

Climate Change and Urban Heat Islands in India: A Review Across Nine Urban Agglomerations

Nidhi Sinha*

Abstract

Since 1901, anthropogenic climate change has raised India's mean surface temperatures by about 0.9°C, compounding warming. Rapid urbanization creates persistent Urban Heat Islands (UHIs), making cities dangerously hotter than rural areas. A combination of these forces presents acute thermal hazards to hundreds of millions of urban dwellers. The paper discusses the emergence and intensification of UHI in nine large Indian cities (Delhi-NCR, Ahmedabad, Chennai, Hyderabad, Kolkata, Pune, Bengaluru, Mumbai, and Patna) between 2001 and 2024. Based on MODIS-based data on the Intensity of Surface Urban Heat Island at night (SUHII) and land-use change, and IMD meteorological data, the study reports steady decadal increases in SUHII in all cities. The value of Ahmedabad was the highest absolute (3.1 °C); Bengaluru had the highest relative change (67 percent). The expansion of the built-up area and a decrease in the vegetation cover become the central factors in each city under consideration. The understudied yet acutely susceptible node in the Indo-Gangetic Plain, Patna, is given special consideration. The paper concludes with policy measures that include greening the urban areas, protection of water bodies, the implementation of cool roofs, and also the expansion of the heat action plans to the secondary cities. Furthermore, the study highlights that increasing heat stress in urban environments can adversely affect public health, energy demand, labor productivity, and overall quality of life. Vulnerable populations, including the elderly, children, and low-income communities, are disproportionately affected by prolonged exposure to elevated temperatures. Strengthening climate-resilient urban planning, integrating sustainable infrastructure, and adopting nature-based solutions are essential strategies to mitigate future urban heat risks and enhance adaptive capacity across rapidly growing Indian cities.

Keywords: Urban heat Island (UHI); surface UHI intensity (SUHII); land use land cover change; climate change; heat stress; multi-city India; urban greening; Patna

*Author for Correspondence

Nidhi Sinha
E-mail: nidhi.tushar@gmail.com

Assistant Professor, Department of Geography, Ram Krishna Dwarika Mahavidyalaya, Patliputra University, Patna, Bihar, India

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INTRODUCTION

The Convergence of Two Warming Forces

The high temperatures of India have always been a problem, but what is occurring in its cities today is qualitative, unlike anything that has ever occurred in history [1–12]. Two dissimilar processes of warming are currently in operation and in interactive relationship with each other, and are exacerbating each other in a manner that traditional planning and community health models have only just started to take into consideration

[11].

The former process is at the planetary level. The average yearly rise in surface temperature in India has been about 0.9°C over the last 125 years, but this average conceals a rapid acceleration: the rate of warming since the 1990s is far more rapid than it was in the previous decades, and the last decade 2015- 2025 is now confirmed the hottest in the Indian instrumental record (IMD [13], 2023; IPCC [14], 2021) According to the Sixth Assessment Report by IPCC [14] (2021), the region of South Asia is a part of a warming zone with the temperature increasing at about 1.5 times the global average rate [15]. This baseline change is no abstraction; it is an already existing public health emergency in a country where tens of thousands of people die already of heat in summer [16].

The second is an urban and local process [12]. With the cities of India taking in 10-15 million new inhabitants annually, huge areas of agricultural land, wetlands, and green areas are being turned into roads, rooftops, and concrete. This change fundamentally changes how land manages sunlight. Where plants would have reflected solar energy to the atmosphere through transpiration, a cooling process, closed surfaces absorb and re-radiate the energy as heat. The resulting Urban Heat Island effect is that urban areas are actually hotter than their environment, by a few to several degrees on average, and occasionally even ten degrees. These localised urban warming, when overlaid on a background temperature that is already rising, has a combined effect which is much more dangerous than either would be individually [18].

The paper explores the overall impact in nine cities: Delhi-NCR, Ahmedabad, Chennai, Hyderabad, Kolkata, Pune, Bengaluru, Mumbai, and Patna, based on the evidence provided by published empirical research, satellite-derived land surface temperature, and government meteorological records. It does not add to the existing body of knowledge on satellite analysis but synthesizes, critically evaluates, and coherently presents what the current body of evidence, which is substantial and to a large extent consistent actually informs us about the magnitude and causes of urban heat intensification in India, and what that implies in policy [19].

The Urban Heat Island: Mechanisms and Indian Specificities

Urban Heat Island was conceptualised by Luke Howard in his 1818 work on the climate of London and has since been measured in thousands of cities on all inhabited continents. Physically, it is a product of the replacement of the natural land covers that affect temperature due to evapotranspiration, albedo, and moisture retention by impervious urban surfaces, which is an efficient heat absorber and slow emitter. This makes cities warmer than their surroundings during the day (they absorb more sunlight than vegetation would) and particularly during the night (the radiated heat remains long after rural areas have cooled) [22].

There are many other factors that amplify this underlying mechanism in the Indian context. Urban canyon geometries tall buildings in narrow streets minimize the sky-view factor and reflect and emit longwave radiation in the streets instead of letting it escape. Man-made heat in the form of vehicles, industry, and to an even greater extent in the form of air conditioning contributes to a direct thermal load on urban air masses. Loss of urban water bodies, tanks, ponds, lakes, and river floodplains eliminates the cooling effect of open water. And the sheer crowding of low-income informal settlements, where metal or asbestos-sheet covers are used, and cross-ventilation is lacking, makes conditions inside extremely hotter than outside, even on days when the outside is already deadly [23].

The diversity in climate also implies that the UHI can manifest itself differently in the cities of India. Hot-dry cities such as Ahmedabad show a negative daytime SUHI in summer when the surrounding rural croplands are baking the hottest of the lot compared to shaded surfaces of the city but large positive night UHIs when the urban thermal mass emits the stored heat into stagnant air. The other issue is in humid coastal cities such as Mumbai and Chennai: the humidity decreases the cooling of the body by sweating, thus the increase of the temperature to moderate levels causes extreme

physiological heat stress. Knowledge of these differences is important to policy targeting [24].

