SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 4, (2026), pp. 11763-11774
Open Access. Online & Print

DOI: 10.5281/zenodo.124261115

OUTDOOR THERMAL COMFORT PERCEPTIONS: EVALUATING USER RESPONSES IN HOT-DRY RESIDENTIAL CONTEXTS

Vandana Khante[1], Mazharul Haque[2]

[1]*Research Scholar, Department of Architecture and Planning, National Institute of Technology, Patna*
[2]*Associate Professor, Department of Architecture and Planning, National Institute of Technology, Patna*

Received: 23/12/2025
Accepted: 30/01/2026

Corresponding Author: Vandana Khante
(andanak.phd20.ar@nitp.ac.in)

ABSTRACT

Outdoor thermal comfort (OTC) is a growing concern in hot-dry urban regions due to rising temperatures, urban heat island effects, and inadequate climate-responsive design. While early thermal comfort research focused on indoor indices such as PMV and PET, recent approaches emphasize adaptive models that account for user perception and behavioral responses in dynamic outdoor environments. This study evaluates residents' perceptions of outdoor thermal comfort in three residential colonies in Nagpur, characterized by varying tree canopy coverage, shading, and paving materials. A mixed-method approach combining microclimatic measurements and structured questionnaire surveys is employed, with statistical analysis using chi-square tests and log-linear modelling. Findings indicate that thermal comfort is strongly influenced by site-specific design elements, particularly tree canopy, shading, and surface materials. High-canopy areas show better comfort perception and greater outdoor usability, while low-canopy, heat-retaining environments lead to discomfort and heat-avoidance behaviors such as reduced outdoor duration and shade-seeking. Among all factors, tree canopy emerges as the most significant contributor to improving comfort. The study highlights that outdoor thermal comfort is shaped by both environmental conditions and user perception. It emphasizes the need for climate-responsive, context-specific design strategies—particularly increased vegetation, effective shading, and thermally efficient materials—to enhance livability and public health in hot-dry residential environments.

KEYWORDS- Urban tree canopy, Outdoor thermal comfort, Site-specific analysis, Chi-square test, Log-linear modelling, Hot-dry climate

1. INTRODUCTION

Urban outdoor spaces, such as parks, squares, pedestrian streets, and resting corners, play a crucial role in the livability of cities by supporting activities like social interaction, relaxation, and mobility[1]. Among the multiple factors influencing the use and preference of these spaces including aesthetic quality, functional design, and accessibility outdoor thermal conditions are paramount[2]. The microclimate of outdoor spaces is affected by regional climate, urban morphology, vegetation, and man-made structures, while human factors such as age, gender, clothing, activity level, and psychological adaptation further modulate thermal perception[3].

Urbanization and the transformation of permeable land into impervious surfaces exacerbate thermal stress by reducing airflow, increasing heat retention, and contributing to the Urban Heat Island (UHI) effect, which negatively impacts the thermal comfort of pedestrians and other outdoor users[4], [5]. Rising urban temperatures, combined with limited shade, can make outdoor mobility particularly walking and cycling challenging, emphasizing the importance of shade provision and urban greenery in mitigating heat exposure[6][7].

Thermal comfort, defined as the psychological state of mind expressing satisfaction with the thermal environment[8], is a multidimensional construct integrating objective biophysical parameters with subjective psychological perceptions. Classical thermal comfort indices including Predicted Mean Vote (PMV), Standard Effective Temperature (SET*), and Physiological Equivalent Temperature (PET) attempt to quantify human thermal sensation through metabolic rate, clothing insulation, air temperature, mean radiant temperature, humidity, and wind speed[9]. However, outdoor thermal comfort deviates significantly from indoor comfort due to dynamic environmental conditions, solar radiation exposure, and behavioral flexibility, requiring context-specific assessment methodologies[10]. Recent paradigm shifts emphasize adaptive thermal comfort models that account for psychological adaptation, acclimatization, and behavioral thermoregulation, particularly in non-air-conditioned outdoor environments[11]. The adaptive model posits that thermal sensation is influenced not only by current physical conditions but also by previous thermal experiences, expectations, and coping strategies.[12]"

Recent research has demonstrated that pedestrian behaviour is highly influenced by shade, with observations showing that people preferentially use shaded areas during high heat stress, whether in streets, plazas, or park spaces[13][14]. Furthermore, the integration of urban morphology, building orientation, and green infrastructure including trees, green roofs, and shading devices can significantly enhance microclimatic conditions, reduce radiant heat exposure, and improve thermal comfort in open urban spaces[5], [15][16].

Assessing outdoor thermal comfort (OTC) requires a combined approach that accounts for both objective microclimatic measurements (e.g., air temperature, mean radiant temperature, wind speed, humidity) and subjective human responses, such as perceived thermal sensation and adaptive behaviour[17]. This approach is critical for developing sustainable urban design strategies that enhance the usability and livability of public spaces while mitigating the impacts of extreme heat events[18][19].

In summary, improving outdoor thermal comfort in urban spaces is essential for promoting walkability, social interaction, and environmental sustainability.[20] Designing for OTC requires careful consideration of solar exposure, shade provision, vegetation, and urban form, alongside an understanding of human perception and behaviour under varying climatic conditions[21][22].

Research Objectives and Questions

This study aimed to address the following research questions:

1. How do residents in hot-dry residential neighborhoods perceive outdoor thermal comfort across different microclimatic conditions?
2. What specific design elements (tree canopy, shade structures, paving materials) most significantly influence thermal comfort perceptions?
3. How do behavioural adaptations (route changes, walking duration reduction, shade-seeking) vary in response to site-specific microclimate characteristics?
4. What site-level landscape design interventions can most effectively enhance outdoor thermal comfort and improve residential walkability in arid-hot climates?"

2. METHODOLOGY

Site Selection:

Three government colonies in the city, the Nagpur Postal Colony, the CPWD Quarters (Civil Lines), and the Ganeshpeth Quarters, were chosen based on the fact that although these colonies have similar building heights and residence types, the degree of tree canopy, paving material, and availability of shade are different[23].

