frontiers in Environmental Science

TYPE Original Research
PUBLISHED 20 April 2026
DOI 10.3389/fenvs.2026.1800415

EDITED BY
Maria Alzira Pimenta Dinis,
University Fernando Pessoa, UFP, Portugal

REVIEWED BY
Ali Sedki,
Applied Science University, Bahrain
Arnab Ghosh,
Cornell University, United States
Luis Orlando,
Instituto de Investigaciones Biológicas Clemente Estable (IIBCE), Uruguay

*CORRESPONDENCE
Jorgelina Hardoy,
jhardoy@iied-al.org.ar

RECEIVED 30 January 2026
REVISED 12 March 2026
ACCEPTED 24 March 2026
PUBLISHED 20 April 2026

CITATION
Guillen Gutierrez G, Felder N, Arriazu-Ramos A, González-Álvarez S, Giusti M, Hardoy J, Almansi F and Kozak D (2026) Assessing the outdoor thermal comfort impact of nature-based urban interventions in dense informal settlement upgrading processes: the case of Barrio 20 in Buenos Aires. *Front. Environ. Sci.* 14:1800415. doi: 10.3389/fenvs.2026.1800415

Assessing the outdoor thermal comfort impact of nature-based urban interventions in dense informal settlement upgrading processes: the case of Barrio 20 in Buenos Aires

Guido Guillen Gutierrez[1,2,3], Natalia Felder[1,2], Ainhoa Arriazu-Ramos[4], Sara González-Álvarez[5], Mariana Giusti[1,2], Jorgelina Hardoy[6]*, Florencia Almansi[6] and Daniel Kozak[1,2]

[1]Universidad de Buenos Aires, Facultad de Arquitectura, Diseño y Urbanismo, Centro de Investigación Hábitat y Energía (UBA, FADU, CIHE), Buenos Aires, Argentina, [2]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina, [3]Administración de Parques Nacionales (APN), Buenos Aires, Argentina, [4]Institute of Technology, Faculty of Engineering, University of Deusto, Bilbao, Spain, [5]Department of Urbanism and Architectural Representation, University of Valladolid, Valladolid, Spain, [6]Instituto Internacional de Medio Ambiente y Desarrollo, IIED-América Latina, Buenos Aires, Argentina

Introduction: The intensification of Urban Heat Islands (UHIs) is increasing urban thermal risk, with heat-related impacts unevenly distributed across populations. In informal settlements, precarious infrastructure, high occupancy densities and limited access to green spaces often converge. Under these conditions, heat stress is frequently experienced as everyday thermal discomfort and remains a persistent yet under-recognised threat to well-being and public health, receiving limited attention in both policy and practice. In this context, spatial design plays a central role in enhancing outdoor thermal comfort, with Nature-based Solutions (NbS) emerging as key strategies for climate mitigation and adaptation. However, evidence remains limited on how vegetation and shading configurations translate into measurable thermal performance at the micro-urban scale, particularly in Latin American informal-settlement upgrading contexts.

Methods: This study examines the contribution and limitations of NbS for outdoor thermal comfort within an informal-settlement upgrading process in Buenos Aires, Argentina. The analysis focuses on two pedestrian passageways, Teresa Rodríguez and Eva Estela Carrizo, in Barrio 20, currently undergoing a comprehensive re-urbanization process. As part of a climate-focused research-action initiative, both passageways were subject to pilot NbS interventions co-designed through participatory processes. While sharing a similar southeast -northwest orientation, they differ markedly in morphology, spatial configuration and urban origin, enabling a comparative assessment of NbS performance under contrasting conditions. Outdoor thermal comfort was assessed through microclimatic simulations and quantified using the Universal Thermal Climate Index (UTCI) across three scenarios: a pre-intervention baseline, a current post-intervention scenario, and a desirable medium-term future scenario incorporating vegetation growth and further NbS strategies. Simulations were conducted under both typical summer conditions and extreme heatwave events.

Results: Results indicate that NbS can substantially reduce pedestrian-level thermal stress, particularly under extreme heat conditions. While post-intervention effects differ between the two passageways, future-oriented scenarios reveal substantial cooling potential, reaching the UTCI category No Heat Stress under typical summer conditions and Moderate Heat Stress during heatwaves.

Discussion: These findings provide comparative evidence to inform urban planning practices and the revision of regulatory frameworks in informal-settlement upgrading processes. In doing so, they highlight that NbS performance is context-dependent, reflecting the combined influence of morphological and climatic conditions as well as institutional and socio-cultural factors, such as community acceptance. This also underscores the role of microclimatic simulation as a decision-support tool in advancing climate-responsive and equity-oriented urban transformation.