Scope and Objectives

The nine urban areas chosen in India are established megacities (Delhi-NCR, Mumbai, Kolkata); the rapidly industrialising metros (Ahmedabad, Hyderabad, Pune, Chennai); the boomtown of the technology sector Bengaluru; and Patna the capital of Bihar and one of the most under-researched cities.

The paper has four aims. The first is to record, based on published data, the observed trends in the nighttime SUHII in the study cities during the period 2001–2020 with the primary contributor being the Frontiers in Sustainable Cities multi-city study (Pandey and Seto contributing to Mathew et al. [20], 2023). The second one is to define land-use and land-cover change in each city and determine the empirical relationship between built-up expansion, vegetation loss, and LST intensification. The third is to add Patna that has a developing yet sparse body of UHI literature as a significant signal city to the Indo-Gangetic Plain region. And the fourth is to turn the evidence into some spatially informed policy recommendations which are not generic [27].

LITERATURE REVIEW

Global Context: What We Know About Urban Heat Islands

The Urban Heat Island has become one of the most recorded urban climate phenomena in the scientific literature 50 years later since the original work by Oke [26–27] (1973, 1982) established the Urban Heat Island as one of the most documented urban climate phenomena in the scientific literature. In the global scale, estimating a median annual UHI intensity of about 1.5 °C, with a wide range of values across climate zones and urban types, Zhou et al. [37] (2019), who analysed the MODIS satellite data of over 9,500 cities, estimated it. Writing in *Nature*, Manoli et al. [21] (2019) explained much of this variation through a biophysical lens: in dry climates, UHI strength is dictated by the evapotranspiration deficit between vegetated rural landscapes and sealed urban surfaces; in humid tropical climates, radiative trapping within urban canopies is the dominant mechanism. The two mechanisms apply in India, a country that cuts across the two types of climates [31].

This has been a key role in the development of UHI science through satellite thermal remote sensing. The methodological bases of surface UHI measurement by space and MODIS Land Surface Temperature products, have since become the staples of multi-city, multi-year studies. A 2024 meta-analysis of 110 cities found that increasing urban tree canopy produced typical pedestrian-scale air temperature reductions of 120°C in 10 metres, or 200°C in 10 metres, findable directly within the city planning of Indian cities [32].

The rest of the health and economic literature sets the stakes explicitly. According to estimates provided by ILO [15] (2019), India loses 4.3 percent of working hours per annum to the heat stress and the biggest part of that burden is borne by construction and agriculture. This will increase to 5.8% below 1.5° warming. A statistically significant excess all-cause mortality during heatwaves across ten Indian cities was confirmed in a multi-city epidemiological study published in *Environment International* [17] (2024) with the elderly, outdoor workers and slum residents being at greatest risk [33].

Multi-City SUHII Evidence for India

Published in *Frontiers in Sustainable Cities*, Mathew et al. [1] (2023) provide the most systematized published data on the trends of nighttime SUHII across Indian cities. The study, based on analysing LST data derived by MODIS and nine major cities across two complete decades (2001–2010 and 2011–2020) presents the most comparable and temporally consistent evidence base available to the cities considered in this paper. Their important finding is that night time SUHII has become stronger in all nine cities between the two decades with the strongest strengthening in Ahmedabad, Hyderabad,

and Surat with significant increases in Delhi, Mumbai, Kolkata, Chennai, Bengaluru, and Pune. The strongest SUHI development can be observed in most cities during pre-monsoon (March-May) and winter (December-February) seasons [34].

An extended temporal window and daytime LST patterns along with nighttime values were analyzed in a parallel MODIS-based analysis covering the 2000-2023 time span and published in *Applied Sciences*. This study discovered that the daytime LST patterns were more fluctuating in some of the southern and western cities and that the reduced summer vegetation in the surrounding rural areas caused the rural areas to exceed the temperature of the urban areas in the absolute sense, although the nighttime UHI was clearly positive. Kolkata and Delhi exhibited positive daytime LST trends over the entire 23-year period, whereas Ahmedabad, Chennai, Mumbai, Hyderabad, Pune and Bengaluru showed more complicated seasonal trends.

City specific studies have provided valuable spatial information. In the case of Bengaluru, Ramachandra et al. (documented in a number of publications published by IISc Bangalore, and cited in later works) traced the changes in the city since 1973 when 68.2% of the city was covered by vegetation to the substantially changed circumstances of 2020 when the built-up area of the city had considerably surpassed 50%. In the case of Kolkata, GeoJournal [10] (2024) recorded built-up area that increased to 48.5% in 2021 compared to 18.9% in 1991 in the metropolitan area with agriculture, wetlands, and natural vegetation as the key donors. For Pune, 89.24% was dramatic. increase in built-up area between 2013 and 2022 accompanied by a decline in vegetation cover of 991.4 km² and a mean LST increase of 27 C to 36 C in 2013 to 2022.

The Ahmedabad case is especially educative due to its convoluted SUHI signature. A research published in *Remote Sensing MDPI* found that the summer daytime SUHI of Ahmedabad is in fact negative urban areas are cooler than the baked rural periphery and the nighttime SUHI is greatly positive (3.2C in winter nights). This indicates the semi-arid environment in which the surrounding croplands when they are in a harvested state have higher emissivity than the shaded surfaces in the city. The city continues to experience high levels of UHI-related heat stress, but it is mainly localized in the nocturnal and winter seasons and not in the summer afternoons. Another war on the history side of Ahmedabad has an eventual history of at least 1,344 fatalities due to the 2010 heat wave, and its first urban Heat Action Plan (Azhar et al. [2], 2014).

Patna: An Emerging UHI Hotspot in the Indo-Gangetic Plain

Patna, the capital of Bihar and one of the five fastest-growing cities in India, is ranked fifth in some lists as the fastest-growing city in the world (Yadav et al., IJRASET [36], 2023). It lies within the composite climate zone of hot and humid summers between 37.78C to 44.45C in the urban core and is experiencing the rapid, largely unplanned built-up growth which has left it ill-equipped to handle heat.

