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Enhancing Outdoor Comfort in Delhi: Urban Heat Island Mitigation with Future Climate Projections

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ABSTRACT

For rapidly warming cities such as Delhi, the real test of an Urban Heat Island (UHI) mitigation strategy is not whether it cools streets today, but whether it still does so under the hotter climate those streets will face decades from now. The surface warming in Delhi due to urbanization is the result of the replacement of vegetation with built-up areas, and with hot surfaces increasing cooling loads, heat management is crucial in sustainable urban development and planning. The current research analysed high albedo pavements as a potential UHI mitigation strategy in a medium-density plotted housing neighbourhood, with respect to the outdoor thermal comfort levels under present-day conditions as well as those projected for the late twenty-first century. New Friends Colony was selected as a representative case study, combining on-site measurements with the Universal Thermal Climate Index (UTCI) and ENVI-met microclimate simulations driven by Energy Plus Weather (EPW) data. For the year 2082, the future urban form was extrapolated based on the past trends in green cover increase, along with the rise of the building density and height. The scenario included an approximately 2 °C increase in mean air temperature. Reflective pavements were considered in both cases. It was found out that under present-day conditions, reflective pavements reduced surface temperatures and heat stress levels according to UTCI levels. However, in the case of the future scenario, the increase in the heat level led to a shift in UTCI category towards higher levels, indicating that only these strategies would be insufficient for mitigating the future heat level. Thus, the maintenance of outdoor comfort requires a proactive approach with a number of strategies involving reflective pavements and surfaces, greenery and permeability.

KEYWORDS Urban heat island, Outdoor thermal comfort, High-albedo pavements, Sustainable urban planning, Delhi

1. Introduction

Why has the Urban Heat island been such an important issue? With the development of cities and their expansion from natural environments into a concrete jungle, urban surfaces become much more efficient in absorbing solar radiation than natural landscapes, which result in significantly higher temperatures in cities compared to surrounding rural areas – the Urban Heat island (UHI) effect (Voogt and Oke 2003). Starting off as an interesting phenomenon for nineteenth-century meteorologists, it became a serious problem for today's health, energy and quality of life because increased temperatures in cities not only aggravate the risk of heat illnesses, but also increase the need for cooling, the energy consumed and associated emissions of greenhouse gases, and reduce air quality – and all these negative effects are experienced predominantly by disadvantaged populations (Santamouris 2014). Climate change further sharpens all these issues and makes heat waves more common, intense and long-lasting— so that the cities least equipped to cope are often warming the fastest.

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There is no region where these stresses are more pronounced than in the fast-urbanizing cities of the Global South, with India being in the heart of this phenomenon. Years of population increase and development have deprived cities like Mumbai, Bengaluru and Delhi of their green cover, forcing urban surfaces and urban ambient temperatures to be higher than those of rural regions (Kotharkar *et al.* 2018). Every year, India faces the stress of heatwaves and high cooling loads, with urban regions being several degrees hotter than their rural counterparts. It is impossible to talk about sustainable urban development without tackling the problem of urban heat management.

Delhi exemplifies the issue in its starkest form. In the last few decades, the built-up areas have doubled in the city while the vegetation area has reduced and hence the resultant urban heat island intensity has increased up to 4.6 °C between built-up areas and vegetation zones (Naikoo *et al.* 2022). The impacts are felt every year during summers when the temperature reached 49 °C in 2022, thereby putting pressure on the infrastructure and increasing the risk of people being exposed to extreme heat conditions (India Meteorological Department 2022). With climate change expected to make such extremes more frequent, mitigation measures that can be built into the urban planning process have become increasingly important (Gago *et al.* 2013). Delhi's own planning framework, the Master Plan for Delhi 2041 (Delhi Development Authority 2021), explicitly calls for climate-resilient, sustainable urban development, making the management of urban heat a stated planning priority rather than a purely technical concern.