KEYWORDS

blue-green Infrastructure, informal settlements, microclimatic simulation models, nature-based solutions, outdoor thermal comfort, urban heat Islands, UTCI

1 Introduction

1.1 Thermal vulnerability in informal urban settlements

In a context of growing urbanization and climate change, cities face significant challenges in terms of livability, public health and energy efficiency (UN-Habitat, 2024). Climate change is increasing the frequency, intensity and duration of extreme heat events worldwide, posing growing risks to human health, ecosystems and urban systems (Akinsanola et al., 2025; Arrighi et al., 2025; IPCC, 2023). One of the most critical phenomena associated with these processes is the intensification of Urban Heat Islands (UHIs), characterized by higher temperatures in densely built areas compared with rural or peri-urban zones. During extreme heat waves, UHIs exacerbate thermal stress–particularly as experienced through everyday thermal discomfort–and associated morbidity (Aké Turriza and Rivera-Arriaga, 2025; Santamouris, 2020; Tapia, 2022). Thermal discomfort is therefore recognized as a key environmental determinant of human health and wellbeing (Arrar et al., 2024).

In informal settlements, precarious infrastructure and services, together with high occupancy densities and limited access to public green spaces, heighten residents' exposure to extreme heat and climate-related risks (Revi et al., 2014). In these contexts, heat stress is further amplified by energy poverty and thermally inefficient housing, limiting households' ability to maintain safe indoor conditions during hot periods. Despite its relevance, heat stress often remains as a "silent risk" in these vulnerable communities, receiving limited attention in both policy formulation and urban-scale practice, where people perceive the increase of heat without being explicitly linked to climate change and its worsening (Arrighi et al., 2025; Zheng et al., 2026). Yet across Latin America, informal settlements remain a critical blind spot in urban climate strategies, despite their scale, exposure and the disproportionate burdens borne by low-income residents (Gertner and Goytia, 2025). Therefore, recognizing the unequal distribution of UHI-related impacts and their interaction with socio-spatial vulnerabilities is essential for advancing climate-responsive urban transformation.

Urban space design plays a key role in enhancing urban thermal comfort, with Nature-based Solutions (NbS) emerging as fundamental mitigation and adaptation strategies to climate change. The integration of vegetation and water-sensitive design into urban structure can offer combined environmental, social, and economic benefits (Costadone and Zhang, 2025; Majidi et al., 2019): factors such as tree shade, plant evapotranspiration, and the capacity of vegetated soil to infiltrate water and buffer heat help mitigate UHIs and improve the thermal comfort of public spaces (Soltanifard and Amani-Beni, 2025). When properly planned, vegetation-based interventions can reduce pedestrian-level air temperatures by 1.5 °C–2.5 °C (Bowler et al., 2010; Ji et al., 2025; Knight et al., 2021; Mansoldo et al., 2024).

1.2 UTCI-based microclimatic simulation for urban thermal comfort assessment

Thermal comfort results from the interaction between individuals' physiological, psychological, and cultural conditions, and a range of environmental, meteorological, and urban morphological factors. Its assessment provides a basis for evaluating the effects of climate on people's quality of life (Smith and Henríquez, 2019).

Accordingly, the Universal Thermal Climate Index (UTCI) has been widely adopted as a biometeorological metric for assessing outdoor thermal stress across a broad range of climatic conditions (Jendritzky et al., 2012; Błażejczyk et al., 2013; Bröde et al., 2013). It expresses thermal stress as an equivalent temperature (°C) derived from an advanced thermoregulatory model that integrates air temperature, humidity, wind speed and mean radiant temperature under standardized assumptions of activity and clothing insulation. Resulting values are classified into heat and cold stress categories according to expected physiological responses, as shown in Table 1.

TABLE 1 UTCI categories.

UTCI (˚C)	Stress category
Above +46 ˚C	Extreme heat stress
38 ˚C–46 ˚C	Very strong heat stress
32 ˚C–38 ˚C	Strong heat stress
26 ˚C–32 ˚C	Moderate heat stress
9 ˚C–26 ˚C	no thermal stress
0 ˚C–9 ˚C	Slight cold stress
−13 ˚C to 0 ˚C	Moderate cold stress
−27 to −13 ˚C	Strong cold stress
−40 to −27 ˚C	Very strong cold stress
Below −40 ˚C	Extreme cold stress

Heat stress categories according to the UTCI index. Prepared by the author based on data from the European Environment Agency (2020).

Compared with other thermal indices, UTCI has demonstrated higher sensitivity to changes in ambient parameters such as solar radiation and wind speed, capturing temporal and spatial variability more effectively than traditional indices (Błażejczyk et al., 2012). This sensitivity makes it particularly suitable for urban-scale microclimatic assessments and the evaluation of nature-based interventions such as vegetation and shading strategies, where radiative and aerodynamic effects are key drivers of outdoor thermal comfort.