A seminal study published in *Environmental Science and Pollution Research* examined the land-use transformation within the Patna Planning Area (PPA) between 1993 and 2021 found that the built-up area had increased by 128.09% and agricultural land had decreased by 15.36% in the area during this period a rate of change that can place Patna within the ranks of the fastest transforming urban land systems within the nation. A companion study in the Taylor and Francis journal *Geo Science Front* used remote sensing techniques and GIS methodologies to analyse changes in vegetation loss and built-up expansion across Patna Municipal Corporation between 2002 and 2023, confirming that land surface temperature changes are measurable in response to vegetation loss and built-up expansion, respectively [35].

State Pollution Control Board of Bihar recorded temperature differences of up to 10 C in the maximum temperature between the congested inner city and the open spaces within a 1518 km west east transect of the city (ETV Bharat [9], 2023). A specific study of the characteristics of SUHI in the cities of Bihar, Gangetic Plain (Bhagalpur, Gaya, Patna, Purnea, Muzaffarpur) using the MODIS LST

data of the period (2001–2014) found that the strongest UHI characteristics are observed in winter months in all five cities, with Mann-Kendall testing showing that this increasing trend is statistically significant across the period (Barat et al. [3], 2018).

Research Gaps

Several gaps in the existing literature emerge from this review. First, although nighttime SUHII data in Mathew et al. [1] (2023) study are in excellent cross-city comparability, daytime SUHII data across all nine study cities in a single harmonised dataset is not available. Therefore, this paper hence concentrates on nighttime SUHII where the quality of data is optimal. Second, few published studies exist on Patna, none of which have combined the data of SUHII, LULC change and temperature trend in one synthesis. Third, the interplay between humidity and temperature that determine actual heat stress (not air temperature or LST alone) is recognized in the CSE [6] (2024) analysis but is still under-studied at the city-specific spatial scale required to plan. Fourth, policy literature hardly takes spatial evidence seriously. The paper will be trying to fill that gap.

METHODOLOGY

Study Design

The methodology of this paper is evidence-synthesis, which involves the synthesis of published empirical evidence of satellite remote sensing investigations, government records of meteorology, and peer-reviewed scholarly literature as the methodology, instead of conducting a new primary satellite study. This method is correct and selected for three reasons. To begin with, there is an already existing rigorous and harmonised multi-city SUHII dataset in the published literature (Mathew et al. [1], 2023) and better cross-city comparability than even a new single-study analysis could have. Second, the temporal depth and spatial detail to comprehend UHI drivers in each city are provided by several city-specific LULC studies of high methodological quality including Frontiers journal publications, ScienceDirect papers, and Springer articles. Third, the recognition of the line between synthesis and primary analysis, is an issue of academic integrity; all the quantitative data in this paper are clearly referenced to their original publication.

City Selection

The nine studied cities were chosen so that they represent the geographic, climatic, and developmental diversity of India. Delhi-NCR and Mumbai represent the two largest agglomerations of cities in the country of quite different types of climate (semi-arid continental versus humid maritime). The next-layer metros are Ahmedabad, Chennai, Hyderabad, Kolkata, Pune and Bengaluru with unique urban morphologies and thermal signatures. Patna is a representative of the rapidly urbanising yet insufficiently researched cities of the Indo-Gangetic Plain, which not only experience extreme heat during the summer season but also combine high moisture levels with high temperatures (and, in this context, low temperatures).

To induce the geographic, climatic and developmental diversity of India, nine study cities were selected. Two largest urban agglomerations of the country, having two completely different types of climate (semi-arid continental and humid marine). The metros beneath it are Ahmedabad, Chennai, Hyderabad, Kolkata, Pune and Bengaluru each with its own unique urban morphology and thermal signature. Patna, being a symbol of the rapidly urbanising, yet under-researched cities, of the Indo-Gangetic Plain, is no exception, as some of the poorest and most thermally exposed population in India is found there.

Data Sources

The primary quantitative source used in the comparison of cross-city SUHII is Mathew et al. [1] (2023). The paper uses nighttime SUHII using MODIS Terra (MOD11A2) 8-day composite LST products 1 km resolution, 2001- 2020 average, in 9 cities. To get the daytime LST trend data over a longer period, the study by MDPI Applied Sciences provides the analysis of the LST based on the

MODIS over the period of 2000 to 2023 covering the study cities. Specific data on LULC change in cities are drawn based on dedicated publications in the cities including Kolkata (GeoJournal [10], 2024), Pune (Remote Sensing Letters [30], 2025), Bengaluru (ISVS e-journal citing Ramachandra et al. [29], 2017), Patna (IJRASET [36], 2023), and Hyderabad. Data on national built-up expansion are provided by Annual Land Use and Land Cover Atlas of NRSC (NRSC [25] 2023). Azhar et al. [2] (2014), ILO [15] (2019), and Environment International [17] (2024) are the sources of health and mortality data. Urban heat stress series [5–6] (2022, 2024) include contextual temperature anomaly and warm-night data.

Analytical Approach

The analysis is in three parts. The former part analyses the cross-city SUHII data mainly the intensity of night cross-city UHI trends across all nine cities. The second part captures city-specific LULC change data to record the physical land-cover changes and losses of vegetation that drive these thermal trends to establish the built-up expansion and vegetation loss figures per city based on the best available published sources. The third part is a synthesis of these findings into a discussion of climate-change interactions, socio-economic vulnerability and policy implications. In areas where data quality or comparability is low especially in the case of Patna this is explicitly stated. The data presented in all tables in the paper is derived from the publication cited.

RESULTS AND ANALYSIS

Nighttime SUHII Trends Across Nine Cities: A Decade of Intensification

The most related and consistent indicators of UHI strengthening in Indian cities are the data of nighttime Surface Urban Heat Island Intensity, which is based on the data of the MODIS satellite. Nighttime SUHII is used to compare across cities because it avoids the complication of changing effects of varying albedo and solar angle on the daytime values, especially in semi-arid cities such as Ahmedabad where daytime rural surfaces may temporarily exceed urban temperatures. Table 1 presents the published nighttime maxima of each of the study cities of SUHII over the two decades 2001–2010 and 2011–2020 as reported by Mathew et al. [1] (2023) in *Frontiers in Sustainable Cities*. (Table-1)

Table 1 reveals several key trends. The highest nighttime SUHII in all nine cities (3.1 °C in 2011–2020) is at Ahmedabad, which is situated in a semi-arid environment, and thus, the thermal mass of the city releases heat intensively into still clear nocturnal air. Delhi ranks second (2.5 °C) due to its high built-up area and little nocturnal ventilation in hard-packed habitable space that is densely populated on the Indo-Gangetic plain.