Several options have been suggested by researchers, including increased vegetation, improved design of the urban morphology, and cool or reflective materials. Among these, cool pavements have been widely recognized because of their ability to reflect the heat coming from the sun, reduce the surface temperature and consequently make the cooling load due to the hotter surfaces manageable (Akbari *et al.* 2001). In Delhi's climate, high-albedo (cool-roof) surfaces at a solar reflectance of 0.8 have been estimated to save around 23 kWh/m^2 per year in cooling energy and to cut peak temperatures by up to 3.9 °C, underlining the energy stakes of surface albedo in the city (Rawat and Singh 2022). Despite being an efficient material in different climatic contexts, not much work has been carried out regarding their performance in the particular urban context of Delhi – and very few have taken into account the warmer future climate of Delhi. It becomes important as a standard which is tested based only on present climate conditions fails to predict the future conditions of the city and will not be effective. The medium-density plotted housing that characterises much of residential Delhi, with its mix of paved streets and moderate green cover, has been largely overlooked, leaving a gap between global evidence and local planning practice.

In an effort to plug that research gap, the aim of this paper is to determine the ability of pavements with high albedo in improving outdoor thermal comfort of a typical neighbourhood of Delhi – not just today, but also in a future climate scenario predicted for the end of the twenty-first century. By using on-site data, Universal Thermal Climate Index (UTCI) and ENVI-met microclimatic models, the study seeks to achieve four goals: to characterize existing thermal comfort at the neighbourhood; to assess the use of high albedo pavements as mitigation measures; to quantify how a projected future, physically changed climate affects outdoor comfort in 2082; and to determine whether such pavement surfaces are able to provide long-term resilience. In doing so, the study offers a replicable, planning-oriented framework for evaluating UHI mitigation in similar residential settings, and a grounded basis for the urban development decisions that will shape how comfortable and energy-efficient Delhi's streets remain in a warming future.

2. Background

Three major categories of interventions have emerged in the context of UHI mitigation research: greening measures, alteration of urban geometry to enhance shading and ventilation, and using reflective or "cool" surfaces as alternatives to traditional surfaces. Vegetation reduces the temperature of its surroundings through shading and evaporation, and has been widely recognized as the most efficient singular measure against the UHI effect. Urban geometry – height of buildings,

width of streets and built versus open space ratio – controls how heat moves through urban environment, and can be optimized to achieve cooling effects in canyon-shaped cities (Oke 1982). Reflective surfaces comprise the third category of UHI mitigation efforts; through increased reflection of sunlight they keep the surface cooler, thus reducing the amount of radiation transferred to adjacent areas.

This study deals with high-albedo pavements, which belong to this third group. They reflect sunlight away from paved surfaces, thus reducing heat absorption. They can reduce ambient temperatures by up to 1–2 °C in hot climate, with corresponding reductions in the cooling energy demand of nearby buildings (Akbari *et al.* 2001). They're especially attractive in dense residential neighbourhoods where over-pavement, not under-planting, is the problem causing localized heat. However, their performance is not unconditional: depending on the surrounding geometry, reflected radiation can increase the radiant load on pedestrians, which means that their net effect on comfort should be assessed in context rather than assumed (Salman and Saleem 2021).

Assessing that comfort requires a robust index. There are many indices, such as the Physiologically Equivalent Temperature (PET), the Standard Effective Temperature (SET) and the Wet Bulb Globe Temperature (WBGT), but none have been fully documented for open outdoor space. WBGT does not factor in wind speed and radiation, which are significant outdoors. The Universal Thermal Climate Index (UTCI) was chosen because it is a measure of equivalent temperature that is affected by air temperature, humidity, wind speed and mean radiant temperature. It has been validated in various climates, including the subtropical climates of Delhi, India (Bröde *et al.* 2012). The UTCI is not derived from Indian climate data and thus does not reflect Indian thermal preferences, but the UTCI covers a broad range of temperatures, which is the best that is currently available.

A research gap exists. The majority of existing research is set in the Mediterranean, tropical, or arid contexts (Labdaoui *et al.* 2021; Khaire *et al.* 2023), and the research that does address mitigation is mostly theoretical or focuses on the present. There is a lack of studies that examine high-albedo pavements as a mitigation strategy at the neighbourhood scale in Delhi or evaluate how those methods would work in the future with more warming. This research aims to directly address this gap by combining fieldwork and simulations to assess high-albedo pavements in a medium-density, developed, plotted housing neighbourhood, for both current and future (late 21st century) climate scenarios.