Microclimatic simulation tools have become key instruments for assessing urban thermal comfort, predicting heat stress scenarios, and validating mitigation interventions such as NbS. Among the most widely used platforms is Rhinoceros–Grasshopper, which is employed in this study due to its flexible environment for urban microclimatic simulation. Its integration with Ladybug Tools allows the import of real climatic data (EPW), solar radiation analysis, the modeling of complex urban geometries and materials, and the estimation of pedestrian-level thermal comfort indicators, such as UTCI.

A growing body of recent research has applied these microclimatic simulation tools to evaluate vegetation-based interventions in diverse urban contexts. Studies using ENVI-met have demonstrated the capacity of trees, green façades and small-scale vegetated elements to reduce pedestrian-level thermal stress, with reported UTCI reductions ranging from moderate average values to localised peak differences of several degrees during extreme heat conditions (Bajšanski et al., 2015; Sabrin et al., 2023; Kozak and Lipecki, 2025). Similarly, applications of Grasshopper and Ladybug have shown that variations in street geometry, tree arrangement and canopy density can lead to UTCI reductions of up to 5 ˚C–6 ˚C in shaded areas, highlighting the sensitivity of thermal comfort outcomes to urban morphology and solar exposure (Bajšanski et al., 2015; Nicholson et al., 2024).

At the local level in Latin America, research addressing outdoor thermal comfort in vulnerable and marginalised communities remains highly incipient. Oraiopoulos et al. (2026) are among the first to integrate ground-based microclimatic measurements with simulation-based UTCI assessments to evaluate the role of trees, shaded routes and low-cost shading structures in mitigating heat stress in an informal settlement in Lima, Peru. Results indicate that, while small green spaces may have limited effects on air temperature, their contribution to reducing thermal stress–particularly through solar radiation control–is substantial, underscoring the relevance of scalable shading strategies in dense and resource-constrained contexts.

Despite ongoing challenges related to data availability, morphological heterogeneity and model calibration in informal settlements, the geometric flexibility and relatively low computational demands of the Grasshopper environment make it a suitable tool for these contexts. Parametric models enable rapid scenario adaptation based on three-dimensional surveys and allow for the evaluation of microclimatic impacts across different times of day and thermal conditions. Moreover, the visualisation of spatial UTCI patterns facilitates the integration of microclimatic analysis with urban design and policy discussions focused on climate adaptation and environmental justice.

1.3 Research objectives and contribution of the study

While the benefits of NbS are increasingly documented, knowledge gaps persist regarding their implementation. One key gap concerns the relationship between vegetation design and thermal performance (Sodoudi et al., 2018). This lack of documentation can hinder cost-benefit evaluation and replicability, both key factors in decision-making, especially in contexts of extreme vulnerability and constrained budgets.

Bridging this gap requires articulating microclimatic assessment tools with conceptual and methodological frameworks that, while informed by experiences in different contexts, are tailored to local particularities and capable of generating contextualized evidence (Dobbs et al., 2019). As noted, parametric simulation environments such as Rhinoceros–Grasshopper, combined with UTCI-based evaluation, enable scenario-based exploration of alternative design configurations. Beyond their analytical capacity, these tools also support the comparison of intervention strategies under different morphological and climatic conditions, thereby facilitating the alignment of thermal comfort objectives with urban design in upgrading processes.

Against this background, the main objective of this paper is to evaluate the impact of NbS interventions on urban thermal comfort in two pedestrian passageways in Barrio 20, an informal settlement in the city of Buenos Aires undergoing a participatory upgrading process. The selected passageways differ in morphology and urban genesis. Using a microclimatic simulation model, the study examines the contributions, limitations, and potential of NbS interventions to improve outdoor thermal comfort in contexts of urban informality.

The specific objectives are to:

- Quantify the impact of the implemented improvements on urban thermal comfort by comparing the Universal Thermal Climate Index (UTCI) across three scenarios: (S1) the pre-intervention baseline; (S2) the current post-intervention scenario; and (S3) a desirable medium-term future scenario incorporating vegetation growth and additional NbS strategies based on established design criteria.
- Assess when NbS interventions are most effective in improving urban thermal comfort during summer, by analysing and quantifying variations in UTCI across

FIGURE 1
Plan view and an aerial photograph of Barrio 20, with the newly completed Papa Francisco housing project in the foreground. Image Credit: GCBA (left); IVC (right).

different times of the day and under representative summer conditions (typical and extreme days).

- Explore the potential gains in urban thermal comfort achievable through enhanced NbS strategies, with the aim of informing urban planning practice and supporting the revision of regulatory frameworks in informal settlement upgrading processes.