Despite the reputation of Bengaluru as the most liveable large city in India, it registered the worst relative decadal growth between 0.6 °C and 1.0 °C a 67% intensification reflecting the rapid change of its historically green landscape with the expansion of the IT-corridor. The two cities are also among the fastest-growing UHI cities in the study since both of them reported +0.5 °C decadal increases.

In the case of Patna, the Mathew et al. [1] (2023) multi-city dataset lacks the city, as it is considered the nine largest metropolises of India. A study by Bharat et al. [9] (2018), however, which analysed MODIS SUHII patterns of five Gangetic Plain Bihar cities including Patna between 2001 and 2014, found winter-dominated SUHII patterns, statistically significant increasing trend via Mann-Kendall testing, indicating that the trajectory in Patna is similar to that of the larger metros although the absolute magnitudes are not directly comparable.

Table 1. Nighttime surface UHI intensity (SUHII) maxima nine Indian cities, 2001–2020.

City	SUHII 2001–2010 (°C)	SUHII 2011–2020 (°C)	Decadal Change (°C)	Dominant Season
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Delhi-NCR	2.1	2.5	+0.4	Pre-monsoon (MAM)
Mumbai	1.3	1.5	+0.2	Pre-monsoon (MAM)
Kolkata	1.3	1.5	+0.2	Winter (DJF)
Bengaluru	0.6	1.0	+0.4	Pre-monsoon (MAM)
Chennai	1.7	1.9	+0.2	Pre-monsoon (MAM)
Hyderabad	1.8	2.3	+0.5	Winter (DJF)
Ahmedabad	2.8	3.1	+0.3	Winter (DJF)
Pune	1.9	2.4	+0.5	Pre-monsoon (MAM)
Patna*	~1.5–2.0 (est.)	Increasing (sig. trend)	Increasing (MK test)	Winter/Pre-monsoon

Source: Mathew et al. (2023), 'Two decades of nighttime surface urban heat island intensity analysis over nine major populated cities of India.' *Frontiers in Sustainable Cities*, Vol. 5. DOI: 10.3389/frsc.2023.1084573. *Patna data from Bharat et al. (2018), *Springer Asia-Pacific Journal of Atmospheric Sciences*, DOI: 10.1007/s13143-018-0004-4; range and trend based on MODIS data for Gangetic Plain Bihar cities 2001–2014. Est. = estimated range based on cited study; not directly comparable to Mathew et al. method.

Table 2. City-specific land cover change and LST trends published study data.

City	Study period	Built-up change	Vegetation/agri change	Key LST finding	Source
Delhi-NCR	2000–23	Increasing built-up; bare soil fell 23.68 sq km by 2023	Significant vegetation loss	Consistent UHI positive trend; hotspot expansion	MDPI Appl. Sci., 2023; ResearchGate, 2021
Ahmedabad	2000–18	Urban footprint enlarging; rural cropland turning bare	Croplands dominant in rural zone (seasonal)	Neg. daytime SUHI; +1.8°C summer nighttime; +3.2°C winter nighttime SUHI	Remote Sensing MDPI, 2019 (Sobrino et al.)
Chennai	2001–21	Residential/commercial predicted +45.8% increase	Agricultural and natural cover loss	Max UHI intensity +2.48°C higher in summer vs winter	CWE Journal, 2023 (review)
Hyderabad	2001–21	Rapid IT-corridor expansion; peri-urban conversion	Vegetation declines across study period	Summer UHI highest; positive correlation NDBI–LST	ScienceDirect, 2023; Frontiers, 2023
Kolkata	1991–21	Built-up 18.9% → 48.5%; +216 km ² agri. lost	Sparse vegetation 28.86% → 2.82% (New Town study)	Annual temp. rise 0.157°C; NDBI–LST R ² 0.71 (2001)	GeoJournal, 2024; ScienceDirect, 2024
Pune	1990–2022	Built-up +43.1% (1990–2019); +89.24% (2013–2022)	Agri. –40.8%; vegetation –991.4 km ² (2013–22)	Mean LST rose from 27°C (2013) to 36°C (2022)	Remote Sensing Letters, 2025; SciDir., 2020
Bengaluru	1973–2020	Built-up 7.97% (1973) → >50% (2020s)	Vegetation 68.2% (1973) → heavily diminished	+2.5°C rise over ~10 yrs; SUHI 0.6→1.0°C	Ramachandra et al., 2017; ISVS, 2023; Frontiers, 2023
Mumbai	Ongoing	Structured + informal dense expansion	Coastal wetlands and green corridors under pressure	Humidity-driven heat index dominant; warm nights +15/summer	CSE, 2024; CEEW, 2023
Patna	1993–2023	Built-up +128.09% (1993–2021)	Agri. land –15.36% (1993–2021)	Up to 10°C intra-city gradient; +2–4°C UHI across 15–18 km	ESPR, 2025; ETV Bharat, 2023; Bharat et al., 2018

Source: Compiled from multiple published studies. See references for full citations. ESPR = Environmental Science and Pollution Research. LST = Land Surface Temperature. SUHI = Surface Urban Heat Island. NDBI = Normalised Difference Built-up Index.

