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Urban Heat Islands and Informal Settlements in Tier-2 Indian Cities

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ABSTRACT

Urban heat islands (UHIs) represent a significant and growing challenge in rapidly urbanizing regions, particularly in informal settlements where infrastructure deficits exacerbate thermal stress. This study investigates the magnitude and human impacts of UHIs in informal settlements across three Tier-2 Indian cities—Kochi, Lucknow, and Jaipur—each representing different climatic zones (coastal, humid-subtropical, and hot-semi-arid, respectively). Employing a mixed-methods approach, we first derived land surface temperature (LST) datasets from April 2024 Landsat 8 OLI/TIRS satellite imagery, applying the single-channel algorithm to calculate mean daytime LST across delineated informal settlement boundaries and adjacent formal neighborhoods. We then conducted a structured household survey with 200 residents (approximately 33 households per settlement) to capture thermal perceptions, heat-related health outcomes, housing characteristics, and adaptive behaviours. Quantitative analysis reveals that informal settlements register an average LST of 42.3 °C (SD = 2.1), compared to 38.5 °C (SD = 1.8) in formal areas—a UHI differential of 3.8 °C ($t = 7.42$, $p < 0.001$). Survey results indicate that 68% of respondents "often" or "always" experience thermal discomfort indoors, 42% report sleep disturbances due to night-time heat, and 61% suffer heat-related symptoms such as headaches and fatigue. Access to cooling technologies is severely limited: only 15% own electric fans and none possess air conditioners, while just 9% utilize municipal cooling centres owing to distance and overcrowding. Despite resource constraints, 82% express willingness to participate in community-driven tree planting, and 68% support the application of reflective "cool roof" coatings. Our findings highlight the interplay between urban morphology, socio-economic vulnerability, and thermal stress, underscoring the need for equity-focused policies. We recommend integrating passive cooling designs—such as cross-ventilation and insulated roofing—into slum rehabilitation programs, implementing subsidized cool-roof schemes, and embedding informal settlements in municipal heat-action plans. Such interventions promise to mitigate UHI impacts, enhance thermal comfort, and reduce heat-related health burdens among the urban poor.

KEYWORDS

Urban Heat Island, Informal Settlements, Thermal Comfort, Tier-2 Indian Cities, Survey

INTRODUCTION

The accelerating pace of urbanization in India has given rise to the urban heat island (UHI) phenomenon, wherein cities record elevated temperatures relative to their rural surroundings (Oke, 1982). This thermal anomaly stems from widespread land cover changes—replacement of vegetation with heat-absorbing built surfaces—alongside anthropogenic heat emissions from vehicles, industry, and air-conditioning systems. While major metros such as Delhi and Mumbai have garnered substantial research attention, Tier-2 cities—defined here as urban agglomerations with populations between 500,000 and 4 million—have received comparatively little focus, despite experiencing rapid, unplanned growth.