2 Materials and methods

2.1 Case study

Barrio 20 is a historic informal settlement located in Commune 8 in the south of the city of Buenos Aires, Argentina (Figure 1). According to the most recent census conducted in 2016, the neighbourhood covers 48 ha with 27,990 people living in 4,559 housing units. This corresponds to an estimated population density of approximately 58,300 inhabitants per km^2 - nearly four times the citywide average for the city (around 15,161 inhabitants per km^2 in 2022). Census data further indicates that 14% of housing units experienced critical overcrowding (compared with 1.5% citywide) while 45% were classified as being in regular or poor condition. In terms of basic services, only 14% of dwellings had formal access to electricity, 25% were connected to the sewer system and 95% relied on informal water connections (IVC, 2016).

In 2016, Barrio 20 became the focus of a large-scale state-led upgrading programme: The Comprehensive Re-urbanization Project (Proceso Integral de Reurbanización, PIRU), implemented by the Institute of Housing of the City of Buenos Aires (Instituto de Vivienda de la Ciudad, IVC) under the framework of Law N° 5.705. PIRU aims to achieve the social and urban integration of the neighbourhood through a gradual and participatory process combining new housing construction, infrastructure provision, public space creation, street opening, and land tenure regularization. A central feature of PIRU is its strong participatory platform, articulated through multiple formal mechanisms that enable residents to take part in decision-making processes related to urban design, relocation, land subdivision, and tenure arrangements (Almansi et al., 2020).

During the first 6 years of implementation, PIRU enabled the relocation of 1,416 families to newly built housing units, which in turn allowed for the demolition of around 16% of the pre-existing housing stock within the consolidated urban fabric. These actions facilitated the opening of four streets and ten pedestrian passageways and enabled the execution of more than 70% of the main infrastructure networks (water supply, sewerage, stormwater drainage and electricity), as well as the formal connection to the public water network in part of the neighbourhood (Reverter et al., 2023). Although the re-urbanization process remains unfinished, the interventions implemented to date define the spatial conditions analysed in this article.

While the re-urbanization process (PIRU) was ongoing, Barrio 20 was incorporated into the Transformative Urban Coalitions (TUC). TUC is a 6-year initiative (2021–2026) financed by the International Climate Initiative (Internationale Klimaschutzinitiative, IKI) of the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) and coordinated locally by the International Institute for Environment and Development - Latin America (Instituto Internacional de Medio Ambiente y Desarrollo - América Latina, IIED-AL).

Building on the spatial and institutional transformations enabled by PIRU, the TUC project introduced a climate action and NbS agenda. Through participatory workshops, NbS interventions in public spaces were defined with the aim of extending the benefits of planned actions to a wider number of residents (Hardoy et al., 2022). In this context, the Urban Laboratory for Barrio 20 (UL-BA) was established as a participatory platform that coordinated neighbourhood residents, technical and academic professionals, and public institutions throughout all the stages of co-design, decision-making, and implementation.

Creating space for natural environments in such a densely occupied neighborhood, where open space is scarce and constantly contested, posed a significant challenge. Addressing this required interventions to adopt flexible design strategies that responded to both spatial constraints and consensus-based requirements: whenever possible, new trees were planted; when space was insufficient or unviable, vegetated pergolas or vertical gardens were used instead. In all cases, the proportion of absorbent and semi-permeable surfaces was increased, and native plant species were introduced in open ground, planters or rain gardens.

2.1.1 Study passageways and intervention criteria

Within this framework, this paper examines the impact of NbS interventions in two pedestrian passageways: Teresa Rodríguez (P01) and Eva Estela Carrizo (P02). Both interventions were guided by a shared set of objectives: improving microclimatic conditions and thermal comfort, contributing to carbon capture and the avoidance of emissions, and enhancing the quality and liveability of everyday public spaces through increased urban vegetation (prioritising native species) and the expansion of absorbent and semi-permeable surfaces. Together these effects improve outdoor thermal comfort and help reduce indoor temperatures during the summer, thereby lowering the need for artificial cooling and avoiding associated emissions.

Beyond these material objectives, the interventions also sought to promote community collaboration and deliver cultural ecosystem services by enhancing landscape quality, fostering social interaction and supporting mental wellbeing. More broadly, they aimed to advance a climate action agenda at the neighbourhood scale by supporting shifts in local mindsets and strengthening coalitions of actors engaged in transformative processes. While changes in perception and everyday practices tend to occur gradually, the interventions functioned as tangible demonstrations capable of accelerating these shifts. By contrast, regulatory frameworks proved to be significantly more rigid. As a result, the extent to which these objectives could be implemented differed between the two passageways, reflecting contrasting spatial configurations, regulatory constraints, and the participatory design outcomes.

