahmedabad, Joshi et al. (2015) used satellite remote sensing data, specifically Landsat ETM band-6 thermal infrared data, to monitor temperature differences across different land use classes. They also collected in-situ surface measurements using an IR gun in various zones of Ahmedabad to identify urban hot spots and combined satellite remote sensing data and field measurements to characterise the UHI effect in Ahmedabad (Joshi, Patel, & Shukla, 2015).

Researchers from IIT Bhubaneswar, Sethi and Vinoj (2024), revealed that urbanisation has significantly contributed to nighttime warming in over 140 Indian cities, with temperatures rising 60% more than in surrounding non-urban areas. The study found an average urban warming effect of 0.2°C per decade across these cities. This indicates that 37.73% of the total urban warming can be attributed to urbanisation, resulting in nearly a 60% increase in warming compared to adjacent rural areas. Due to increased concretisation, the cooling-down process has been reduced. In other words, night-time warming in the cities is not cooling down as required (Sethi & Vinoj, 2024).

Veena et al. (2020) evaluate the trends of UHI studies in Indian cities, including heat island classification, methods of studying UHI, and their limitations, and compare the new trends of UHI studies in the world and identify areas where India lacks growth in UHI research. The **researchers have found that urbanisation and population growth have led to the formation of UHIs in Indian cities**. Also, research on UHI in India has been limited, with a lack of numerical modelling studies compared to global trends. The table below[1] provides an overview of UHI studies conducted in various Indian cities over the years. It highlights the key variables analysed in these studies, covering research efforts up until 2018 (see Table 1 for details).

Sl no.	Year	Location of the Study	Paper	Variables used	Method of study
1	2000	Pune	Deosthali (2000)	AT	Mobile survey
2	2003	Chennai, Bangalore, Hyderabad	Gopalakrishnan et al. (2003)	AT, ST	Mesoscale models
3	2006	Visakhapatnam	Devi (2006)	ST	Field survey
4	2009	Bhopal	Gupta et al. (2009)	ST	Satellite data
5	2010	Bangalore	Ramachandra and Kumar (2010)	AT, LST	Satellite data

[1] AT: Air Temperature, LST: Land Surface Temperature, ST: Surface Temperature, PET: Physiological Equivalent Temperature.

6	2011	a. Delhi b. Delhi c. Bangalore	a. Mohan et al. (2011) b. Ahmad et al. (2011) c. Ambinakudige (2011)	a. AT b. LST c. LST	a. Fixed station data b. Satellite data c. Satellite data
7	2012	a. Delhi b. Pune c. Delhi d. Jaipur	a. Mohan et al. (2012) b. Nesarikar-Patki and Raykar-Alange (2012) c. Pandey et al. (2012) d. Gupta (2012)	a. AT, LST b. LST c. ST d. ST	a. Satellite data, Field survey, Fixed station data b. Satellite data c. Satellite data d. Satellite data
8	2013	a. Delhi	a. Mohan et al. (2013)	LST	a. Satellite data, Fixed station data
9	2014	a. Kochi b. Guwahati	a. Thomas et al. (2014) b. Borbora and Das (2014)	a. AT b. AT	a. Mobile survey, Fixed recording station b. Instrumental measurement
10	2015	a. Bathinda b. Tiruchirapalli c. Delhi, Mumbai d. Delhi e. Ahmedabad	a. Sharma and Pandey (2015) b. Kannamma and Sundaram (2015) c. Grover and Singh (2015) d. Babazadeh and Kumar (2015) e. Joshi et al. (2015)	a. ST b. PET c. LST d. LST e. ST	a. Instrumental measurement b. Instrumental measurement c. Satellite data d. Satellite data e. Satellite data, Field data
11	2016	a. Ernakulam b. Chennai c. Uttarakhand d. Ahmedabad e. Bhubaneshwar f. Noida g. Kanpur	a. Baby and Arya (2016) b. Amirtham (2016) c. Goswami et al. (2016) d. Swain et al. (2016) e. Kikon et al. (2016) f. Chakraborty et al. (2016) g. Kumar and Singh (2016)	a. AT b. AT c. ST d. LST e. LST f. AT, LST g. LST	a. Instrumental measurement b. Fixed station data c. Satellite data d. Satellite data e. Satellite data f. Fixed station data, Mobile survey, Satellite data g. Satellite data
12	2017	a. Lucknow b. Delhi c. Andhra Pradesh	a. Aslam et al. (2017) b. Kumar et al. (2017a) c. Kumar et al. (2017b) d. Singh et al. (2017)	a. AT b. LST c. LST d. LST	a. Satellite Data, Fixed station data, Mesoscale model b. Instrumental measurement c. Satellite data d. Satellite data