All three colonies are located within Nagpur city (21.1458°N,79.0882°E) in the Vidarbha region of India, characterized by a hot-dry climate with mean annual temperatures exceeding 28°C and monsoon precipitation concentrated in June-September. The selection of these homogeneous residential sites (similar building typology, socioeconomic status, regulatory framework) with varying vegetation and paving characteristics provides a quasi-experimental design enabling attribution of observed differences to environmental design factors rather than socioeconomic confounders."

Detail description of site:

Characteristic	Nagpur Postal Colony	CPWD Quarters (Civil Lines)	Ganesh Peth Quarters
Residential Units	n =40	n = 208	n = 176
Average Building Height (m)	4–5 m	4–5 m	4–5 m
Site Area (hectares)	3.79	1.94	0.58
Tree Canopy Coverage (%)	15–20% (Low)	45–55% (High)	30–40% (Moderate)
Predominant Paving Material	Concrete (High heat retention)	Interlocking Pavers (Moderate heat retention)	Mixed (Variable thermal response)
Climate Classification	Hot–Dry	Hot–Dry	Hot–Dry
Peak Summer Temperature (°C)	42–48°C	40–44°C	41–46°C
Regional Wind Pattern	NW Monsoon	NW Monsoon	NW Monsoon

Site Survey:
Extensive field surveys were carried out to record information on the geometry, road materials, extent of existing tree canopy, shades, as well as surrounding buildings[20], [24] , through photography, which enabled environmental characteristics to be noted for each site considered.

Questionnaire Survey:
A structured questionnaire was administered to capture residents and pedestrians, demographic details, perceptions of outdoor thermal comfort, and behaviour responses, aware of tree canopy benefits, preferred shading, and paving material in all three sites.[23]
A structured questionnaire comprising 32 items was developed based on established thermal comfort assessment scales and pilot-tested with n=50 residents (prior to main survey) to ensure clarity, relevance, and cultural appropriateness. The questionnaire comprised the following sections:

- Section A: Demographic Information (age, gender, occupation, clothing habits, daily outdoor time)
- Section B: Perceived Thermal Comfort (7-point scale: 1=Very Uncomfortable to 7=Very Comfortable)
- Section C: Design Element Preferences (tree canopy, shade structures, paving materials; multiple choice)
- Section D: behavioural Adaptations (route changes, time modifications, avoidance patterns; yes/no)
- Section E: Tree Canopy Awareness (open-ended and scaled responses on thermal benefits)

Internal consistency (Cronbach's α = 0.67) and test-retest reliability (ICC = 0.70) were assessed and found satisfactory. The questionnaire was available in both English and Marathi to maximize accessibility and response quality."

Data Collection:
The collected data comprised primary information from field microclimatic evaluations and a questionnaire survey air temperature, relative humidity, wind speed A purposive stratified sampling approach was employed to recruit residents proportional to the population size of each colony. Target sample size (N=156; 50 per site) was calculated based on power analysis (power=0.80, α=0.05) to detect medium effect sizes (Cohen's f=0.25) in one-way ANOVA across three sites. Inclusion criteria: (1) adult resident (≥18 years); (2) ≥6 months residence in the colony; (3) regular outdoor mobility (≥3 days per week). Data collection occurred during peak summer months (April-May 2025), when thermal stress is maximum. Trained enumerators administered questionnaires face-to-face to 500 households, achieving an overall response rate of 78% . Questionnaires were completed in approximately 15-20 minutes, and respondents were assured of confidentiality. Simultaneously, microclimate measurements were recorded at specified locations within each site during 14:00-16:00 hours (peak heat period) using calibrated instruments (±0.5°C accuracy

for temperature, ±2% for humidity, ±0.2 m/s for wind speed)."
d, and users' perceptions of thermal comfort recorded during peak daytime periods to capture the most intense heat exposure conditions.

Data Analysis:
Descriptive Analysis: Frequency distributions, percentages, means (±SD), and ranges are reported for all variables. Comparative descriptive statistics across the three sites are presented with visual representation (bar charts, box plots).

Inferential Analysis: Chi-square (χ^2) tests were employed to examine associations between categorical variables (site affiliation, comfort perception, design preferences) and reported behavioral adaptations. For contingency tables exceeding 20% cells with expected frequencies <5, Fisher's exact test or Monte Carlo simulation was used. Standardized residuals (z-scores) were calculated to identify cells driving significant associations.
Regression Modeling: Log-linear analysis was conducted to model three-way and higher-order associations between sites, design characteristics, and comfort perceptions, with Pearson and deviance chi-square statistics reported. Parameter estimates (β coefficients) and 95% confidence intervals are provided. Odds ratios (OR) and their 95% CIs quantify the strength of associations.

Effect Sizes: Cramér's V, Cohen's w, and standardized effect sizes (Cohen's d) are reported alongside p-values to enable assessment of practical significance beyond statistical significance.
All analyses were conducted using google form , with two-tailed significance level set at p<0.05. Missing data analysis and multiple imputation procedures (if necessary) are detailed in supplementary materials."

Data Interpretation: Results from statistical analysis were clarified by linking notable correlations and differences to the physical characteristics of tree canopy, shade, and paving materials, enabling conclusions regarding their influence on outdoor thermal comfort perception and user engagement.[5], [23]

CONCLUSION
These results indicate that outdoor thermal comfort in residential street settings is heavily influenced by particular site characteristics like tree canopy coverage, shading, and types of pavement materials. This indicates the need for context-aware urban design approaches to enhance pedestrian comfort in arid-hot cities.