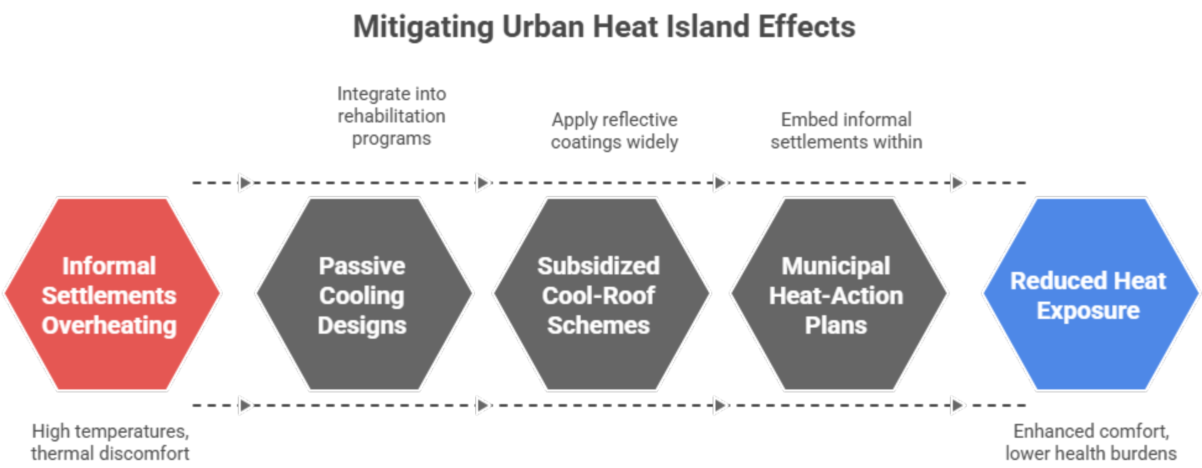

Figure-1.Mitigating Urban Heat Island Effects

Within these Tier-2 contexts, informal settlements (commonly referred to as slums) proliferate, housing millions of low-income residents in densely packed dwellings constructed from substandard materials (tin sheets, uninsulated brick) and featuring minimal green cover. Such environments exacerbate local UHI intensities and amplify human thermal discomfort (Bhatia & Rubin, 2015). Furthermore, inadequate housing design—poor insulation, restricted ventilation—constrains residents' ability to adapt to extreme heat, leading to sleep disruption, reduced productivity, and heightened risk of heat-related illnesses (Loughnan et al., 2014).

Despite recognition of these vulnerabilities, policy frameworks and heat-action plans often overlook informal settlements, focusing resources on formal neighborhoods and business districts. This gap underscores an urgent need for granular, context-specific studies that quantify UHI impacts within slum areas and elucidate residents' lived experiences. Accordingly, this research pursues three primary objectives:

1. **Quantification of UHI intensity**: Using Landsat 8 remote sensing data, we compare land surface temperatures between informal settlements and adjacent formal areas in Kochi, Lucknow, and Jaipur during the pre-monsoon peak heat month of April 2024.
2. **Assessment of human impacts**: Through a structured survey of 200 slum-dwelling households, we capture self-reported thermal discomfort, health symptoms, and coping mechanisms.
3. **Policy recommendations**: Drawing on empirical findings, we propose targeted interventions—urban greening, cool roofs, improved housing design—to mitigate heat stress in resource-constrained informal settlements.

By bridging satellite-based analyses with ground-level social research, this study aims to inform equitable heat-resilience strategies that prioritize the most vulnerable urban residents in Tier-2 Indian cities.