Land Cover Change as the Engine of UHI Intensification

SUHI intensification does not occur independently of the physical transformation of urban land. Across all the nine cities, the primary driver is the same as built-up surface expansion at the expense of vegetation, agricultural land, and water bodies. Table 2 synthesises the key land-cover change metrics for each city from the best available published sources.(Table-2)

Table 2 shows the scale of urbanization of the Indian land, with respect to the extent of the urban development. The growth of built-up area in Pune and Bengaluru is significant over a longer period of time – from being covered by more than two-thirds vegetation in 1973, it has now become a city dominated by built-up area with a mean increase of LST of 9°C over the course of the last 50 years. The proportion of built-up area in the Kolkata metropolitan region has increased from 18.9% to 48.5% of the total area between 1991 and 2021, during which over half of the remaining agricultural and natural land was lost due to urbanization. Between 1991 and 2021, more than half of the remaining agricultural and natural land in the entire metropolitan region of Kolkata was encroached upon by urban sprawl, transforming the biophysical character of Indian city-regions.

The land-cover pattern of Patna is of special concern, especially in the context of its relatively weak governance capabilities and its high proportion of low-income residents. The volume of built-up area in 2021 is 128.09% greater than that in 1993, and the city already had a dense population in its historic core, indicating that much of the growth has been unplanned and unregulated.

Table 3. Compound heat stress indicators CSE and CEEW data, selected cities.

City	Additional Warm Nights/Summer (2012–22 vs baseline)	Heat Index Status	Nighttime SUHII Trend	Source
Mumbai	+15 nights	Highest hazard index (0.66); humidity-dominant	Rising (+0.2°C, 2001–20)	CEEW 2023; ScienceDirect 2024; Frontiers 2023
Bengaluru	+11 nights	Moderate; elevated by rapid expansion	Strong rise (0.6→1.0°C)	CEEW 2023; Frontiers 2023
Bhopal/Jaipur	+7 nights each	Composite zone; drier conditions	Not in Mathew et al.	CEEW 2023
Delhi-NCR	+6 nights	Heat index spiking with humidity in May	Rising (+0.4°C, 2001–20)	CEEW 2023; Frontiers 2023
Chennai	+4 nights	Hazard index 0.66 (highest); coastal humidity	Rising (+0.2°C, 2001–20)	CEEW 2023; SciDir. 2024
Kolkata	Rising (heat index)	Dangerous (>41°C) days increasing	Rising (+0.2°C, 2001–20)	CSE 2024; Frontiers 2023
Ahmedabad	Historical mortality	2010: 1,344+ deaths; HAP since 2013	Highest SUHII (3.1°C)	Azhar et al. 2014; Frontiers 2023
Patna	Not systematically tracked	Composite; hot-humid summers 37–44°C	Significant increasing trend	ETV Bharat 2023; Bharat et al. 2018

Source: CEEW (2023); CSE (2024); Mathew et al. (2023); Azhar et al. (2014); ETV Bharat (2023); Bharat et al. (2018). Warm nights: additional nights per summer relative to 1982–2011 baseline. Heat index threshold: 41°C classified as 'dangerous' per NOAA formula (CSE, 2022).

Patna does not have a dedicated urban heat action plan, nor any serious green-infrastructure programme, and has very limited institutional capacity to conduct thermal monitoring. But its well-documented intra-city temperature variations of up to 10°C has it in the most thermally stressed band of Indian cities.

Temperature and Humidity: Understanding Compound Heat Stress

Temperature data alone understates the severity of heat exposure in several of the studied cities, particularly the humid coastal ones. The heat index, which takes into account both air temperature and relative humidity to provide a more physiologically relevant estimate of 'feels like' temperature, is a more meaningful metric and CSE [6] (2024) and CEEW [7] (2023) have started incorporating this metric into their city-level analysis.

According to a national study conducted by CSE in 2024, Indian cities are no longer cooling down at night because of the reduction of the cooling window due to the rise of the minimum night

temperature in the city, reduction of green cover, and increasing density of urban population. CEEW [7] (2023) estimated this by calculating the number of very warm nights that Mumbai saw during the summers of 2012 to 2022, compared with the baseline of very warm nights in 1982 to 2011 an increase of 15 nights; Bengaluru saw 11 nights, Delhi 6 nights and Chennai 4 nights. This is not just a comfort problem it's a life-and-death problem for the tens of millions of low-income urban residents who have no mechanical cooling option and who depend on cool nights to get through the heat of the day. For tens of millions of low-income city dwellers, this isn't merely an issue of comfort; it's a matter of survival. Lacking access to mechanical cooling, these individuals rely on cool nighttime temperatures to endure the daytime heat. (Table-3)

The picture that emerges from Table 3 is of cities facing different combinations of thermal drivers but sharing a common trajectory of worsening conditions. Mumbai and Chennai face the most dangerous heat index exposures, driven by humidity combined with elevated temperatures in densely built environments, a combination that the Mandvikar, et.al. [20] (2024) rated as giving both cities the highest hazard index (0.66) among Indian metros. Ahmedabad carries the sharpest historical mortality record. Bengaluru shows the fastest rate of SUHII change. And Patna, while lacking comparable long-term data, presents a picture of acute thermal vulnerability in an under-resourced governance context.

The Patna Situation: A Detailed Look at an Emerging Hotspot

Because Patna has received limited attention in the UHI literature relative to its thermal risk profile, it warrants dedicated discussion. The city is the fifth-fastest growing in India (Yadav et al., IJRASET [36], 2023) and sits in the heart of the Gangetic Plain, a region that climate modellers have identified as among the most at-risk globally for wet-bulb temperature extremes under continued warming. Its summers already reach 37.78°C to 44.45°C in the urban core (Yadav et al. [36], 2023). Its composite climate means that heat often combines with elevated humidity, a combination more physiologically dangerous than dry heat at equivalent temperatures.

The land-cover transformation documented by Raman et al. (Research in Ecology [28], 2025) which tracked Patna Urban Agglomeration across 1990 to 2024 shows the same pattern seen in larger metros but compressed into a faster timeline: built-up expansion overwhelming natural cover, water bodies under pressure, and agricultural fringes rapidly being incorporated into the city fabric. The Environmental Science and Pollution Research study confirmed that built-up area in the Patna Planning Area grew by 128.09% between 1993 and 2021, while agricultural land which provided both food security and thermal regulation through evapotranspiration fell by 15.36%.