3. Methodology

A combination of field measurements and microclimate simulations was used to investigate how high albedo paving affects outdoor thermal comfort in both current and predicted future climates. This approach involved selecting the right case study and time periods, collecting and validating data, and finally using ENVI-met scenarios. The overall research framework is summarised in Figure 1, which traces the study from its aim through the key design decisions to simulation and analysis.

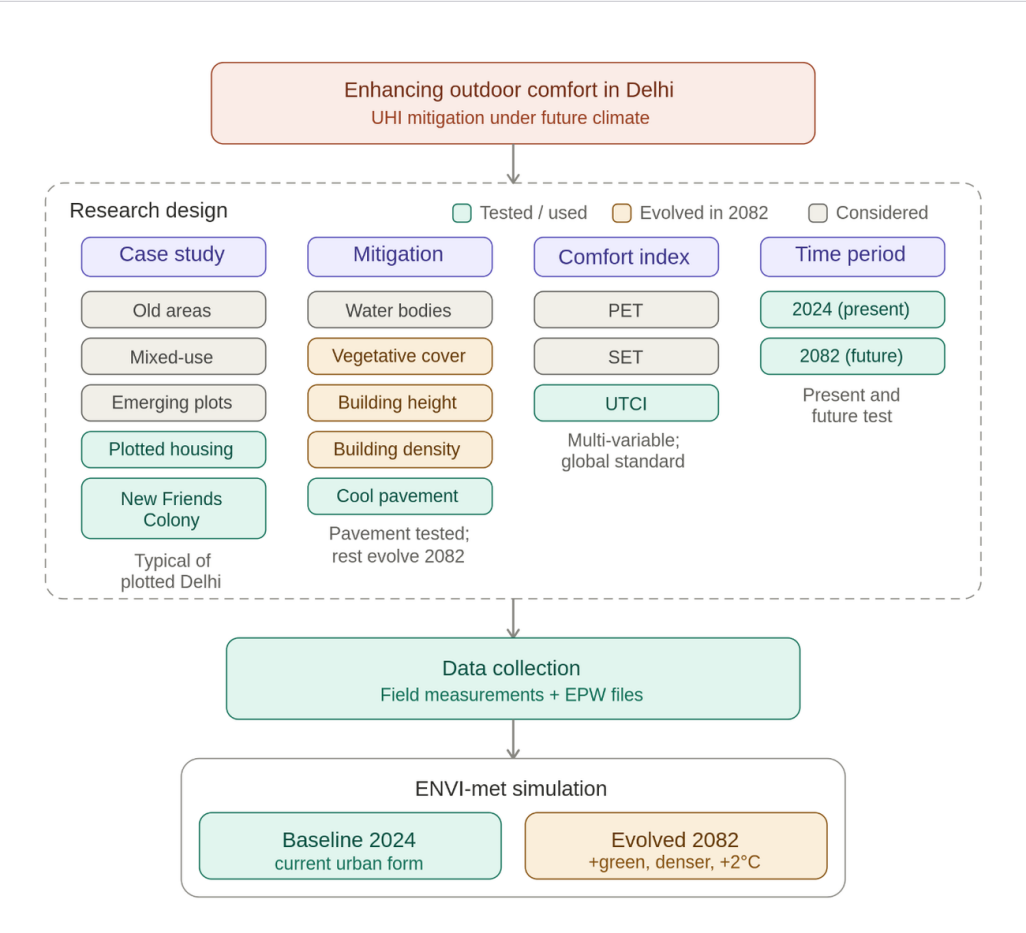

Figure 1. Research framework showing the study's design decisions and workflow (Source: Author).

3.1. Study area and time periods

New Friends Colony (NFC) is a medium-density residential and commercial neighbourhood in South Delhi (Figure 2). It features a combination of low-rise independent houses and mid-rise apartments, along with moderate green spaces and easy access to major roads. This makes it a good example of plotted housing across the city, making it ideal for testing mitigation strategies. Block B was modelled in detail. Measurements were taken at two daily times: early morning (4–6 am) and afternoon (2–4 pm). These times were chosen to capture the period of greatest overnight heat retention and the peak solar stress, providing a balanced view of comfort throughout the day.