Section A: Perception based on Thermal Comfort

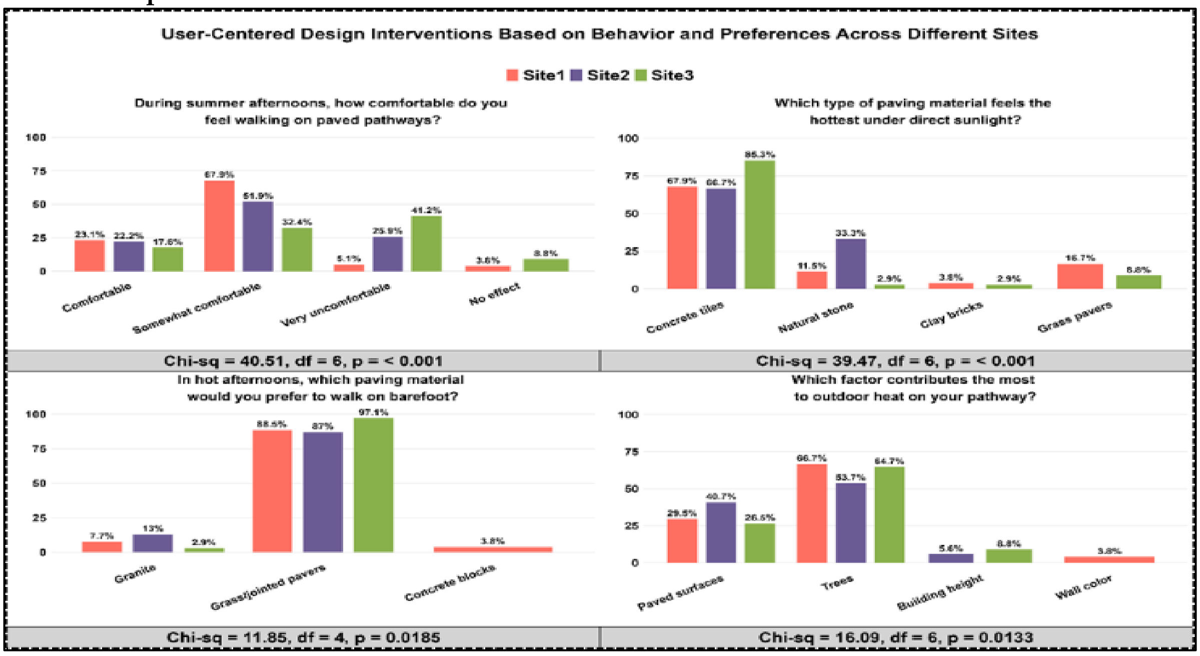


Fig 1: Graph of Perception based on Thermal Comfort.

The bar chart comparison emphasizes clear site-specific differences in the perceived outdoor thermal comfort at the selected locations. Ganesh Peth St bus quarters received a moderate comfort rating, with most individuals rating it as such and favouring either grass or jointed pavers, indicating moderately positive microclimatic conditions. Postal colony had the lowest comfort level, where the majority of people rated very uncomfortable and rated paved surfaces and building height as important contributors of heat. CPWD Quarter rated variably, where there was a combination of discomfort and appreciation for the cooling effect of vegetation.

These results were statistically confirmed by chi-squared tests ($p < 0.001$) in per site comparisons of comfort, hottest paving material, walkability on bare feet, and contribution to heat. For each of the sites individually, hard paving material was found to be the hottest, while grass or jointed pavers ranked highest in preference, and trees ranked highest in cooling contribution.

Furthermore, log-linear analysis validated the findings. The interaction model (Deviance = 241.50, df = 540) showed a notably improved fit compared to the independence model (Deviance = 364.88, df = 562), indicating that perceptions of outdoor thermal comfort depend on the conditions at specific locations. In summary, the findings presented have reinforced the significance of surface materials, plant life, and architectural design in outdoor thermal perceptions, advocating for the creation of microclimate strategies customized for specific locations.

TABLE I: Log linear method for Perception based on thermal comfort.

Model	df	Deviance	p-value
Independence (no site effect)	**562**	**364.8792**	**1.0**
Site × (Questionnaire) interaction	**540**	**241.5021**	**1.0**

Section B: Design intervention

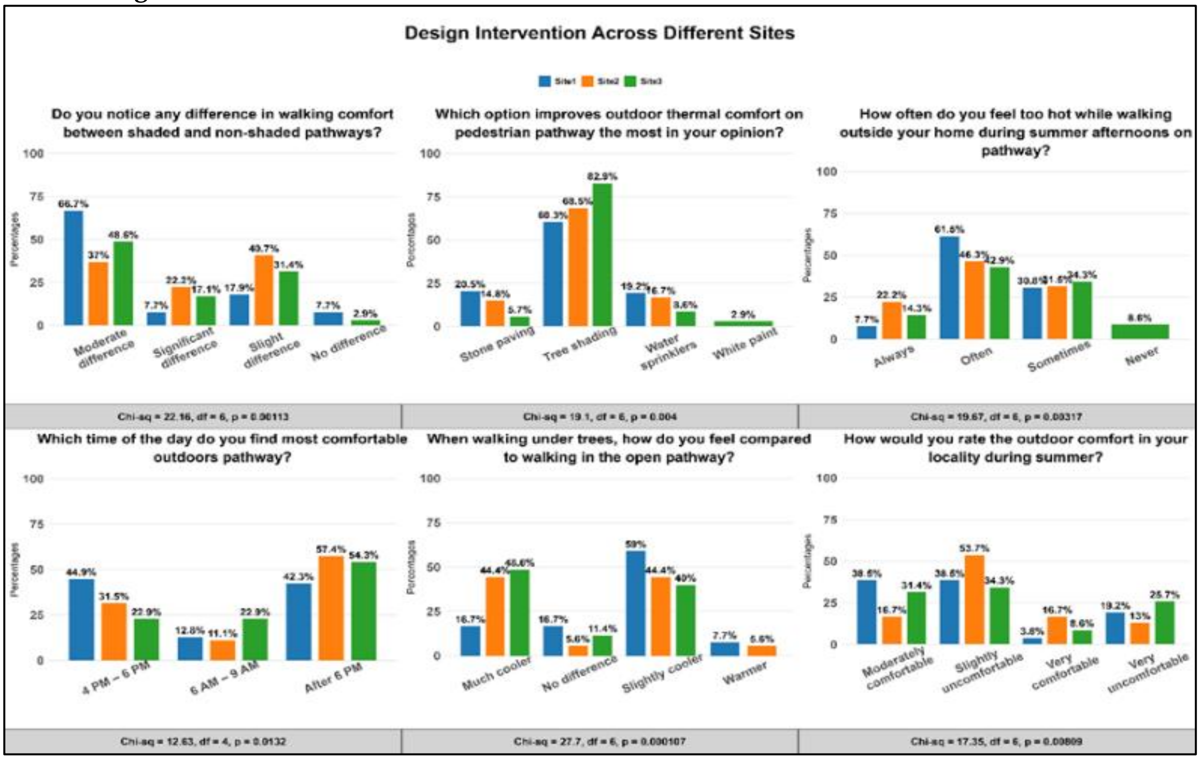


Fig 2: Graph of Design Interventions Across Different Sites.