Although both passageways share a similar southeast-northwest orientation (SE–NW), they differ significantly in terms of urban origin, morphology and spatial configuration. P01 is located in an area of recent formal urbanization and has a wider and more regular layout. By contrast, P02 is a recently created passageway situated within Barrio 20s historic urban core, characterized by a narrow, irregular alignment and few façade openings. These contrasting conditions–together with household needs, existing infrastructure layout and applicable regulations–shaped the design strategies adopted in each case. Taken together, the two cases allow a comparative assessment of how urban form, environmental characteristics and participatory processes interact in the design and implementation of NbS in informal-settlement upgrading contexts.

2.1.2 Passageway teresa rodríguez (P01)

P01 is located within the Papa Francisco housing complex, an area resulting from a more recent and planned phase of Barrio 20s re-urbanization process. The passageway presents a relatively wide and regular cross-section, with a clear and continuous alignment and a largely homogeneous configuration along its length. Morphologically, it is comparatively open, with an average canyon width of 10 m and surrounding building heights of 12 m (H/W = 1.2), resulting in a high sky view factor (SVF = 0.85, computed at 1.5 m). Although it functions primarily as a pedestrian route and cannot be used as a through street due to level differences at its ends, applicable regulations establish a minimum clear width of 4 m (Agencia de Planificación, 2017). This requirement structured the overall layout of the intervention, defining circulation space and delimiting the placement of NbS elements.

Under these conditions, the intervention strategy in P01 combined multiple NbS components. Ground-level interventions included the replacement of impermeable paving with permeable and planted surfaces, while above-ground elements incorporated street trees and a vegetated pergola designed to provide shading along the pedestrian path. In the baseline scenario (S1), the passageway was modeled as fully impermeable pavement with no vegetation, consistent with the condition still observed in other non-intervened pedestrian passages in Barrio 20. The as-built scenario (S2) represents the implemented configuration, while the future scenario (S3) incorporates additional NbS elements, including increased tree canopy dimensions and the planting of additional trees to create a continuous overhead tree canopy, forming a "green tunnel" that provides uninterrupted shading along the passageway. This scenario also includes an expansion of permeable surfaces, achieved by reducing the free circulation space to a width that is not strictly constrained by the minimum regulatory requirement, but aligns with the passageway's actual patterns of use, while still ensuring bidirectional pedestrian movement and allowing for vehicular access when required. Figures 2, 3 illustrate the spatial configuration of P01 and the changes introduced across the three analysed scenarios, highlighting the progressive integration of vegetation and shading structures.

2.1.3 Passageway eva estela carrizo (P02)

P02, by contrast, is located within the historic core of Barrio 20 and reflects the incremental and self-built urbanization processes characteristic of older informal fabrics. The passageway is significantly narrower and more irregular than P01, with variable widths and a reduced sky opening. Morphologically, the average canyon width is 3.8 m, while the mean surrounding building height is 6.9 m (range 2.5–12 m), resulting in a more confined geometry (H/W = 1.8) and markedly reduced sky exposure (SVF = 0.41, computed at 1.5 m).

In addition, the space remains morphologically open-ended, as dwellings continue to evolve. During the participatory design process, a larger number of vertical supports and vegetated elements had initially been proposed. However, residents expressed concerns that fixed structures could restrict future façade modifications, such as windows and doors[1]. As a result, the final design reflects a negotiated outcome with fewer vertical elements than originally envisioned.

Additional constraints affected the feasibility of horizontal shading systems. Regulations imposed by utility providers–particularly those related to water and sanitation infrastructure–require both a minimum clear width and an unobstructed aerial plane (Agencia de Planificación, 2017). These requirements significantly limited the implementation of overhead shading solutions, further narrowing the range of NbS measures that could be implemented within the Urban Laboratory framework.

These characteristics imposed substantial constraints on both the design and implementation of NbS interventions, which shaped a distinct set of design responses. Green surfaces were expanded by replacing sections of concrete pavement with planted areas, and vertical greening systems supported by lightweight metal structures were attached to existing façades. Where space allowed, a limited number of trees were incorporated.

As in P01, scenario S1 represents a fully impermeable, non-vegetated baseline, while S2 represents the implemented/as-built configuration. S3 reflects a desirable medium-term configuration that enhances vegetation cover and shading: an urban grove was introduced in a section of the passageway whose dimensions and patterns of use allowed for tree planting, while a vegetated pergola was installed along the entire length of the passageway at a height that does not interfere with the

---

[1] In line with PIRU's framework, while IVC delivers the passageway with paving, infrastructure, lighting and plastered facades following street openings, any subsequent facade opening remains a decision for residents.

FIGURE 2
P01 Scenario S1 - pre-intervention no vegetation (left) and S2 - current state with vegetation (right). Image Credit: Kozak 2025.

operation and maintenance of existing infrastructure. Vegetation growth is additionally represented through increased tree canopy dimensions. Figures 4, 5 illustrate the spatial layout and NbS configurations adopted in P02 across the analysed scenarios.

Table 2 summarises the main morphological descriptors of the two analysed passageways.