Figure 2. A street in New Friends Colony, Delhi (Source: Author).

3.2. Data collection and validation

Primary data included on-site measurements of temperature and humidity collected within the neighbourhood using a handheld heat-stress meter (Figure 3) during the autumn transitional season on 5 September 2024.



Figure 3. Heat-stress meter used for on-site temperature measurements at New Friends Colony, Block B (Source: Author).

Secondary data came from Energy Plus Weather (EPW) files provided by the ZED-I project (ZED-i, n.d.). These files included temperature, humidity, wind speed, and solar radiation data for both current and projected future conditions. Field measurements were used to validate the EPW data, ensuring that the weather inputs driving the simulation reflected actual conditions on the ground. Detailed urban features—building heights, road networks, tree cover, and open spaces—were surveyed and modelled to ensure that the simulated microclimate matched the real environment of Block B (Figure 4).



Figure 4. Satellite view of New Friends Colony, Block B, the study area in South Delhi (Source: Google Earth, 2024).

Field measurement is widely regarded as the foundation of outdoor thermal comfort assessment, complementing simulation and providing an empirical check on the modelled weather inputs (Watanabe *et al.* 2014; Johansson *et al.* 2014).

3.3. Thermal comfort index

Outdoor thermal comfort was measured using the Universal Thermal Climate Index (UTCI). This index combines air temperature, humidity, wind speed, and mean radiant temperature into a single equivalent temperature, classifying it into categories of thermal stress. UTCI was consistently applied across all scenarios to enable direct comparison. Although it is built on global datasets and does not fully capture the hot-humid conditions of Indian cities, UTCI has been validated across diverse urban climates and was selected for its multi-variable formulation and cross-regional comparability (Bröde *et al.* 2013; Park *et al.* 2014).

3.4. Simulation and scenarios

ENVI-met, a three-dimensional microclimate model, was used to simulate temperature distributions across Block B over time. Two climate contexts were modelled, with and without the high-albedo intervention. The present-day context reflected current (2024) conditions and urban design. The future context simulated late-century (2082) conditions. The urban design was changed to reflect realistic shifts. Green cover was increased in line with the neighbourhood's past greening trend. Building height and density were raised in accordance with the provisions of the Master Plan for Delhi 2041. Within each context, a baseline with conventional paving was compared to a scenario where high-albedo pavement materials were applied to streets and open areas— the pavement albedo was raised from 0.4 in the base case to 0.8 — with all other variables held constant, isolating the effect of the intervention. All other variables were kept constant to isolate the impact of the intervention. Comparing UTCI outputs across these scenarios allowed us to assess the present-day benefits of high-albedo pavements and the durability of those benefits in a warmer and denser future.

High-albedo pavement was the evaluated mitigation strategy, separate from the projected baseline changes mentioned earlier. Literature identified reflective surfaces as the most feasible and effective way to lower surface temperature in densely paved residential areas (Ren *et al.* 2023). Thus, these materials were tested in both present and future contexts. The increased greenery and building density in the 2082 context were not seen as interventions but rather as expected features of the future urban form, against which the ongoing effectiveness of reflective paving was evaluated.

4. Results and analysis

The results are presented in three parts: the present-day baseline and the effect of high-albedo pavement (2024); the projected future scenario (2082); and a synthesis comparing the two. UTCI values for all scenarios are reported in Tables 1 and 2, and the corresponding spatial distributions are shown in Figures 5 and 6.

Table 1. UTCI values for the 2024 base case, with and without high-albedo pavement (Source: Author).