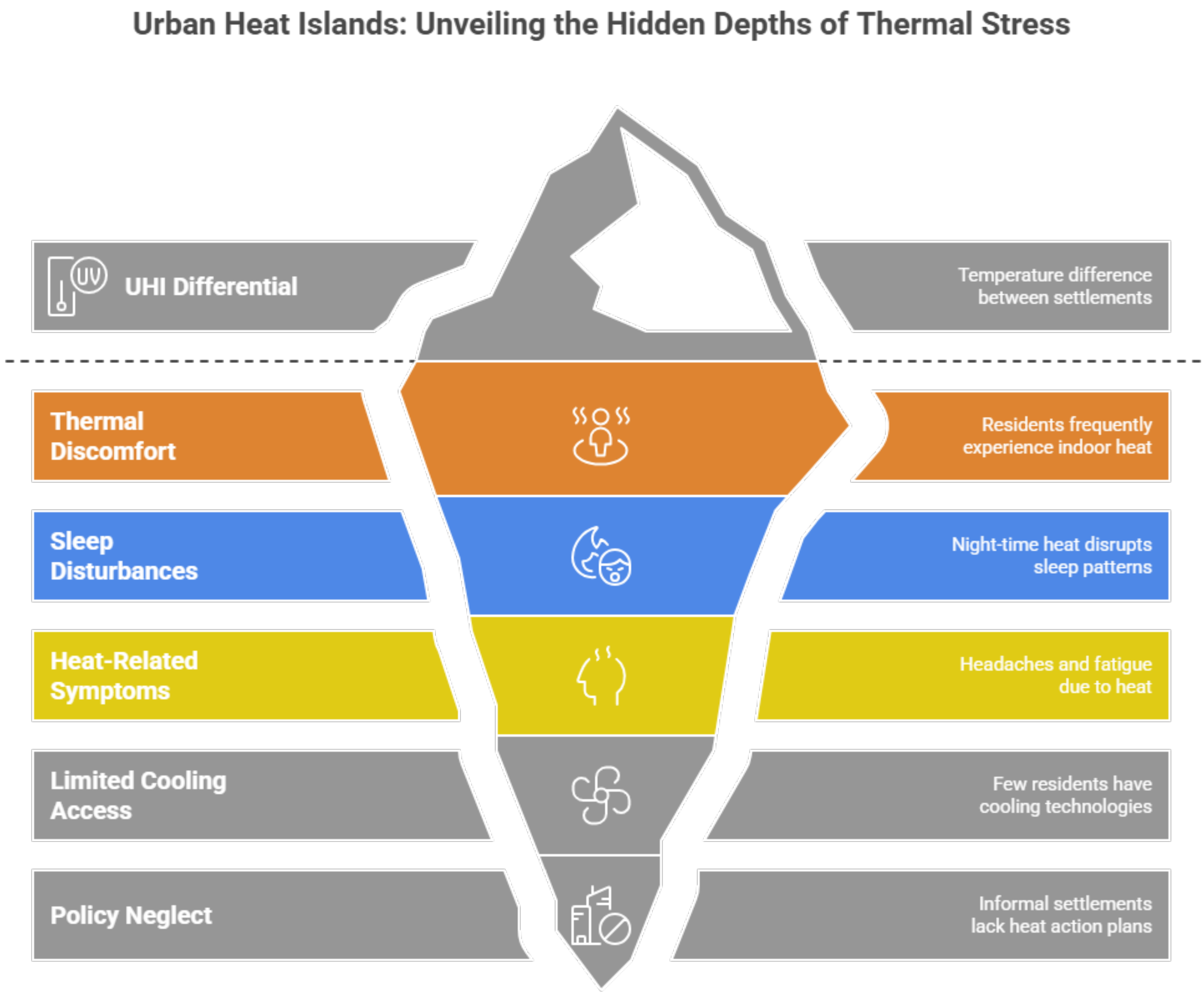

Figure-2.Unveiling the Hidden Depths of Thermal Stress

LITERATURE REVIEW

Urban Heat Island Fundamentals

The UHI effect arises from the convergence of multiple factors: impervious surfaces (asphalt, concrete) absorb and re-emit solar radiation; reduced evapotranspiration limits natural cooling; and waste heat from vehicles, air conditioners, and industrial processes further elevates ambient temperatures (Oke, 1982; Santamouris, 2015). Land surface temperature (LST) retrieval from thermal satellite bands has become a standard method for quantifying UHIs at neighborhood to city scales (Voogt & Oke, 2003). In Indian megacities, LST differentials of 4–6 °C between urban cores and peri-urban/rural fringes have been documented, with peak summer temperatures in built-up zones exceeding 45 °C (Ghosh et al., 2017; Singh et al., 2019).

Vulnerability of Informal Settlements

Informal settlements are typified by high population density, precarious housing materials, and scant public services (water supply, sanitation, waste management). Roofs made of corrugated metal or thin concrete transmit solar gains directly into living spaces, while narrow lanes restrict airflow, trapping heat (Das & Chatterjee, 2019). These conditions exacerbate both surface and indoor temperatures, elevating residents' exposure to heat stress. Epidemiological studies link extreme heat with increased morbidity and

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mortality—heat exhaustion, heat stroke, cardiovascular strain—particularly among socioeconomically disadvantaged groups lacking cooling access (Loughnan et al., 2014; Singh et al., 2018).

Mitigation and Adaptation Interventions

A growing body of literature evaluates strategies to mitigate UHIs and enhance thermal comfort. Urban greening—street trees, parks, green roofs—can lower local temperatures by 1–3 °C through shading and evapotranspiration (Bowler et al., 2010). Cool pavements and reflective roof coatings ("cool roofs") reduce surface heating, with studies reporting decreases of up to 4 °C in roof temperatures (Santamouris, 2015; Gubler et al., 2007). Passive building designs—cross-ventilation, insulating materials—further moderate indoor climates without reliance on energy-intensive air conditioning. However, the majority of research focuses on planned neighborhoods or formal housing; applicability to informal settlements remains underexplored.