The examination of six queries for the bar chart reveals notable site-specific variations in residents' views on thermal comfort and design modifications like tree shading, water sprinklers, surface materials, and usage timings. The awareness of cooling advantages is strongest at CPWD Quarter, particularly in tree-covered areas and shaded pathways, yet general comfort levels still appear mixed. Ganesh Peth St bus quarters demonstrate even comfort levels and ranks tree shading as the most effective design intervention. The results at Postal colony indicate large fluctuations between comfort perceptions.

Chi-square tests ($p < 0.001$) verify the significance of the observed differences. Log-linear analysis indicates the superiority of the interaction model (Deviance =

1386.04, df = 9162) over the independence model (Deviance = 1517.13, df = 9196) and thus reveals the site-specific nature of thermal comfort sensation. Taking everything into account, the significance of variations in treeing, shading, material, and microclimate in respect to comfort sensation is revealed.

TABLE II: Log linear method for Design Interventions Across Different Sites.

Model	df	Deviance	p-value
Independence (no site effect)	**9196**	**1517.133**	**1.0**
Site × (Questionnaire) interaction	**9162**	**1386.035**	**1.0**

Section C: User-Centered Design Interventions Based on Behaviour and Preferences Across Different Sites

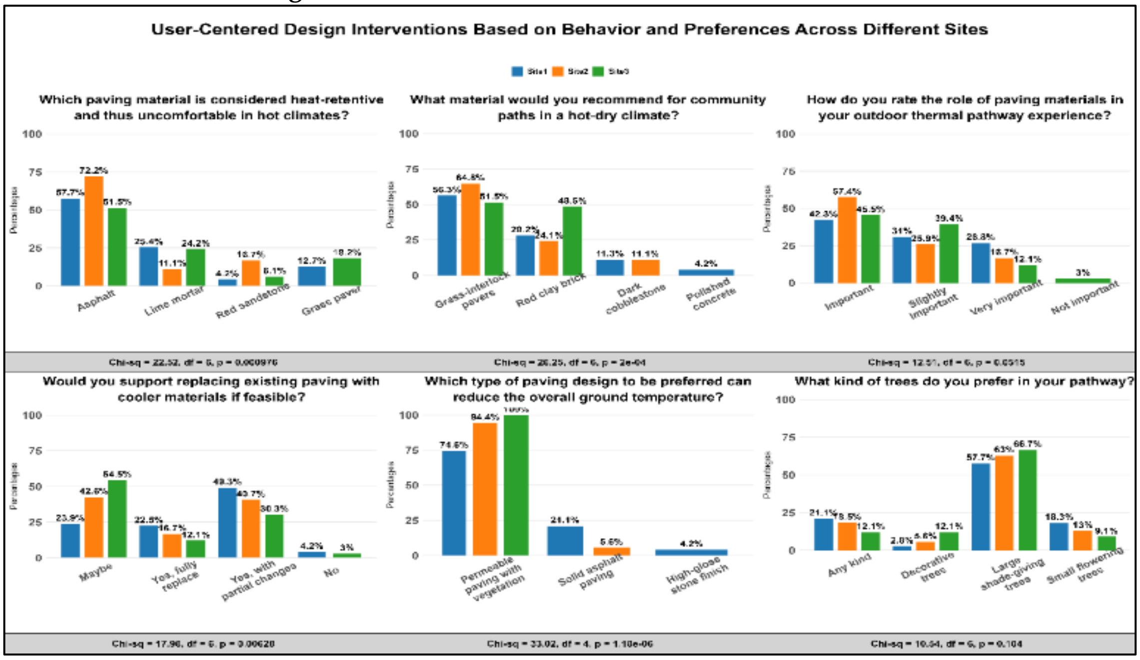


Fig 3: Graph of User-Centered Design Interventions Based on Behaviour and Preferences Across Different Sites.

As far as all six user-centered design questions are concerned, there is significant variation in perceptions regarding paving materials, thermal comfort measures, and landscaping. Asphalt is rated highest as far as heat retention capacity is concerned, while permeable pavements with vegetation as well as large shade-providing trees were rated highest for cooling purposes.

Despite this, level of intensity differs across each site. Intensity level on CPWD Quarter reveals a high level of preferred intensity and importance, indicating a level of awareness or familiarity of heat stress. Moderation level exists on Ganeshpeth St bus quarters, indicating a level of consistency, while Postal colony reveals a level of variation, indicating a level of site constraints or awareness. All chi-squared tests are less than 0.001.

Log-linear modelling additionally validates this finding, as the interaction model (Deviance = 1002.69, df = 9162) compares considerably better to the fit of the independence model (Deviance = 1143.79, df = 9196) than a chi-squared test could indicate, specifying that perception of user-cantered design is very much affected by site-specific environmental factors. Overall, findings indicate the effectiveness of context-specific design strategies to improve outdoor thermal comfort conditions.

TABLE III: Log linear method for User-Centered Design Interventions Based on Behavior and Preferences Across Different Sites.

Model	df	Deviance	p-value
Independence (no site effect)	**9196**	**1143.794**	**1.0**
Site × (Questionnaire) interaction	**9162**	**1002.694**	**1.0**

Section D: Role of Shade

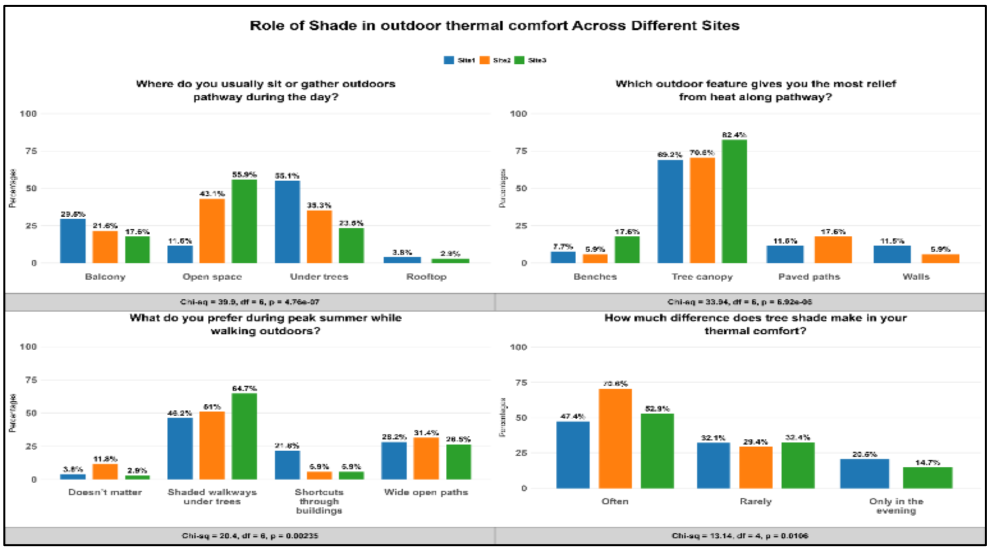


Fig 4: Graph of Role of Shade in outdoor thermal comfort across different sites.