		Base Case	With Pavements
Date	**Time**	**UTCI (°C)**	**UTCI (°C)**
05.09.2024	04:00 AM	27.05	26.92
05.09.2024	05:00 AM	27.37	27.05
05.09.2024	02:00 PM	33.25	33.18
05.09.2024	03:00 PM	34.24	33.55

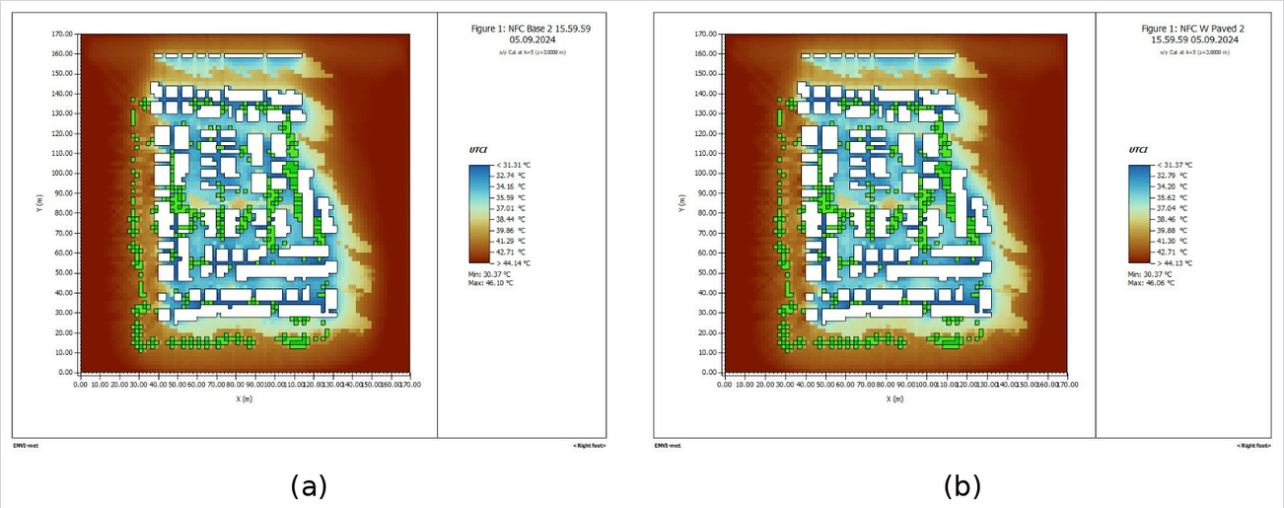

Figure 5. Universal thermal climate index (UTCI) distribution across New Friends Colony, Block B, at the 2–4 PM peak on 5 September 2024. Block B was reconstructed in ENVI-met from surveyed building heights, road networks and tree cover, and driven by zEDi EPW data validated against on-site measurements. The model was first run with conventional paving of albedo 0.4 (a), then re-run with all paved surfaces reassigned a high-albedo material of albedo 0.8 (b), with every other input held constant so that the difference isolates the effect of the pavement. Warmer colours denote higher UTCI (greater heat stress), on a scale from 31 °C to 44 °C. (Source: Author, generated in ENVI-met).

Table 2. UTCI values for the projected 2082 scenario with high-albedo pavement (Source: Author).

		With Pavements
Date	**Time**	**UTCI (°C)**
05.09.2082	04:00 AM	25.87
05.09.2082	05:00 AM	26.79
05.09.2082	02:00 PM	34.66
05.09.2082	03:00 PM	35.34