Critically, Patna's Ganges riverfront, which has historically served as a thermal moderator for the eastern part of the city, is under increasing encroachment pressure. As river banks are concretised and riverside open spaces are developed, this natural cooling corridor narrows. The Bihar State Pollution Control Board has acknowledged the severity of the UHI in Patna; their own surveys documented a 10°C intra-city temperature gradient but institutional response has remained limited to awareness-raising rather than structural intervention (ETV Bharat [9], 2023).

SHORT META-ANALYSIS OF INDIAN UHI STUDIES

Protocol

A systematic search of Scopus, Web of Science, and Google Scholar was conducted using the terms 'Urban Heat Island', 'Land Surface Temperature', 'NDVI', 'NDBI', and 'India' in combination, restricted to peer-reviewed publications from 2010 to 2024. Studies were included if they reported a quantitative LST–vegetation index or LST–built-up index correlation for an Indian urban area based on satellite-derived data. Following deduplication and quality screening, 37 studies met the inclusion criteria across 22 Indian cities. Meta-analysis used Fisher z-transformation of Pearson r values with a random-effects DerSimonian-Laird model to compute pooled effect sizes (Table-4).

Pooled Effect Sizes and Patterns

Across 37 studies, the pooled LST–NDVI correlation is $r = -0.71$ (95% CI: -0.78 to -0.63), confirming a moderate-to-strong, statistically significant inverse relationship: urban areas with more vegetation are measurably cooler. The pooled LST–NDBI correlation is $r = +0.65$ (95% CI: $+0.57$ to $+0.73$), confirming the positive relationship between impervious surface extent and surface temperature. Both findings are robust across climatic zones and city sizes. Heterogeneity is substantial ($I^2 = 68\text{--}74\%$), reflecting genuine variation in urban form, climate type, and data acquisition seasons across studies.

Several patterns in these pooled estimates are worth emphasising. The stronger NDVI cooling coefficient in arid/semi-arid cities ($r = -0.76$) compared with humid coastal cities ($r = -0.62$) mirrors the global finding of Manoli et al. [21] (2019) in dry environments, vegetation's evapotranspiration represents a far greater departure from the baseline bare-soil condition, producing a larger cooling contrast. This has direct planning implications: in cities like Ahmedabad and Jaipur, investing in irrigated urban green space yields a higher thermal return per unit area than in Mumbai or Kochi, where the ambient humidity already reduces the evapotranspiration advantage.

Table 4. Meta-analysis summary of LST–Index relationships across indian UHI studies (2010–2024).

Relationship	No. of Studies	Pooled r (95% CI)	I^2 (%)	Interpretation
LST vs. NDVI (all cities)	37	-0.71 (-0.78 , -0.63)	71%	Moderate-strong negative: vegetation cools consistently
LST vs. NDVI (arid/semi-arid)	14	-0.76 (-0.83 , -0.67)	62%	Stronger cooling effect in dry cities
LST vs. NDVI (humid-coastal)	10	-0.62 (-0.72 , -0.50)	65%	Somewhat weaker; radiation mechanism dominates
LST vs. NDBI	31	$+0.65$ ($+0.57$, $+0.73$)	68%	Moderate-strong positive: built-up heats surfaces
LST vs. MNDWI (water index)	18	-0.53 (-0.64 , -0.41)	74%	Moderate negative: water bodies cool
UHI intensity, daytime ($^{\circ}\text{C}$)	37	2.8 (2.3, 3.4)	79%	Typical daytime SUHII $\sim 2\text{--}3^{\circ}\text{C}$ above rural
UHI intensity, nighttime ($^{\circ}\text{C}$)	22	1.6 (1.2, 2.1)	65%	Lower nocturnal value; coastal cities dilute average

Source: Author's meta-analysis. Random-effects DerSimonian-Laird model. Fisher z -transformation applied before pooling. Studies drawn from peer-reviewed journals indexed in Scopus, Web of Science, and Google Scholar (2010–2024). I^2 indicates between-study heterogeneity.

The pooled daytime SUHII of 2.8°C substantially exceeds the global median of 1.5°C reported by Zhou et al. [37] (2019), which is consistent with the intensity of Indian urbanisation relative to global averages and the strong pre-monsoon solar forcing in India's tropical and sub-tropical latitudes. The lower nighttime value of 1.6°C below the daytime figure is an artifact of the maritime influence on several coastal cities included in the meta-analysis; for inland cities like Delhi and Ahmedabad, nighttime SUHII values often exceed daytime values, particularly in winter.

DISCUSSION

What the Evidence Collectively Establishes

Each of the nine studied cities has experienced measurable Urban Heat Island intensification over the period for which comparable data exist. The nighttime SUHII values reported by Mathew et al. [1] (2023) are all higher in 2011–2020 than in 2001–2010, without exception. The land-cover change studies for each city document the same fundamental transition: sealed impervious surfaces expanding, vegetation contracting, and water bodies under pressure. The LST trends documented in city-specific studies consistently show mean surface temperatures rising, with the most dramatic single-city figure being Pune's 9°C mean LST increase between 2013 and 2022.

This convergence across multiple independent studies, using different sensors, different classification methods, different cities, and different time periods, is precisely what gives the overall

evidence base its credibility. No single study is definitive, but the consistency across them is. Indian cities are becoming hotter faster than their surrounding rural areas. The driving mechanism, the replacement of land covers that regulate temperature with ones that amplify it is the same in every city.

Climate Change as an Amplifier, Not Just a Background

It would be a mistake to treat climate change and the Urban Heat Island as simply additive processes, a fixed UHI sitting on top of a slowly rising baseline. The interaction between them is more dynamic. As background temperatures rise, the same magnitude of UHI becomes more dangerous because it pushes populations closer to physiological limits. The 2024 heatwave, which drove temperatures in Delhi–NCR to 47.3°C and led to over 40,000 reported heatstroke cases across India, underscores the intensifying and compounding nature of these impacts (India Meteorological Department [8], 2024). That extreme could not have occurred without both the background warming trend that has raised India's mean temperature by 0.9°C since 1901 and the UHI effect that concentrates that warming in the urban core.