13	2018	a. Mumbai b. Kolkata	a. Mehrotra (2018) b. Ali Gazi and Mondal (2018)	a. ST b. LST	a. Satellite data b. Satellite data

Table 1: Past studies on UHI in Indian cities. *Source*: Adapted from Veena et al. (2020) and personal findings.

The table highlights that most studies on UHI have been conducted using satellite data. These satellites are equipped with advanced sensors, including the National Oceanic and Atmospheric Administration (NOAA), Multispectral Scanner (MSS), Geostationary Operational Environmental Satellite (GOES), Moderate Resolution Imaging Spectroradiometer (MODIS), Terra (formerly EOS AM-1), Thermal Infrared Sensor (TIRS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Advanced Very High-Resolution Radiometer (AVHRR), and Optical Land Imager (OLI), among others. In contrast, field measurements, which provide on-ground data, are carried out using two main methods: stationary surveys and mobile surveys. These approaches complement satellite observations by offering more localised insights.

5. Drivers of the Urban Heat Island Effect

The environmental Kuznets curve outlines a theoretical link between economic development and environmental degradation. According to Stern (2003), in the initial stages of economic growth, environmental degradation and pollution increase. However, after reaching a certain income threshold—which varies depending on the specific environmental indicator—this trend begins to reverse, and further economic growth leads to improvements in environmental conditions. This relationship forms an inverted U-shaped curve. Expanding on this concept, Liu and Zhang (2024) highlight that the transformation and modernisation of industrial structures, alongside economic growth, not only reduce pollution but also generate financial resources to improve urban living environments. They suggest that these changes contribute to mitigating the Surface Urban Heat Island (SUHI) effect, aligning closely with the framework of the environmental Kuznets curve (Stern, 2003; Liu & Zhang, 2024).

The exploration of the UHI phenomenon typically involves three primary approaches: GIS-based methods, observation-based methods, and numerical simulations (Assenova, Vitanova, & Petrova-Antonova, 2024). Research indicates that UHI effects and their variations are influenced by factors such as surface biophysical composition and configuration (Yu et al., 2019), local climate conditions (Wang et al., 2018), and socio-economic drivers (Peng et al., 2012). Santamouris et al. (2007), Akbari et al. (2001), and Oke (1987) identified key causes of UHI, including:

a. There is less evapotranspiration due to a decrease in vegetation
b. Low albedo surfaces absorb more solar radiation
c. The higher rugosity creates obstacles in air flow
d. High amount of anthropogenic heat release.

After reviewing several research articles and reports, we have identified several other causes of heat islands. Some of the key ones are as follows:

a. **The Decline of Natural Landscapes:** Natural elements like trees, plants, and water bodies play a critical role in cooling the environment by offering shade, releasing water vapour through leaves, and facilitating water evaporation from surfaces. However, urban environments dominated by dry, rough surfaces such as buildings, parking lots, sidewalks, and roads provide limited shade and moisture, leading to increased heat accumulation. According to Bouyer et al. (2009), albedo[2] directly impacts the formation of a city's microclimate, with its value varying based on surface orientation, material heterogeneity, and design. Nuruzzaman (2015) explains that low albedo surfaces tend to absorb and store more solar energy, which exacerbates urban temperatures and contributes to the development of urban microclimates. This highlights the need for thoughtful urban design and materials to mitigate the UHI effect (Bouyer et al., 2009; Nuruzzaman, 2015).
b. **Types of Urban Materials:** Urban environments are often dominated by materials such as pavements and roofs that reflect less solar energy and instead absorb and retain more heat compared to natural surfaces like vegetation. This contributes to the formation of heat islands, which are most noticeable during the day and become even more pronounced after sunset as these materials release the stored heat slowly. Additionally, the increased use of air conditioning, while effective at cooling indoor spaces, transfers the absorbed heat into the atmosphere, further intensifying urban temperatures (Okwen, Pu, & Cunningham, 2011).

[2] Albedo is the fraction of light that a surface reflects. If it is all reflected, the albedo is equal to 1. If 30% is reflected, the albedo is 0.3. The albedo of Earth's surface (atmosphere, ocean, land surfaces) determines how much incoming solar energy, or light, is immediately reflected back to space [NASA. (n.d.). *What is albedo?* Retrieved from https://mynasadata.larc.nasa.gov/mini-lessonactivity/what-albedo]

c. **Urban Geometry:** When tall buildings surround shorter ones, they create what is referred to as the "urban canopy," trapping heat and reducing airflow (Masson, 2006). In densely built areas, narrow streets and closely packed structures act as heat traps, making it difficult for these spaces to cool down. Additionally, cities with many narrow streets and high-rise buildings often form "urban canyons," which obstruct natural wind flow that would otherwise help cool the area. This lack of airflow exacerbates the heat retention, contributing to higher temperatures in urban environments.

d. **Heat from Human Activities:** Everyday actions, such as driving vehicles, operating air-conditioning units, running industrial factories, and maintaining buildings, release heat into the surrounding environment. This accumulation of heat from anthropogenic sources intensifies the UHI effect and raises local temperatures.

e. **Weather and Geography:** Calm and clear weather allows more solar energy to reach urban surfaces, trapping heat and preventing its escape, which worsens the heat island effect. Conversely, strong winds and cloud cover can mitigate heat island formation by promoting cooling and reducing heat retention. Geographic features, such as nearby hills or mountains, also influence the effect by either blocking wind flow or creating unique wind patterns that impact how heat is distributed within the city.

6. Recommendations

To make recommendations that employ a holistic perspective, and acknowledge the interrelationships of climate, economic activities, policy and social dynamics, we used the STEP framework. STEP stands for social, technological, economic and physical aspects. A study by Benz, S. A., & Burney, J. A. (2021) finds that low-income communities, particularly large populations with people of colour, often experience significantly higher heat conditions than in surrounding areas. These communities are more vulnerable to heat-related fatalities—also partially due to poor housing conditions that lack functional air-conditioning. Additionally, they are lacking in having access to resources that could help them find cooler and safer places to stay during heat waves.

The social aspect of this solution focuses on raising awareness among local communities and involving them in creating and maintaining green spaces. Engaging residents directly—through activities like planting trees, park upkeeping, and rooftop or neighbourhood gardening—helps foster a sense of shared responsibility for local green spaces. This participation can also boost community bonds by providing welcoming areas where people can connect, exercise, and simply enjoy nature. Additionally, encouraging women and youth involvement in these initiatives can promote social equity, ensuring that all groups benefit from improved urban environments.

To address the technology component, a blend of smart planning and sustainable green infrastructure will go a long way. Modern technologies like satellite imagery and sensor networks can be used to map temperature patterns across neighbourhoods, giving real-time data on heat levels and allow to monitor how effectively green spaces are cooling the environment; besides, citizens can take possible health and well-being measures based on the available data. Additionally, low-tech solutions like cool roofs (reflective materials for buildings) and green roofs (vegetation on rooftops) can be implemented. These solutions have been shown to significantly reduce the heat absorbed by buildings, thereby decreasing the energy needed for cooling. Combining such technologies with solar panels on green roofs could also make these areas self-sustaining in terms of energy.