2.2 Climate data and definition of thermal conditions

Buenos Aires (34°35′59″S, 58°22′55″W) has a humid subtropical climate (Cfa) according to the Köppen–Geiger classification (Beck et al., 2018), characterised by warm, humid summers and cool winters. In summer, the mean air temperature is 24.4 °C, and typical maximum temperatures can reach 36.8 °C.

Weather inputs were obtained from an EnergyPlus Weather (EPW) file and used consistently across all passageways and urban scenarios. The EPW provides hourly air temperature, relative humidity, global radiation, wind speed and wind direction. Specifically, meteorological data were taken from a Typical Meteorological Year (TMYx, 2009–2023) for Buenos Aires-Central Observatory (WMO 875850), provided in EPW format by Climate.OneBuilding.org (Lawrie and Crawley, 2022). The meteorological station closest to Barrio 20 is the Buenos Aires Central Observatory (Servicio Meteorológico Nacional), located approximately 7.5 km from the study area (SMN, 2018).

While we use a city-scale EPW file to ensure consistent boundary conditions across all passageways and scenarios, no site-specific calibration was performed. Because the representative days were extracted from a Typical Meteorological Year dataset (TMYx) rather than a specific observed year, a direct day-by-day comparison against the local monitoring system referenced in this project is not meaningful within this workflow. Accordingly, results are interpreted primarily in comparative terms (inter-scenario ΔUTCI under identical forcing). Existing neighbourhood-scale monitoring in Barrio 20 reports substantial microclimatic contrasts (e.g., sun–shade differences in air and surface temperatures), reinforcing the need for future calibration using co-located measurements. (Agencia de Protección Ambiental, 2020).

Based on the EPW, two thermal conditions were defined to represent contrasting summer situations: (i) a typical summer day, with temperatures close to the period's mean values, and (ii) an extreme heat day (heatwave conditions), with particularly high temperatures. January was selected as the reference month because it concentrates the highest mean temperatures. The typical day was defined as the day whose hourly air-temperature profile most closely matched the month's mean profile. Under this criterion, 28 January was selected as the most representative. The extreme day was defined as a day with severe maximum temperatures; accordingly, 21 January was selected, as it approximates heatwave conditions recorded in the city[2].

Simulations were run at an hourly time step, covering the period 05:00–20:00 (local time). For cross-scenario comparison, representative hours of the diurnal cycle were selected: 09:00, 12:00, 13:00, 14:00 and 17:00.

2.3 3D modeling of the passageways

As previously introduced, for each passageway, three urban scenarios were modeled: S1 (pre-intervention), representing the baseline condition without vegetation and without permeable ground surfaces; S2 (as built/current), representing the NbS already implemented on site; and S3 (mid-term desirable)[3], representing vegetation growth plus additional NbS elements. S3 projects the mean growth rate of the selected species over a 20-year horizon, adjusted to the specific environmental conditions of Barrio 20[4].

---

[2] In the City of Buenos Aires, heatwaves are defined according to the Argentine National Meteorological Service (SMN) criteria, as periods of at least three consecutive days in which minimum temperatures exceed 22 °C and maximum temperatures exceed 32.3°C.

[3] Scenario S3 does not represent a predictive or immediately implementable design outcome. Rather, it constitutes a climatically optimized reference scenario intended to explore the upper bound of microclimatic improvement achievable through NbS under the given morphological conditions. By relaxing current regulatory and service-related constraints, S3 serves as an analytical benchmark to support discussion on design potential and the implications of existing urban standards for heat adaptation.

[4] Growth rates were estimated based on technical input provided by APrA (Agencia de Protección Ambiental), the agency responsible for environmental management in Buenos Aires. According to APrA's expertise, tree growth in informal settlements tends to occur at lower rates due to constrained soil conditions, limited rooting volume and other environmental factors.

FIGURE 3
Comparative plan views of the NbS interventions in the Passageway Teresa Rodríguez (P01) across the three analyzed scenarios.

The 3D geometric model of the passageways was developed in Rhinoceros 7 and Grasshopper, using the environmental-analysis plug-in Ladybug Tools to link geometry with climate data and compute microclimatic variables (Sadeghipour Roudsari et al., 2013). The model represents the street-canyon configuration and the elements relevant to the pedestrian-level radiative balance and shading (facades, roofs and ground surfaces), together with the NbS components defined for each urban scenario.

Base geometry was constructed from re-urbanization process documentation (PIRU drawings and IVC records), complemented with photographic surveys and site visits conducted within the Barrio 20 Urban Laboratory. Building envelopes were digitised

FIGURE 4
P02 Scenario S1 - pre-intervention no vegetation (left) and S2 - current state with vegetation (right). Image Credit: Giusti 2021; Hardoy 2023.

from these sources. Fixed architectural elements such as balconies and overhangs were explicitly modeled due to their direct influence on shading and, consequently, on mean radiant temperature. In contrast, movable or temporary elements were not included, given their temporal variability and because they do not constitute stable urban modifications attributable to the evaluated scenarios.