Looking forward, IPCC [14] (2021) projections for South Asia under SSP2-4.5 and SSP5-8.5 scenarios indicate further mean temperature increases of 1.5–3.5°C by 2050 relative to the 1981–2010 baseline. If SUHI continues to intensify at the rates documented by Mathew et al. [1] (2023) roughly 0.2–0.5°C per decade for the cities studied then urban core temperatures in cities like Ahmedabad and Delhi could routinely exceed 50°C on peak summer afternoons by mid-century. The 53.9°C LST recorded in Delhi during the 2020 COVID lockdown (Kaur & Somvanshi, CSE [5], 2022) an anomaly only partly attributable to the UHI suggests that this is not an alarmist projection but a physically plausible trajectory.

Who Bears the Burden

The thermal burden of urban heat is not distributed equally, and the evidence reviewed here points consistently toward the same vulnerable groups. Low-income residents of informal settlements face the worst microenvironments: metal-roofed structures in dense slum colonies can exceed outdoor temperatures by 4–7°C on peak summer days eliminating the distinction between indoor and outdoor refuge from heat. Outdoor workers in construction, agriculture, and the informal service economy face the highest exposure to peak daytime heat, often without access to cooling, adequate hydration, or occupational health protection.

Children and the elderly face elevated physiological risk from heat exposure, and neighbourhoods where these populations concentrate including many of India's oldest and most densely settled inner-city areas are often precisely the zones with the lowest green cover and highest LST. The health risk study Mandvikar, et. al. [20], 2024 found that cities including Chennai, Mumbai, Kolkata, and Ahmedabad, despite their large populations, are rated among the least liveable due to high heat health risk indices, with Chennai and Mumbai both scoring a hazard index of 0.66 the highest in the country.

This spatial and social concentration of heat burden makes a purely technical framing of the UHI inadequate. A policy response that plants trees in wealthy neighbourhoods, installs cool roofs on commercial buildings, and leaves informal settlements where the greatest thermal danger exists unaddressed is not a climate adaptation strategy; it is a climate equity failure. Effective heat action must prioritise the most exposed communities, not the most visible or organised ones.

Patna: A Warning Signal for Secondary Cities

Patna deserves special attention not just for its own population but as a signal for a category of city the rapidly growing Tier-2 and Tier-3 urban centre of the Indo-Gangetic Plain that is largely absent from the UHI research and policy literature. Cities like Patna, along with Agra, Varanasi, Lucknow, Kanpur, Ranchi, and Bhagalpur, are growing at rapid rates in one of the world's most thermally extreme and climatically vulnerable regions. They are doing so largely without dedicated heat action

plans, without urban greening targets, without cool-building standards, and without the research attention that would identify their specific thermal vulnerabilities.

The CEEW [7] (2023) finding that over 70% of Indian districts now experience at least five additional very warm nights per year suggests that the heat crisis is no longer confined to the largest metros. It is spreading across the urban hierarchy. Addressing it requires scaling the evidence base and the policy response down to these secondary cities before they lock in the thermally suboptimal development patterns that the larger metros are now struggling to remediate.

POLICY IMPLICATIONS AND RECOMMENDATIONS

From Emergency Response to Structural Prevention

India's most significant institutional response to urban heat has been the Heat Action Plan framework, pioneered by Ahmedabad in 2013 following the 2010 heat wave catastrophe and since extended, with NDMA support, to over 100 cities. These plans have saved lives: the combination of early warning systems, community outreach, and cooling-centre provision has demonstrably reduced heat-wave mortality in cities that implement them seriously. But they are essentially emergency management frameworks. They respond to heat rather than reducing it.

The evidence in this paper points toward a different kind of policy ambition: structural reduction of UHI intensity through land-use governance, green infrastructure, and building performance standards. This is harder, slower, and more politically complex than distributing water packets during heat waves. But the trajectory documented in Tables 1 and 2 SUHII rising, built-up area expanding, vegetation declining, city after city cannot be reversed by emergency management alone. The physical transformation of urban land that drives UHI intensification will continue as long as the regulations governing that transformation treat thermal outcomes as irrelevant.

Land Use and Development Control

The most important policy lever for UHI mitigation is urban land conversion governance. India's Development Control Regulations and Master Plans dictate how land can be used and developed, but they almost never include thermal performance requirements. Adopting mandatory green space minimums specifying minimum canopy cover rather than merely open space, since paved open space provides no evaporative cooling in all new development approvals would be a significant structural change. A minimum canopy cover target of 20–25% in new developments, with species selection guided by transpiration efficiency, would begin to reverse the vegetation loss trends documented across all nine study cities.

Thermal Impact Assessments analogous to existing Environmental Impact Assessments should be required for large-scale development proposals in cities identified as high-SUHII zones. Chennai, Ahmedabad, Hyderabad, Delhi, and Kolkata, based on the data in Table 1 and Table 3, would be the priority candidates for such requirements. Tamil Nadu and Karnataka have both considered relevant provisions in recent town planning act revisions; national guidance from MoHUA would help generalise this approach.

Urban Water Body Protection and Restoration

Water bodies are among the most thermally efficient urban cooling mechanisms available. The meta-analysis in Table 4 records a pooled LST–MNDWI correlation of -0.53 , confirming that open water consistently reduces surrounding surface temperatures. India's urban water bodies, the tanks of Chennai and Bengaluru, the ponds of Kolkata, the river floodplains of Patna and Delhi are also its most rapidly disappearing urban land features. CPCB [4] (2022) estimates that India's urban areas have lost 30–40% of water body area since 1990.

Protecting existing water bodies through strict enforcement of lake boundary regulations using the framework established by the Supreme Court and investing in restoration programmes (like HMDA's Lake Rejuvenation initiative in Hyderabad) should be reframed explicitly as heat mitigation infrastructure, not merely ecological or aesthetic amenity. For Patna, protecting the Ganges riverfront from further encroachment and ensuring green corridor connectivity between the river and urban neighbourhoods is particularly urgent given the city's rapid development pressure and the river's demonstrated thermal moderation role.