The economics of tackling the UHI effect, particularly in Indian cities, involves a multifaceted approach. As mentioned earlier, UHI effect refers to the phenomenon where urban areas experience higher temperatures compared to nearby rural regions. This temperature increase not only leads to higher energy demands for cooling but also poses serious health risks and negatively impacts human productivity. Mitigating such effects yields substantial economic advantages, primarily the ones we have mentioned—a decrease in energy consumption and costs, an improvement in public health and a livable urban environment. For instance, the rising cost of energy and air conditioning systems are increasingly becoming a significant portion of business expenses. As per a report by Moody's, in reaction to rising temperatures, employees, particularly those in factories or outdoor environments, are adjusting their work schedules to cooler parts of the day. At the same time, businesses are under pressure to install additional air conditioning systems to reduce heat-induced drop in productivity. Such efforts to maintain a comfortable working environment necessitate higher operational costs, but it is necessary to avoid unwanted loss in revenue and worker output.

Internationally, many cities are now incorporating UHI mitigation strategies into their broader climate action plans. For example, the European Union Green Deal focuses on building a cleaner, healthier, and climate-neutral Europe. It aims to revolutionise production and consumption practices, transforming the economy into one that is modern, resource-efficient, and highly competitive (European Commission, n.d.). The World Bank has also supported UHI mitigation projects, emphasising the long-term financial benefits of investing in green infrastructure and energy-efficient buildings.

A recent study by the Centre for Science and Environment India (2024) examined heat patterns in six major Indian cities: Kolkata, Delhi, Mumbai, Hyderabad, Bengaluru, and Chennai. The study emphasises the need for city-specific heat management plans that go beyond emergency responses to summer heatwaves. These plans should aim to tackle all potential sources of heat generation while addressing the loss of green spaces and water bodies due to urban land-use changes. Furthermore, the study highlights the importance of developing robust systems to monitor trends in temperature, humidity, heat indices, and land-use patterns. It also stresses the need to consider both daytime and night-time temperature variations to ensure comprehensive and effective urban heat management strategies.

While in India, UHI has not yet been centrally addressed in national policy, local governments are starting to recognise its effects. For instance, Delhi's air quality and temperature monitoring initiatives are part of a broader effort to understand and combat the city's UHI. Measures such as promoting urban green spaces, cool roofing materials, and urban heat action plans are gaining traction. The India Meteorological Department report (2023) highlighted that the rise in urban temperatures significantly impacts energy consumption, making it crucial for cities to integrate UHI mitigation strategies. **India is at a critical juncture where policy can drive systemic change. Urban planning needs to prioritise energy efficiency, green infrastructure, and low-impact materials, especially in rapidly growing Indian mega-cities.** Nationwide programmes like the Smart Cities Mission and National Adaptation Fund for Climate Change (NAFCC) can further support UHI mitigation through funding for sustainable urban design and green space development.

A policy brief by the European Commission (2024) highlights the growing challenge of rising heat exposure in urban areas. It reveals that nearly half of the 10,000 cities studied worldwide have seen an increase in heat exposure between 1983 and 2016. The report also notes that over 1.7 billion people living in cities are now at risk of extreme heat, underscoring the urgent need for better urban planning and climate adaptation strategies. The policy brief highlights a few strategic recommendations, such as:

a. To utilise available data, monitoring, and modelling technologies for the urban thermal environment. It could signal the need to upgrade the urban governance team, including employees who are well aware of new technological tools and techniques.