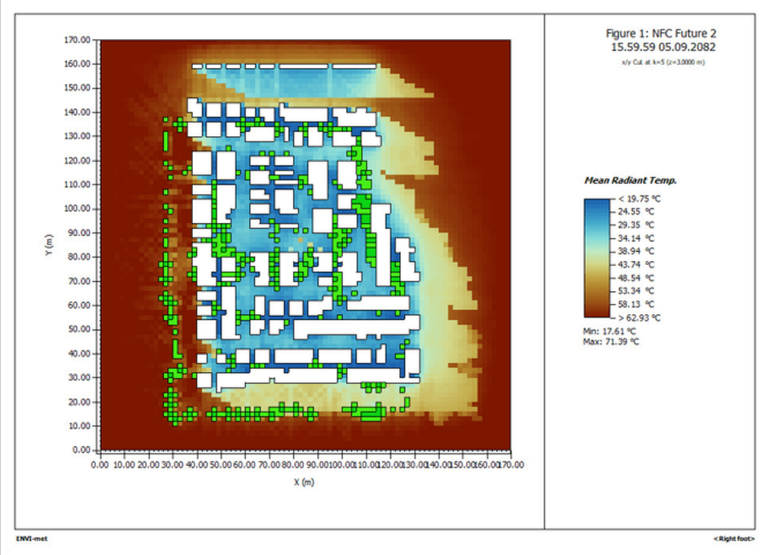

Figure 6. Mean radiant temperature (MRT) distribution across New Friends Colony, Block B, at 2–4 PM for the projected 2082 scenario. The 2024 model was evolved to represent the anticipated future: green cover was increased in line with past trends, building height and density were raised following the Master Plan for Delhi 2041, and an approximate 2 °C temperature rise was applied to the EPW inputs; high-albedo pavement (albedo 0.8) was then applied and the case simulated in ENVI-met. Because full UTCI fields could not be generated for this scenario, MRT is mapped as the spatial indicator of radiant heat load, on a scale from 20 °C to 63 °C. (Source: Author, generated in ENVI-met).

4.1. Present-day baseline and the effect of high-albedo pavement (2024)

Under current (2024) conditions, the baseline simulation indicated that outdoor thermal comfort in Block B fell within the strong heat stress category during the afternoon peak (2–4 PM), with UTCI values reaching approximately 34 °C in the most heavily paved zones; in the early morning (4–6 AM) values were lower, at around 27 °C. Applying high-albedo pavement reduced surface temperatures and lowered afternoon UTCI values by up to 0.7 °C, in the afternoon time. Table 1 reports the UTCI values for the base case with and without high-albedo pavement, and Figure 5 shows the corresponding UTCI distributions at the afternoon peak.

The reduction was most pronounced in the afternoon, when solar load is greatest, and minimal in the early morning — consistent with the reflective mechanism of high-albedo surfaces, which act chiefly by reducing absorbed shortwave radiation during daylight hours.

4.2. Future scenario (2082)

For the projected 2082 scenario, the urban form was evolved to reflect anticipated change — green cover was increased in line with the neighbourhood's past greening trend, and building height and density were raised in line with the densification provisions of the Master Plan for Delhi 2041 — alongside an approximate 2 °C rise in mean temperature, with high-albedo pavement again applied. Software constraints prevented the generation of full UTCI fields for this scenario; mean radiant temperature (MRT) is therefore presented as the spatial indicator of radiant heat load, while UTCI values are reported in Table 2. Afternoon UTCI values for 2082 reached approximately 35 °C, corresponding to strong heat stress — an increase of about 1 °C relative to the treated 2024 case, despite both the additional greenery and the reflective pavement. Figure 6 shows the MRT distribution for the 2082 scenario at 2–4 PM.

4.3. Synthesis

The results, shown in Tables 1 and 2, indicate that high-albedo pavement provided a noticeable comfort improvement under current conditions. It reduced the peak UTCI by up to 0.7 °C and

decreased afternoon heat stress by one category. However, in the future scenario for 2082, the same pavement applied to a warmer and denser urban environment resulted in a UTCI that was about 1 °C higher than in the treated 2024 case. This suggests that the warming climate had a larger impact than the cooling benefits of the pavement. While reflective paving remained helpful, it was not enough on its own to maintain current comfort levels by the end of the century.

It's important to note that the comparison between with and without pavement was only available for today's conditions. The 2082 analysis compares the treated present with the treated future. This isolates the combined effects of climate change and shifts in urban form, rather than just the additional benefits of high-albedo pavement in future conditions.

5. Conclusion

This study examined how high-albedo pavements could improve outdoor thermal comfort in a medium-density housing neighbourhood in Delhi, considering both current and projected late-century climate conditions. Using field measurements, the Universal Thermal Climate Index, and ENVI-met simulation, the research focused on New Friends Colony as a representative case. It compared current conditions to a high-albedo mitigation scenario and a projected scenario for 2082.