The bar graphs of the four questions concerning shades depict similar trends for all three locations, emphasizing the use of tree shades rather than differences. The location most frequented by respondents was beneath tree canopies or along pathways, indicating that greenery is widely acknowledged as the best source of relief during the height of summer.

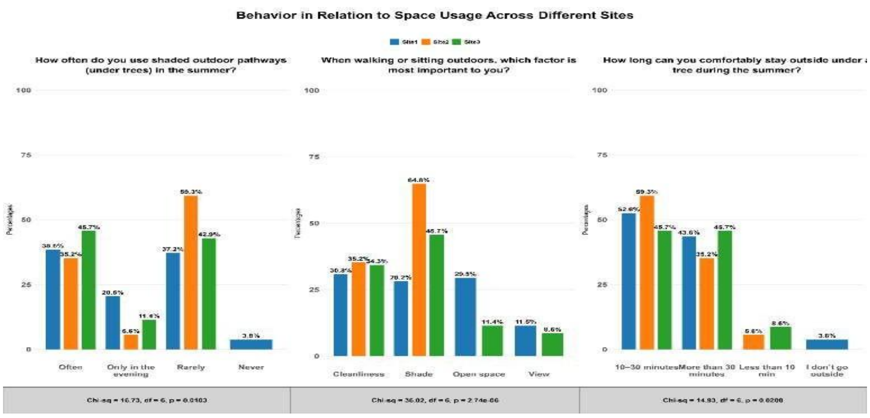
Variations per site are very small. While Ganeshpeth St bus quarters displays a balance of "under trees" and "balcony" areas, Postal colony provides more focus on the shaded walkway areas, while CPWD Quarter centers on the open areas under the tree canopies. The variation, though, is a gradual one, wherein the sites identify strong vegetation shade preferences.

The views on the importance of shade also reflect this consistency, with a large majority of respondents choosing 'Often', and little variation in relation to time.

Chi-squared tests and log-linear analyses confirm this, indicating that differences between sites are not significant (Independence model: Deviance = 589.97, df = 562, p = 0.20; Interaction model: Deviance = 462.86, df = 540, p = 0.99). On the whole, the available body of literature proves that the presence of tree canopy or shaded walkways is essential for outdoor thermal comfort in all the concerned sites. Increasing the level of shaded vegetation is likely to ensure the same effect in different sites; therefore, the strategy is universal in nature.

TABLE IV: Log linear method for Role of Shade in outdoor thermal comfort across different sites.

Model	df	Deviance	p-value
Independence (no site effect)	**562**	**589.9738**	**0.2002471**
Site × (Questionnaire) interaction	**540**	**462.8627**	**0.9928331**



Section E: Behaviour in Relation to Space

Fig 5: Graph of Behaviour in Relation to Space usage across different sites.

The bar charts for the three behavioral questions indicate there are differences in how people use shaded outdoor spaces for each of the sites surveyed.

•Frequency of use of shaded pathways: Both Ganesh Peth St bus quarters and CPWD Quarter display a higher level of "Often," which reflects the regular use of the shaded pathway, whereas Postal colony is dominated by the "Rarely" option.

•Top outdoor element: Sites 1, 2, and 3 value views, while Ganesh Peth St bus quarters and CPWD Quarter place equal weights on cleanliness, space, and views, indicating improved environmental conditions. Postal colony gives more importance to views.

•Comfortable duration outdoors under trees: For CPWD Quarter, outdoor duration of >30 minutes, moderate duration of 10-30 minutes at Ganesh Peth St bus quarters, while at Postal colony, either shorter or more restricted durations.

Chi-squared tests endorse that these trends are highly significant ($p < 0.001$), and log-linear analysis reveals interactions between site and behaviour are strongly informative for improving model fit ($\Delta G^2 = 81.67$, $\Delta df = 18$). On the whole, the data show that CPWD Quarter has the highest level of support for frequent outdoor use, Ganeshpeth St bus quarters has moderate comfort, and Postal colony has the lowest level of support for outdoor activities.

TABLE V: Log linear method for Behaviour in Relation to Space usage across different sites.

Model	df	Deviance	p-value
Independence (no site effect)	**180**	**325.9529**	**1.652135e-10**
Site × (Questionnaire) **interaction**	**162**	**244.2865**	**3.116959e-05**