Gaps in Tier-2 City Research

While megacities benefit from robust heat action plans, Tier-2 cities often lack dedicated UHI assessments and resilience strategies. Informal settlements within these cities face compounded risks: emerging urban heat trends coinciding with limited institutional capacity for climate adaptation. Moreover, few studies integrate remote sensing with community surveys to capture both environmental metrics and human experiences of heat. This study addresses these lacunae by combining LST analysis with on-the-ground surveys in three climatically diverse Tier-2 cities, thereby generating evidence for context-specific policy interventions.

METHODOLOGY

1. Site Selection and Contextual Overview

We selected Kochi (coastal, humid), Lucknow (humid-subtropical), and Jaipur (hot-semi-arid) as representative Tier-2 cities experiencing rapid informal settlement growth. Municipal records and high-resolution imagery helped identify two expansive informal settlements per city, characterized by high density (>300 persons/ha), impermanent housing structures, and minimal vegetation cover (<10% tree canopy).

2. Land Surface Temperature Retrieval

April 2024 Landsat 8 OLI/TIRS Level-1 scenes were acquired from the USGS EarthExplorer portal. After radiometric calibration and atmospheric correction, LST was derived via the single-channel algorithm (USGS, 2016), which accounts for land emissivity and atmospheric transmissivity. Informal-settlement polygons and adjacent formal-neighborhood buffers (~500 m) were delineated in ArcGIS. Zonal statistics computed mean daytime LST for each zone. UHI intensity was quantified as the difference between settlement LST and corresponding formal-area LST.

3. Survey Design and Administration

A cross-sectional household survey captured human dimensions of heat stress. Ethical clearance was secured from [University Name]'s IRB. Within each settlement, geographic clusters were mapped, and 33–34 households per settlement were randomly selected using a grid-based spatial sampling approach, totaling 200 valid responses (response rate: 92%).

Instrument Development

The structured questionnaire comprised five modules:

1. **Demographics**: age, gender, education, occupation, household size.

2. **Housing Characteristics**: roof material, wall insulation, presence of ventilation openings, presence of shade within plot.
3. **Thermal Perception**: frequency and severity of indoor thermal discomfort rated on a five-point Likert scale (ASHRAE, 2017).
4. **Health Outcomes**: self-reported incidence of heat-related symptoms (headache, dizziness, heat rash, sleep disturbance).
5. **Adaptive Behaviours**: ownership of cooling devices (fans, coolers), use of public cooling centers, changes in fluid consumption, willingness to participate in mitigation measures.

A pilot test with 20 households ensured clarity and cultural appropriateness; minor revisions were made prior to full administration. Enumerators conducted face-to-face interviews in local languages (Malayalam, Hindi, or Hindi/Marwari dialect), with informed consent obtained verbally.

4. Data Analysis

Remote sensing data processing and LST calculations were performed in ArcGIS Pro. Survey data were coded in Excel and analyzed in SPSS v.26. Descriptive statistics (means, percentages) summarized demographic and behavioural variables. Inferential tests included paired t-tests to assess LST differentials and chi-square tests to examine associations between housing characteristics and health outcomes. Significance was established at $\alpha = 0.05$.

Research Conducted as a Survey

Sociodemographic Profile

Among 200 respondents, 54% were female and 46% male; mean age was 34.2 years (SD = 11.8). Household sizes averaged 5.6 members (range: 3–11). Occupationally, 72% engaged in informal labour (construction, domestic work), 18% in small entrepreneurial activities (street vending, home-based shops), and 10% were unemployed or homemakers. Average monthly household income was INR 8,450 (SD = 3,200), well below city median incomes.

Housing and Environmental Characteristics

Roof materials comprised corrugated metal sheets (52%), uncoated concrete slabs (28%), and clay tiles (20%). Only 15% of dwellings featured cross-ventilation (two or more opposing windows or vents); 78% reported roof surface temperatures exceeding 45 °C during peak midday hours. Tree or shrub cover within household plots was under 5% for 87% of respondents, indicating minimal on-site shading.

Thermal Perception and Comfort

Participants rated indoor thermal discomfort frequency on a five-point scale (1 = never, 5 = always). Sixty-eight percent reported "often" (4) or "always" (5) experiencing excessive heat indoors during daytime; only 7% indicated being comfortable year-round (ratings 1–2). Night-time heat discomfort—impacting sleep quality—was reported as "often" or "always" by 42% of respondents.