NbS interventions were represented using simplified geometries consistent with their microclimatic role: (i) trees as cylindrical trunks with spherical or ellipsoidal canopies, (ii) vertical greening as vegetated surfaces attached to façades, (iii) pergolas as horizontal surfaces supporting a vegetated layer where applicable, and (iv) permeable areas/planters explicitly distinguished from impermeable paving. For the as-built scenario (S2), tree canopy dimensions and crown-base height were set based on photographic records and site visits, to reflect the implemented condition at the time of survey.

2.4 Physical parameters and optical properties of surfaces and vegetation

To represent pedestrian-level radiative exposure and shading, the model differentiated between (i) opaque building envelopes (façades and roofs), (ii) ground surfaces (impermeable pavement and permeable ground), and (iii) vegetated elements associated with NbS interventions. Urban-surface properties were implemented in Honeybee/EnergyPlus (U.S. Department of Energy, 2022) through material and construction definitions that include thermophysical parameters (layer thickness, conductivity, density and specific heat) and radiative properties *via* absorptance terms. The constructions and radiative properties effectively used in the simulations are reported in Table 3.

For opaque materials, solar reflectance was derived from the EnergyPlus solar absorptance ($\rho\_solar = 1 - \alpha\_solar$), and longwave emissivity was represented by thermal absorptance. The adopted reflectance values are consistent with commonly reported ranges for urban materials, in which mineral pavements and urban soils typically exhibit intermediate-to-low reflectance depending on material type and ageing (Anand et al., 2021; Sanjuán et al., 2022; Santamouris, 2014; Sen and Roesler, 2019). Reported U-factors were extracted from Honeybee. For ground-bound surfaces, u-factor is included as a diagnostic indicator of the adopted ground material representation and should not be interpreted as a conventional air-to-air U-value (Table 3).

Scenario S1 represents the pre-intervention condition and includes no vegetated ground and no above-ground NbS elements (i.e., fully impermeable pavement). Permeable ground in the implemented and enhanced scenarios (S2 and S3) was represented using a vegetation EnergyPlus object, which includes a simplified soil layer and moisture-related parameters. Across scenarios, NbS interventions are reflected in changes in the spatial extent of each ground-surface category and the addition of vegetated elements; material properties assigned to each category were held constant, while their coverage and location varied between scenarios.

Vegetation above ground (trees, vegetated pergolas and vertical greening) was modeled as porous shading geometry rather than as energy-simulated vegetated constructions. To maintain a conservative estimation of the benefits, the evapotranspirative cooling effect on air temperature was not explicitly included in the simulation. Therefore, the calculated UTCI improvements rely primarily on the reduction of Mean Radiant Temperature (MRT). Accordingly, Ta and RH inputs for UTCI were prescribed from the EPW to maintain consistent forcing across scenarios; evapotranspiration-related plant–air coupling effects (including local humidity changes) were not modelled explicitly. Trees were parameterised by total height, crown-base height and crown dimensions; pergolas and vertical