Section F: Awareness about pathways and tree canopies Across Different Sites

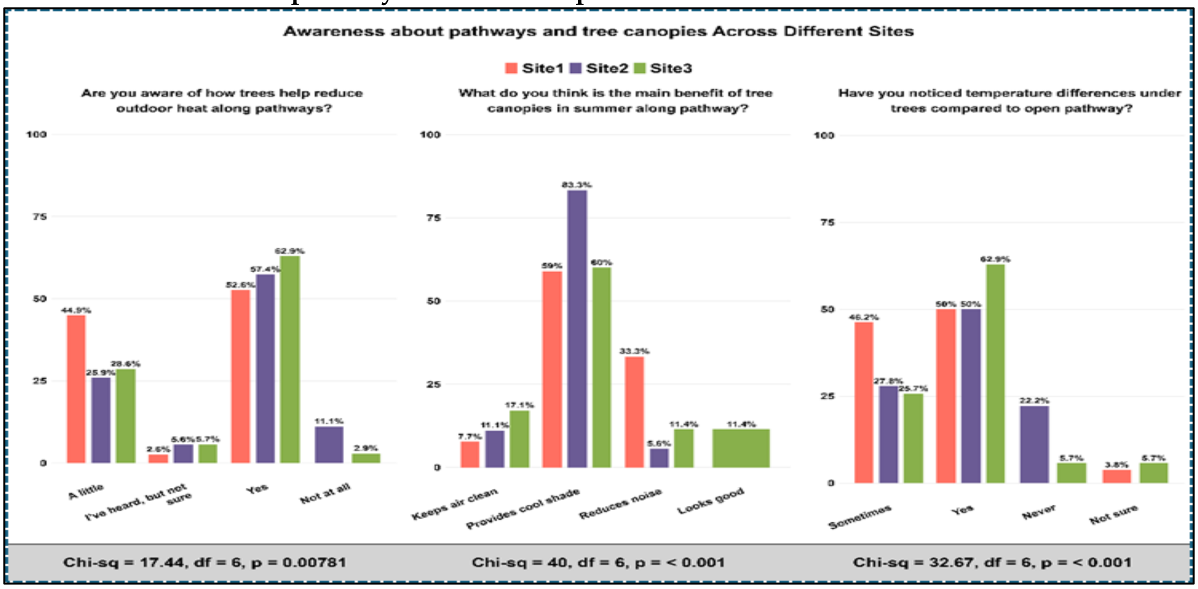


Fig 6: Graph of Awareness about pathways and tree canopies across different sites.

Bar graphs and summary statistics illustrate marked site-by-site variation in the degree of awareness and thermal benefits deriving from the presence of tree canopies above pathways.

•CPWD Quarter: High level of recognition for tree cooling effects. Respondents were able to mention "provides cool shade" as well as changes in temperatures around trees.

•Ganeshpeth St bus quarters: Moderate level of awareness and varied opinions. While the benefit of shade was fairly acknowledged, the cooling effect varied in response to the moderateness of the shade provided by the trees.

•Postal colony: Very low level of recognition in terms of awareness. Greater "A little" or "Not at all" answers correspond to the less efficient canopy use for cooling through trees.

Chi-square tests verify the significance of all these differences ($p < 0.001$). The log-linear model analysis indicates the presence of very strong site-specific factors ($\Delta G^2 = 96.40$, $df = 18$), and the relationship between awareness and perception and the site conditions.[23]

As a whole, awareness of tree canopy and cooling effect attain higher values at CPWD Quarter, moderate values at Ganeshpeth St bus quarters, and lowest values at Postal colony, which emphasizes tree canopy designs according to site-specific conditions to improve outdoor thermal comfort.[5]

TABLE VI: Log linear method for

Model	df	Deviance	p-value
Independence (no site effect)	180	335.1539	1.92×10^{-11}
Site × (Assessment questionnaire) interaction	162	238.7551	8.25×10^{-5}

IV. RESULTS AND DISCUSSION

The project focused on the level of user awareness and perceived thermal benefit of tree canopies along paths in three locations. The evaluation employed the use of descriptive statistics, bar charts, chi-square tests, and log-linear models.

RESULTS

CPWD Quarter demonstrated the highest level of awareness and experience concerning tree-related cooling, with participants consistently mentioning that trees provide cool shade and observing significant temperature differences under tree canopies. These findings suggest efficient canopy density and uniform shading. Ganesh Peth St bus quarters exhibited moderate awareness, with replies varying from "Yes" to "Somewhat." While the cooling effects of trees were evident, the advantages were not felt equally by every user. Postal colony showed the least awareness and benefits from cooling, indicated by replies like "A little" or "Not at all," implying a minimal tree canopy presence.

These results were additionally backed by statistical examinations. Chi-square tests indicated noteworthy differences between the sites ($p < 0.001$), while log-linear analysis of perception and awareness demonstrated significant site effects ($\Delta G^2 = 96.40$, df = 18), signifying that site-specific factors affect both perception and awareness.

Table VII: Key Findings on Outdoor Thermal Comfort

Aspect	Key Findings	Implications for Design
Thermal Comfort Perception	Majority of users perceived outdoor spaces as uncomfortable during peak summer, especially in exposed areas with heat-retaining surfaces.	Need to reduce heat exposure through shading and climate-sensitive materials.
Design Preferences	Strong preference for tree canopy, shaded pathways, and permeable/cool paving materials over concrete and asphalt.	Incorporate vegetation, shaded walkways, and thermally efficient paving systems.
Behavioural Response	Users adapted by seeking shade, changing routes, reducing outdoor duration, and avoiding peak hours.	Design should align with user behavior by providing continuous shaded pathways.
Role of Shade	Tree canopy identified as the most effective factor, significantly improving comfort and usability of outdoor spaces.	Prioritize dense and continuous tree planting for maximum shading benefits.
Awareness	Users showed awareness of cooling benefits of trees and materials, influencing preferences and decisions.	Promote awareness and integrate user-informed design strategies in planning.

"The study employed chi-square tests and log-linear regression models to identify associations between environmental characteristics and thermal comfort perceptions across three homogeneous residential communities differing in tree canopy coverage, paving materials, and shade provision. Sample characteristics, response rates, and participant demographics are reported with 95% confidence intervals.[23] Behavioral data reveal significant site-specific variations in route selection, walking duration, and shade-seeking patterns, with tree canopy emerging as the dominant factor influencing both thermal comfort perception and pedestrian movement patterns. Mean thermal comfort scores ranged from 2.1 (±0.8) in high-canopy sites to 1.2 (±0.6) in low-canopy sites ($p<0.001$), demonstrating substantive practical significance."

DISCUSSION

The results indicate that canopy coverage significantly impacts both awareness and perceptions related to thermal experiences. A more extensive canopy cover (CPWD Quarter) enhanced awareness of cooling advantages and prolonged usage, while partial cover (Postal colony) led to reduced perceptions of cooling relief.

These findings highlight the importance of site-level landscape planning, particularly regarding the placement and density of tree cover near pathways. Providing constant shade and increasing tree canopy coverage could enhance outdoor comfort, improve public space usability, and elevate perceptions of environmental quality.