b. Planning interventions to address both high-exposure locations and vulnerable neighbourhoods.
c. Considering the distinctive nature of each city, create urban adaptation strategies such as urban greening that are sensitive to spatial dimensions.
d. Ensuring that there is a balance among buildings, green spaces, and pavement. It can significantly impact local temperatures; proper land use patterns are crucial for influencing the local microclimate.
e. In line with the EU soil strategy for 2030 and the Thematic Partnership on Greening Cities within the Urban Agenda for the EU, mapping and identifying the underused urban areas and reintroducing urban greenery where soil conditions give a positive signal.
f. Moreover, implementing a holistic approach that incorporates many tactics tailored to local circumstances. For instance, the natural cooling capacities of water bodies and the role of green infrastructure should be taken into account. Promoting citizen engagement and communication, along with behavioural change, can improve awareness and strengthen protection for vulnerable groups.
g. Establish heat action plans and heat officers. Additionally, integrating different levels of government and cross-sectoral urban departments, such as addressing building size, can bring about significant changes and provide benefits.

Many communities worldwide have implemented various mitigation and cooling strategies to combat the effects of heat islands. These strategies focus on making urban spaces cooler and more livable. They include: a. Planting more trees and expanding green spaces, b. Installing green roofs, c. Using cool or reflective materials, d. Improving urban planning and land use, and e. Adopting smart conservation methods.

Expanding tree and vegetation cover plays a vital role in cooling both surface and air temperatures by offering shade and promoting evapotranspiration. Beyond temperature regulation, trees and plants help manage stormwater flow and prevent soil erosion. Similarly, rooftop gardens, or green roofs, contribute to cooling by absorbing heat from the air through evapotranspiration. These green layers not only reduce the temperature of the roof surface and surrounding air but also enhance stormwater management, making urban environments more sustainable and resilient. Cool roofs, reflective pavements, or coatings reduce energy demands and create indoor cooling effects, thereby enhancing the energy efficiency of the building. Using paving materials on streets, parking lots, and sidewalks enhances solar energy reflection and improves water evaporation. Promoting mixed land use patterns, which create a balance between different land uses, can optimise spaces and provide optimal space for green cover.

Raven et al. (2018) identify four fundamental principles for designing buildings and urban environments to mitigate the urban heat island effect. These principles are:

a. **Enhancing the efficiency of urban systems:** This is critical in minimising waste heat and reducing greenhouse gas emissions. This can be achieved by optimising energy use in buildings, modernising public transit systems, and implementing sustainable practices in industrial operations. Such improvements not only contribute to reducing the urban heat island effect but also support broader climate goals (Raven et al., 2018).

b. **Redesign and reorganise urban spaces:** Reorganising the layout and design of cities can significantly enhance airflow and natural cooling. Improved urban planning not only reduces energy consumption but also helps communities adapt to rising temperatures and manage increased stormwater runoff more effectively (Raven et al., 2018).

c. **Use of heat-resistant construction materials:** Incorporating heat-resistant materials in construction, such as those with reflective coatings or low heat retention properties, can optimise how buildings manage heat absorption and release. These materials enhance energy efficiency and improve indoor comfort, particularly during extreme heat events (Raven et al., 2018).

d. **Increasing vegetation and natural cover:** Expanding green spaces, tree cover, and plantations provides multiple benefits, including cooling the urban environment, reducing air conditioning needs, and improving air quality. Additionally, vegetation aids in stormwater management and serves as a carbon sink, making it an essential strategy for addressing climate change (Raven et al., 2018).

Takebayashi (2018) outlines several strategies to implement the principles discussed by Tong, Prior, McGregor, Shi, and Kinney (2021). These strategies, detailed in Table 2 of Takebayashi’s work, emphasise practical approaches to mitigating urban heat impacts. By integrating these measures, urban planners can address the challenges posed by rising temperatures and ensure healthier, more sustainable city environments.