Nature-Based Solutions and Urban Greening

The evidence from the meta-analysis a pooled cooling coefficient of $r = -0.71$ between NDVI and LST combined with the city-specific findings on park cool island effects (for Kolkata; studies for Chennai and Pune in the literature review) supports a strong investment case for urban greening. The 2024 meta-analysis across 110 cities found tree canopy providing 1–2°C of daytime cooling at pedestrian level, with areas lacking canopy within 10 metres being five times more likely to exceed 32.2°C. These are large, plannable thermal benefits.

Urban forestry programmes need to be transformed from tree-planting events into managed canopy systems, with species selection prioritising high-transpiration native species, maintenance protocols that ensure survival past establishment, and spatial targeting that prioritises the highest-SUHII and lowest-green-cover neighbourhoods in each city. Cool-roof programmes applying high-reflectance coatings to the metal and asbestos roofs prevalent in informal settlements offer complementary benefits at very low cost, as demonstrated in pilot programmes in Hyderabad and Chennai. For Patna, where both urban greening infrastructure and institutional capacity are limited, a targeted cool-roof programme for informal settlements, coupled with a riverside greening initiative along the Ganges waterfront, would be high-priority, low-cost, high-impact interventions.

Heat Action Plans for Secondary Cities

Every city in the study that has a published heat action plan principally Ahmedabad has benefited measurably from it. Cities that lack one most prominently Patna among the study cities have no coordinated framework for protecting their populations during heat emergencies. NDMA's framework for HAP development is well-established and has been applied in over 100 cities, but coverage of Tier-2 and Tier-3 cities in the Indo-Gangetic Plain remains incomplete. Extending HAP coverage to cities like Patna, Muzaffarpur, Bhagalpur, Varanasi, and Kanpur with provisions for humidity-adjusted heat index monitoring rather than dry-bulb temperature alone should be an immediate priority.

The CSE [5] (2022) recommendation to reform IMD's heat wave definition to incorporate humidity (using the NOAA heat index formula as a supplementary criterion) is directly relevant here. The Gangetic Plain cities face precisely the compound heat-humidity exposure that dry-bulb temperature thresholds fail to capture. A heat index-based alert system would improve early warning effectiveness in these environments substantially.

Monitoring, Research, and Data Equity

The stark data gap between larger metros and secondary cities like Patna in the research base reflects a structural inequality in research investment that has direct consequences for policy. What is not monitored is not managed. A national Urban Thermal Observatory network building on ISRO's satellite capabilities, IMD's station network, and the Smart Cities Mission's sensor infrastructure should include coverage of Tier-2 cities in thermally vulnerable regions. The Ministry of Housing and Urban Affairs should incorporate SUHII as a performance indicator in the Smart Cities Mission dashboard.

For secondary cities specifically, investing in basic air temperature monitoring infrastructure neighbourhood-level weather stations equivalent to what Delhi and Mumbai have through the CPCB

CAAQMS network would dramatically improve the evidence base for local heat action. The Bihar State Pollution Control Board's existing effort to obtain Landsat imagery for Patna's thermal mapping (ETV Bharat [9], 2023) is a step in the right direction; it needs the resources and institutional support to translate into a sustained monitoring programme.

CONCLUSION

India's cities are getting hotter faster than the countryside around them, and the evidence reviewed in this paper drawn from satellite-derived SUHII data, city-level land-cover change studies, meteorological station records, and published epidemiological research leaves no room for serious doubt about either the direction or the magnitude of this trend. Across nine cities spanning India's full geographic range, nighttime Surface Urban Heat Island Intensity has increased in every city between 2001–2010 and 2011–2020. In every city for which LULC change data are available, built-up area has expanded substantially in Pune's case by nearly 90% in a single decade at the direct expense of vegetation and, in several cities, water bodies. Mean land surface temperatures have risen accordingly: Pune's 9°C LST increase between 2013 and 2022 is the most dramatic, but it is a difference of degree, not of kind, from what other cities are experiencing.

The implications of these findings differ in their details but converge in their urgency. Ahmedabad and Delhi face the highest absolute nighttime SUHII values and carry histories of mass heat mortality that cannot be separated from their urban thermal environments. Bengaluru and Pune face the fastest rates of SUHII intensification, reflecting the pace of their recent built-up expansion. Mumbai and Chennai face the compounding effect of humidity on already elevated urban temperatures. Kolkata is losing the green and water infrastructure that has historically moderated its climate. Patna, the most under-studied of the nine cities may be the most acute warning signal: a rapidly expanding, poorly resourced city in the world's most thermally vulnerable plain, with documented 10°C intra-city temperature gradients and no systematic heat action framework.

The policy response this evidence calls for is layered. In the short term, extending Heat Action Plans to secondary cities with humidity-adjusted alert thresholds; scaling cool-roof programmes to informal settlements; and protecting existing urban water bodies from further encroachment. In the medium term, reforming Development Control Regulations to mandate minimum canopy cover in new developments; requiring Thermal Impact Assessments for large projects in high-SUHII cities, and investing in urban forestry with species selection guided by transpiration efficiency. In the longer term, integrating SUHII as a measurable performance indicator in the Smart Cities Mission, building a national Urban Thermal Observatory network that covers Tier-2 and Tier-3 cities, and incorporating urban heat equity, the principle that UHI mitigation must prioritise the most exposed and most vulnerable communities as an explicit criterion in the National Action Plan on Climate Change.

Several directions for future research are particularly pressing. The compound effect of nighttime warming and heat-related mortality in Gangetic Plain cities like Patna, Varanasi, and Kanpur has not been systematically studied and deserves dedicated epidemiological attention. The long-term cooling effectiveness of urban greening interventions under rising baseline temperatures requires longitudinal evaluation. And the spatial distribution of thermal equity, whether heat action plans and green infrastructure programmes actually reach the most thermally exposed low-income communities, needs to be assessed with the same rigour as the biophysical evidence.

India's trajectory is not inevitable. The physical processes that drive urban heat islands are well understood; the interventions that mitigate them are demonstrated and deployable. What is required is the institutional commitment to treat urban thermal environments not as an externality of development but as a core determinant of whether Indian cities are places where people can live well and, on the hottest days of an increasingly hot century, whether they can live at all.

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