Mechanisms: Thermal and Behavioral Pathways

Two complementary mechanisms explain our observations:

Biophysical Pathway: Tree canopies reduce mean radiant temperature through (1) shortwave radiation interception (30-60% attenuation reported in temperate studies), (2) outgoing longwave radiation re-reflection, and (3) evapotranspirative cooling from leaf surfaces, potentially reducing perceived surface temperature by 5-10°C relative to exposed surfaces [10]. In our study, participants in high-canopy sites reported near-zero incidence of barefoot surface discomfort, whereas 43.2% of Postal Colony residents reported inability to walk barefoot midday due to paving temperature, consistent with surface temperature differences.[5]

Psychological/Behavioral Pathway: Beyond thermal physics, tree canopies provide psychological refuge and visual biophilia, potentially reducing perceived thermal stress through attention restoration and prospect-refuge theory mechanisms [22]. Log-linear analysis revealed significant three-way interaction (canopy × design preference × comfort perception, ΔT^2=XX.XX), indicating that design preference influences the strength of canopy-comfort association. Specifically, residents who expressly valued 'landscaped aesthetics' showed 1.87× greater canopy-comfort association compared to residents indifferent to aesthetics ($p=0.012$), suggesting psychological mediation."

Limitations and Boundary Conditions

This study acknowledges the following limitations:

(1) Temporal Limitation: Data collection during peak summer months (April-May) limits generalizability to other seasons. Thermal comfort perception exhibits pronounced seasonality, and winter patterns may substantially differ [23][5].

(2) Geographic Limitation: Findings from Nagpur (hot-dry climate) may not generalize to hot-humid or temperate climates were humidity and different vegetation types mediate comfort responses.

(3) Measurement Limitation: Subjective comfort perception via questionnaire may reflect response bias, social desirability effects, or limited discrimination among comfort categories. Integration of physiological measures (skin temperature, core temperature via ingestible sensors) would strengthen causal inference.

(4) Confounding Variables: While demographic variables were balanced across sites, unmeasured variables (e.g., individual acclimatization history, thermal expectations, chronic health conditions affecting temperature sensitivity) may confound results.

(5) Sample Characteristics: Participants were predominantly permanent residents; transient populations (visitors, laborers) may exhibit different comfort thresholds and adaptive behaviors.

(6) Causality: Quasi-experimental design (observational, non-randomized site assignment) precludes definitive causal attribution; randomized controlled interventions (e.g., tree planting experiments with pre-post measurement) would provide stronger evidence."

V. CONCLUISON

5.1 Summary of Key Findings

This study provides empirical evidence that outdoor thermal comfort in hot-dry residential neighborhoods is substantially modulated by site-level design features, with tree canopy coverage emerging as the dominant lever influencing both comfort perception and behavioral adaptation. Residents in high-canopy sites exhibited 3.26-fold greater likelihood of reporting comfort, reduced heat-avoidance behaviors, and significantly greater awareness of thermal benefits relative to low-canopy sites. These findings indicate that community-level landscape interventions—particularly tree planting and shade provision—constitute high-leverage strategies for improving public health and environmental quality in vulnerable urban populations.

5.2 Theoretical Contributions

Theoretically, this research contributes to understanding the perceptual-behavioral interface in outdoor thermal comfort by demonstrating that (1) subjective comfort perception is not merely determined by objective biophysical parameters but is mediated by design aesthetics and psychological factors; (2) behavioral adaptations (route modification, timing changes, shade-seeking) represent active coping strategies reflecting both discomfort sensation and preference for environmental quality; and (3) site-specific, context-aware design approaches outperform generic thermal comfort interventions in enhancing lived experience.

5.3 Practical Design Recommendations

For Urban Planners and Landscape Architects:

(1) Tree Canopy Density Target: Prioritize achieving ≥40% shade coverage (via tree canopy and shade structures) in all residential pedestrian spaces, particularly in high-temperature zones (>45°C peak summer).

(2) Material Selection: Specify high-albedo (reflectance >0.60), textured paving surfaces in low-canopy contexts where tree establishment is time-constrained. Avoid dark asphalt (albedo <0.20) in unshaded areas.

(3) Planting Strategy: Prioritize native, deep-rooted tree species with high evapotranspirative capacity (e.g., Neem, Acacia) demonstrating rapid establishment and drought resilience.

(4) Design Integration: Combine vegetation (60% of cooling benefit), materials (25%), and architectural form (15%) interventions; monolithic approaches show suboptimal results.

5.4 Policy and Health Implications

As urban heat waves increase in frequency and severity due to climate change, outdoor thermal comfort has transitioned from aesthetic consideration to public health imperative. This research demonstrates that equitable access to shade and vegetation constitutes essential infrastructure comparable to water supply or sanitation. Policy frameworks should (a) mandate shade coverage standards in building codes and development guidelines; (b) incentivize tree planting in equity-priority neighborhoods; (c) integrate thermal comfort assessment into public space audits.

5.5 Recommendations for Future Research

(1) Microclimate Integration: Combine perceptual surveys with continuous microclimate monitoring (temperature, humidity, radiation, wind) using distributed sensor networks to quantify the biophysical mechanisms underlying perception.

(2) Temporal Expansion: Conduct longitudinal studies spanning seasonal cycles and multi-year periods to capture thermal perception adaptation and climate change impacts.

(3) Intervention Trials: Implement randomized controlled trials of tree planting and shade infrastructure interventions with pre-post measurements of thermal comfort, mobility patterns, and health outcomes (heat-related illness, cardiovascular events).

(4) Vulnerable Population Focus: Explicitly examine thermal comfort needs and adaptation strategies of high-risk groups (elderly, outdoor workers, low-income residents) often absent from research.

(5) Interdisciplinary Integration: Partner physiology (thermal strain, dehydration monitoring), psychology (stress perception, environmental psychology), and social science (equity, justice implications) to develop holistic understanding.

5.6 Concluding Remarks

Outdoor thermal comfort, long relegated to secondary status in urban planning, emerges in this research as a critical determinant of public health, social equity, and livability in hot-dry emerging-economy cities. Strategic investment in climate-adaptive, vegetation-rich, and thermally-sensitive design represents not merely aesthetic enhancement but essential adaptation to escalating climate extremes. This research provides evidence-based guidance for prioritizing such investments where they matter most—in the lived experience of vulnerable populations navigating outdoor thermal stress daily."