The results showed that, under current conditions, high-albedo pavements reduced surface temperatures and lowered UTCI values during peak daytime hours. This change shifted some areas of the neighbourhood from higher to lower categories of heat stress. Reflective surfaces therefore provided a measurable and cost-effective way to improve outdoor comfort in the present climate. However, under the projected 2082 scenario—where the urban landscape included more greenery and taller, denser buildings along with an expected rise of about 2 °C in mean temperature—this intervention alone was not enough. Despite the greenery and reflective surfaces, heat stress categories increased, showing that high-albedo pavements could not compensate for the additional heat expected later in the century.

5.1. Limitations

Several limitations should be considered when interpreting these results. The field measurements focused on validating the weather inputs rather than capturing the entire annual climate and were limited to a single transitional-season day. They reflect the conditions modelled here but do not account for seasonal changes throughout the year. Delhi's dry pre-monsoon peak (May–June) carries higher solar loads and would be expected to widen the absolute UTCI reductions delivered by high-albedo pavement, whereas the humid monsoon would narrow them; the direction of the findings should hold across seasons, even though the absolute magnitudes reported here are specific to the post-monsoon period modelled. The projections for the future carry more uncertainty than the current analysis. Both current and future conditions were based on the same Energy Plus Weather dataset for consistency, and the future scenario applied the expected temperature rise instead of re-simulating every climatic variable. The estimated increases in greenery and density came from past neighbourhood trends rather than a formal land-use model, and software limitations affected the creation of complete future UTCI fields. Therefore, the 2082 results should be viewed as an indicative estimate of trends rather than exact predictions. Furthermore, the study focused on one neighbourhood and one mitigation strategy, which sharpens the assessment of high-albedo pavements but leaves the effects of combined interventions and the applicability of findings to other urban forms untested. In addition, the 2082 scenario was simulated only with high-albedo pavement applied; without a matching unmitigated 2082 baseline, the pavement's relative cooling efficiency under a late-century climate could not be isolated, and constructing that baseline is a priority for future work. These constraints do not diminish the main finding—that reflective surfaces help under current conditions but are not enough by themselves under projected warming—but they do outline the context in which this conclusion applies.

These findings indicate that high-albedo pavements should be viewed as just one part of a broader mitigation strategy, not as a standalone solution. To sustain thermal comfort and resilience as temperatures rise, it will likely be necessary to combine reflective surfaces with expanded green infrastructure and permeable materials. This strategy will also help manage the increased cooling energy demand from hotter outdoor conditions. The research provides a replicable framework for evaluating urban heat island mitigation at the neighbourhood level, combining measured and projected climate data within a single comfort assessment. It can easily scale to other plotted housing neighbourhoods common in residential Delhi. For urban planners and policymakers—and in support of the climate-resilient goals outlined in the Master Plan for Delhi 2041—this work highlights the importance of integrating reflective surfaces with green and permeable strategies to create thermally comfortable, energy-efficient, and climate-resilient residential areas in Delhi and similar rapidly urbanizing cities. For municipal implementation, the durability of reflective surfaces is also a practical concern: field deployments show that high-albedo coatings can lose a substantial share of their reflectance within the first year through dust accumulation, tyre-mark soiling and weathering — degradation that is especially rapid in dusty, aerosol-heavy environments such as Delhi and at high-traffic junctions (Millstein and Fischer 2014; Ko *et al.* 2022). Sustaining the benefit therefore depends on treating maintenance as a recurring cost: cleaning ahead of the hot, dusty pre-monsoon months, recoating on a multi-year cycle, prioritising pedestrian and low-traffic surfaces where wear is slowest, specifying performance at aged rather than initial albedo, and favouring inherently light, durable materials over thin surface coatings where traffic is heavy. The broader takeaway is that urban heat mitigation must be designed with the future climate in mind, rather than solely relying on today's conditions.

Declarations

Author contributions. Het Parikh: Conceptualization, Methodology, Investigation, Formal analysis, Writing (original draft), Visualization, Project administration, Resources, Software, Writing (review and editing). Gunjan Jain: Data curation, Supervision, Validation.

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Conflicts of interest. There are none

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Generative AI. There was none

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