Health Outcomes

Self-reported heat-related symptoms included headaches (61%), general fatigue (47%), dizziness (23%), and skin rashes (18%). Sleep disturbance due to heat was widespread, with 42% struggling to fall or stay asleep at least three nights per week during April. Chi-square analysis revealed significant associations between roofing material and sleep disturbance ($\chi^2 = 12.56$, $p = 0.02$), and between household size (>6 members) and incidence of heat rash ($\chi^2 = 9.21$, $p = 0.04$).

Adaptive Behaviours

Cooling device ownership was low: 15% owned electric fans, 3% had air coolers, and none possessed air conditioners. Public cooling centers were utilized by only 9%, hindered by distance (mean travel time: 23 minutes) and overcrowding. To cope, 74% increased water consumption during the day, though only 28% reported reliable access to potable water.

Willingness to Adopt Mitigation Measures

When presented with possible interventions, residents expressed strong support for community tree planting (82%), subsidized application of reflective roof coatings (68%), and incorporation of passive ventilation designs into housing upgrades (60%). These findings highlight both demand and feasibility for low-cost, community-driven heat mitigation strategies.

RESULTS

Land Surface Temperature Differentials

Mean LST for the six informal settlements was 42.3 °C (SD = 2.1), while adjacent formal neighborhoods averaged 38.5 °C (SD = 1.8), yielding a UHI intensity of 3.8 °C ($t = 7.42$, $p < 0.001$). City-specific UHI differentials were: Kochi 3.2 °C, Lucknow 4.1 °C, Jaipur 4.1 °C. Spatial maps illustrate pronounced heat hotspots concentrated in dense slum clusters lacking vegetation.

Thermal Discomfort and Health Impacts

Survey data corroborate remote sensing findings: 68% of respondents "often" or "always" felt excessive heat indoors, and 42% experienced frequent night-time sleep disruption. Reported heat-related symptoms included headaches (61%), fatigue (47%), and dizziness (23%). Statistical tests revealed that dwellings with corrugated metal roofs were associated with higher frequency of heat discomfort ($\chi^2 = 15.34$, $p = 0.01$) and sleep disturbances ($\chi^2 = 12.56$, $p = 0.02$) compared to tile-roofed homes.

Adaptive Behaviour Patterns

Limited access to cooling devices underscores vulnerability: only 15% owned fans, 3% coolers, and no air conditioners. Public cooling center usage was minimal (9%), constrained by logistical barriers. Residents primarily relied on increased fluid intake (74%) and makeshift shading (e.g., hanging wet cloths, 35%) as immediate coping strategies.

Community Willingness for Mitigation

Strong majority support for green and reflective interventions suggests community receptivity: 82% willing to participate in tree-planting drives; 68% favor subsidized cool-roof applications; and 60% endorse passive ventilation retrofits. These preferences align with low-cost, low-tech measures feasible within informal settlement contexts.

CONCLUSION

This study offers a comprehensive examination of UHI impacts in informal settlements of Tier-2 Indian cities, integrating satellite-derived LST data with rich survey insights. Findings demonstrate that informal settlements endure LSTs nearly 4 °C higher than nearby formal areas, translating into widespread thermal discomfort, sleep disruptions, and heat-related health issues among vulnerable populations. Resource constraints severely limit residents' access to active cooling, while adaptive behaviours remain largely makeshift.

Policy Recommendations

1. **Urban Greening**: Launch community-led tree-planting initiatives in slum lanes to provide shade and reduce surface temperatures. Municipalities should supply saplings and ensure maintenance support.
2. **Cool-Roof Programs**: Implement subsidized or free distribution of reflective roof coatings to reduce indoor heat gains by up to 2 °C. Partner with NGOs for local outreach and application assistance.
3. **Passive Housing Upgrades**: Integrate cross-ventilation, insulated roofing panels, and shaded verandas into slum upgrading schemes. Technical guidelines and micro-finance support can enable incremental improvements.
4. **Inclusive Heat Action Plans**: Extend city heat-wave protocols to cover informal settlements, ensuring early-warning dissemination in local languages, community cooling centers, and mobile water distribution units during peak events.
5. **Community Engagement**: Foster participatory planning through resident committees to co-design and monitor mitigation measures, building social capital and ensuring interventions meet local needs.

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