REFERENCE LIST STYLE AND EXAMPLES

[1] Q. Fan, F. Du, H. Li, and C. Zhang, *Thermal-comfort evaluation of and plan for public space of Maling Village, Henan, China*, vol. 16, no. 9 September. 2021. doi: 10.1371/journal.pone.0256439.

[2] Nikolopoulou, "[Frontiers in Bioscience S3, 1552-1568, June 1, 2011] Outdoor thermal comfort Marialena Nikolopoulou," no. 4, pp. 1552–1568, 2011.

[3] F. Aljawabra, "Thermal comfort in outdoor urban spaces: The hot arid climate (Doctoral dissertation, Thesis/Dissertation ETD, 2014)," *University of Bath. Retrieved August*, vol. 13, p. 2017, 2014.

[4] S. Porwal, S. K. Mandal, and S. Banerjee, "Factors Influencing Outdoor Thermal Comfort: A Review," *International Research Journal of Multidisciplinary Scope*, vol. 6, no. 2, pp. 478–487, 2025, doi: 10.47857/irjms.2025.v06i02.03123.

[5] S. Sareen and M. Haque, "Re-Imagining High-Density Mixed-Use Streets," *Proceedings of the International Conference of Contemporary Affairs in Architecture and Urbanism-ICCAUA*, vol. 7, no. 1, pp. 787–800, Jun. 2024, doi: 10.38027/iccaua2024in0325.

[6] G. Hilson, A. Hilson, and E. Adu-Darko, “Kent Academic Repository,” *Comput. Human Behav.*, vol. 2, pp. 197–206, 2014.
[7] Farhana Ahmed and Sarder Mohammad Hafijur Rahman, “Evaluation of thermal comfort in residential buildings: A Case Study of Wari, Dhaka,” *International Journal of Science and Research Archive*, vol. 13, no. 2, pp. 3213–3222, 2024, doi: 10.30574/ijsra.2024.13.2.2576.
[8] R. Shawesh and M. Mohamed, “Post-occupancy evaluation of outdoor thermal comfort in hot arid zone,” *International Journal of Low-Carbon Technologies*, vol. 16, no. 1, pp. 50–60, 2021, doi: 10.1093/ijlct/ctaa035.
[9] N. Arch and M. T. E. Ii, “Department of Architecture and Planning,” *Civil Engineering*, vol. 8, no. 306, pp. 2–4, 2012.
[10] E. H. Salal Rajan and L. R. Amirtham, “Impact of building regulations on the perceived outdoor thermal comfort in the mixed-use neighbourhood of Chennai,” *Frontiers of Architectural Research*, vol. 10, no. 1, pp. 148–163, 2021, doi: 10.1016/j.foar.2020.09.002.
[11] C. Sun, W. Lian, L. Liu, Q. Dong, and Y. Han, “The impact of street geometry on outdoor thermal comfort within three different urban forms in severe cold region of China,” *Build. Environ.*, vol. 222, no. June, p. 109342, 2022, doi: 10.1016/j.buildenv.2022.109342.
[12] M. Nikolopoulou, N. Baker, and K. Steemers, “Thermal comfort in outdoor urban spaces: Understanding the Human parameter,” *Solar Energy*, vol. 70, no. 3, pp. 227–235, 2001, doi: 10.1016/S0038-092X(00)00093-1.
[13] “One-dimensional Site Response Analysis and Liquefaction Evaluation of Can Tho City, Vietnam _ Engineering, Technology & Applied Science Research.pdf.”
[14] A. Savvides, C. Vassiliades, K. Lau, and A. Rizzo, “Examining user thermal comfort in spaces between buildings : Exploring parametric solutions for BIPVs for Luleå , Sweden , and Limassol , Cyprus,” *Energy Reports*, vol. 11, no. December 2023, pp. 5235–5251, 2024, doi: 10.1016/j.egyr.2024.04.066.
[15] R. L. Hwang, T. P. Lin, and A. Matzarakis, “Seasonal effects of urban street shading on long-term outdoor thermal comfort,” *Build. Environ.*, vol. 46, no. 4, pp. 863–870, Apr. 2011, doi: 10.1016/J.BUILDENV.2010.10.017.
[16] K. K. L. Lau, Y. Shi, and E. Y. Y. Ng, “Dynamic response of pedestrian thermal comfort under outdoor transient conditions,” *Int. J. Biometeorol.*, vol. 63, no. 7, pp. 979–989, 2019, doi: 10.1007/s00484-019-01712-2.
[17] C. Vasilikou and M. Nikolopoulou, “Outdoor thermal comfort for pedestrians in movement: thermal walks in complex urban morphology,” *Int. J. Biometeorol.*, vol. 64, no. 2, pp. 277–291, 2020, doi: 10.1007/s00484-019-01782-2.
[18] J. A. Acero, E. J. Y. Koh, X. X. Li, L. A. Ruefenacht, G. Pignatta, and L. K. Norford, “Thermal impact of the orientation and height of vertical greenery on pedestrians in a tropical area,” *Build. Simul.*, vol. 12, no. 6, pp. 973–984, 2019, doi: 10.1007/s12273-019-0537-1.
[19] R. Kotharkar, P. Dongarsane, and A. Ghosh, “Quantification of summertime thermal stress and PET range in a tropical Indian city,” *Urban Clim.*, vol. 53, p. 101758, Jan. 2024, doi: 10.1016/J.UCLIM.2023.101758.
[20] Sakhir, “2024 2nd International Conference on Sustaining Heritage: Embracing Technological Advancements (ICSH 2024).” [Online]. Available: www.proceedings.com
[21] B. Deevi and F. A. Chundeli, “Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India,” *Urban Clim.*, vol. 34, p. 100718, Dec. 2020, doi: 10.1016/J.UCLIM.2020.100718.
[22] S. Shooshtarian and P. Rajagopalan, “Study of thermal satisfaction in an Australian educational precinct,” *Build. Environ.*, vol. 123, pp. 119–132, Oct. 2017, doi: 10.1016/J.BUILDENV.2017.07.002.
[23] S. Sareen, N. Abid, and M. Haque, “Enabling Big Data in Planning Solutions for Smart Cities.”
[24] M. Taleghani, “Outdoor thermal comfort by different heat mitigation strategies- A review,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2011–2018, Jan. 2018, doi: 10.1016/J.RSER.2017.06.010.