Adaptation option	**Evaluation index**	**Main climate effect**
Green shade and solar transmittance	Evaporative efficiency, sunshade	Evaporative cooling
Solar radiation shade and transmittance	Convection heat transfer coefficient	Sunshade, convective heat transfer
Retroreflective surface	Downward solar reflectance	Solar reflection
Water retentive pavement	Evaporative efficiency	Evaporative cooling
Cool pavement	Solar reflectance	Solar reflection
Green pavement	Evaporative efficiency	Evaporative cooling
Green wall	Evaporative efficiency	Evaporative cooling
Water retentive wall	Evaporative efficiency	Evaporative cooling
Fine mist spray	Evaporation rate	Evaporative cooling
Awning	Solar transmittance	Sunshade
Fractal shaped sunshade	Solar transmittance, convection heat transfer coefficient	Sunshade, convection heat transfer
Mesh shade and water supply	Solar transmittance, evaporative efficiency	Sunshade, evaporative cooling
Evaporative cooling louvre	Evaporative efficiency	Evaporative cooling
Greening cooling louvre	Evaporative efficiency	Evaporative cooling
Tree pot	Solar transmittance, evaporative efficiency	Sunshade, evaporative cooling
Water retentive block	Evaporative efficiency	Evaporative cooling
Water surface	Evaporative efficiency	Evaporative cooling
Fine mist spray with a blower	Evaporation rate	Evaporative cooling
Ceiling cooling system	Surface temperature	Artificial cooling
Water cooling bench	Surface temperature	Artificial cooling
Water surface	Evaporative efficiency	Evaporative cooling
Watering	Evaporative efficiency	Evaporative cooling
Fine mist spray	Evaporation rate	Evaporative cooling
Shading	Solar transmittance	Sunshade
Tree planting	Solar transmittance, evaporative efficiency	Sunshade, evaporative cooling
Roof and ground greening	Evaporative efficiency	Evaporative cooling
Wind and ventilation	Convection heat transfer coefficient	Convective heat transfer
Traffic mode control	Anthropogenic heat release	Reduction of anthropogenic heat release
Unused energy use and natural energy use	Anthropogenic heat release	Reduction of anthropogenic heat release
Information and communication technology use	The human body's physiological amount	Reduction of human thermal load

Table 2: Measures to implement the above four principles provided by Raven et al. (2018).
Source: Adapted from Takebayashi, H. (2018). A simple method to evaluate adaptation measures for urban heat island. *Environments*, *5*(6), 70. https://doi.org/10.3390/environments5060070.

7. Conclusion

The National Disaster Management Authority (NDMA) has reported that heat waves in India caused a significant loss of life, with 24,223 deaths recorded between 1992 and 2015. In response, the NDMA introduced the *Preparation of Action Plan—Prevention and Management of Heat Wave* guidelines to help mitigate the impact of extreme heat events (National Disaster Management Authority, n.d.). In 2013, the Ahmedabad Municipal Corporation set a milestone by launching India's first heat action plan, which inspired other states to develop their own strategies. To remain effective, these heat action plans must be continuously updated to address the ever-changing dynamics of heat waves and climate-related challenges. The establishment of cooling centres and raising awareness among the citizens, especially focusing on vulnerable population groups, are of utmost importance.

We believe there is a need for further research on the UHI effect, specifically in the Indian context. There is a need for enhanced access to publicly available data for research and analysis, as well as a data-driven methodology to develop models that capture the temporal changes in weather and climatic conditions, including warm and cool days, as well as summer and monsoon trends. We need a growing collaboration among government, academia, and civil society organisations to make equitable policy, popularising the green building market in the country, setting up public knowledge forums, and research grant opportunities to attract fellows in this area of research.

Sustainable Development Goal (SDG) 11 emphasises the importance of fostering sustainable cities and communities. This goal highlights the challenges posed by extreme poverty in urban areas, where growing populations often outpace the capacity of local and national governments to provide adequate infrastructure. Achieving sustainable urban environments involves ensuring access to safe, affordable housing, upgrading informal settlements, investing in public transportation, expanding green spaces, and promoting inclusive and participatory urban planning (United Nations Sustainable Development Goals, 2015). The UHI effect is deeply connected to the SDG agenda, as it directly impacts the livability and sustainability of cities. Addressing this issue requires creating cooler urban spaces, reducing heat stress, and transforming cities into equitable, self-sustaining, and inclusive environments for all.

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