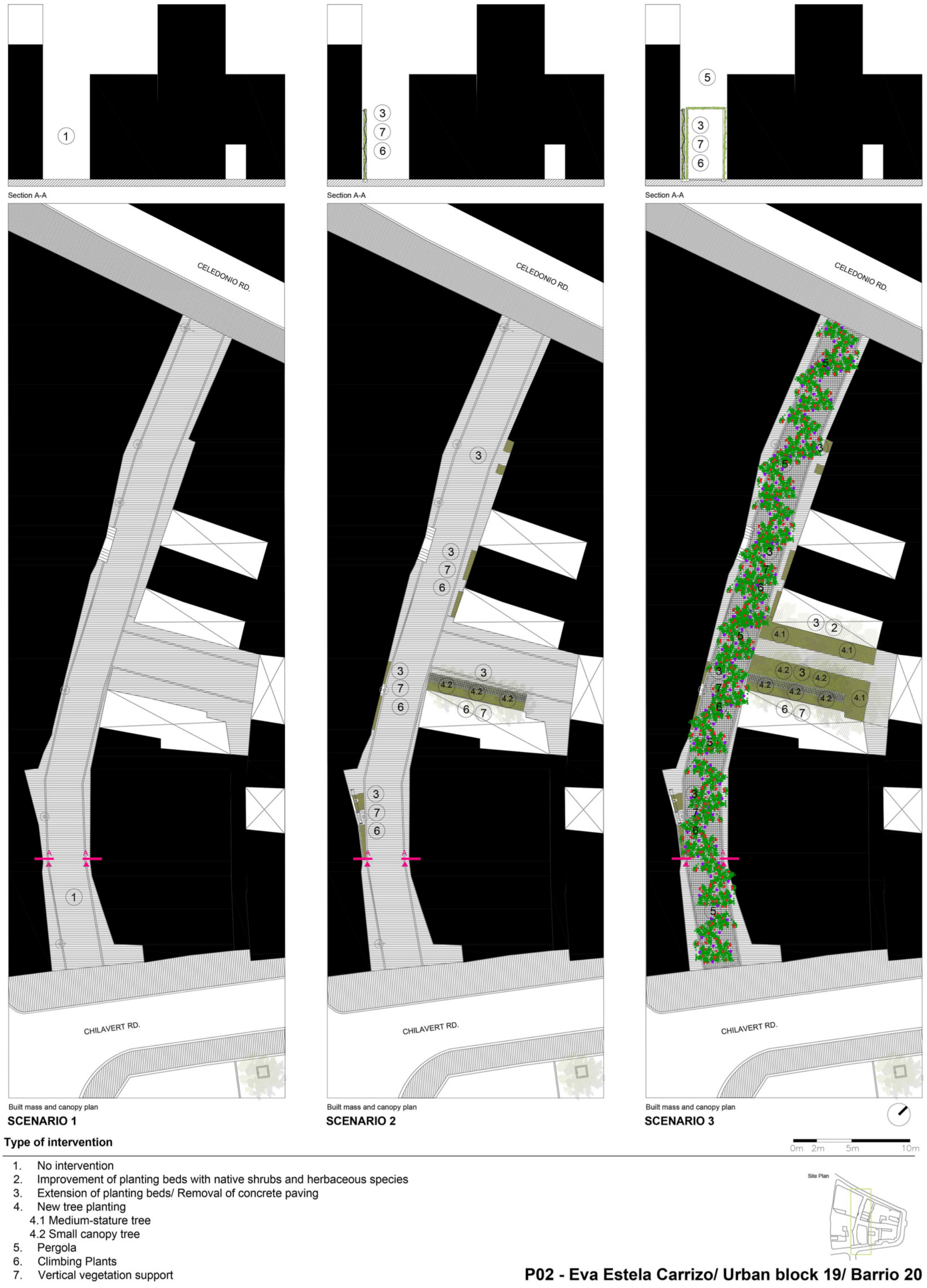

FIGURE 5
Comparative plan views of the NbS interventions in the Passageway Eva Estela Carrizo (P02) across the three analyzed scenarios.

greening were represented as uniform-thickness vegetated layers. In all cases, these elements were implemented as Honeybee shades with an effective solar transmittance (τ) representing canopy openness/foliage density and controlling the fraction of incident solar radiation transmitted through the element (Konarska et al., 2014; Pérez et al., 2014; Wu et al., 2025). In EnergyPlus, τ was implemented as a constant shade transmittance for the corresponding vegetation-layer geometry (held constant across reporting hours and scenarios). This approach isolates the shortwave radiative shading effect on Tmrt/UTCI and ensures comparability across scenarios. Table 4 summarises the τ values used for each NbS element, and Table 5 reports the tree geometry

TABLE 2 **Morphological descriptors of the analysed passageways.**

Parameter	Passageway teresa rodríguez (P01)	Passageway eva estela carrizo (P02)
Orientation	SE–NW	SE–NW
Average canyon width (W)	10 m	3,8
Average building height (H)	12m	6,9 (range from 2,5–12m)
Aspect ratio (H/W)	1,2	1,8
Avg. Sky view factor (SVF)	0,85	0,41

Average canyon width (W) and mean building height (H) were computed from the simplified geometry of each passageway; for P02, the observed height range is reported to reflect heterogeneity. SVF was computed at 1.5 m to approximate standing eye-level exposure, whereas UTCI was evaluated at 1.10 m as the pedestrian comfort assessment height

TABLE 3 **Surface constructions and radiative properties used in the simulations.**

Element	E+/HB object	Layer build-up	Total thickness (m)	U-factor u_fac_si (W/m^{2}K)	ε_LW	ρ_solar (albedo)
Exterior wall	Opaque construction	Plaster (0.025 m) + Hollow brick (0.18 m) + Plaster (0.025 m)	0.23	2,44	0.90	0.30 (sol_abs = 0.70)
Roof	Opaque construction	Metal sheet (0.004 m) + Pine board (0.025 m)	0.029	3,95	0.90	0.55 (sol_abs = 0.45)
Ground – pavement	Material	Concrete pavement (0.20 m)	0.20	3,57	0.90	0.35 (sol_abs = 0.65)
Ground – permeable	Material: RoofVegetation (+soil)	Vegetation: Height 0.20 m; soil: 0.10 m	0.10 soil (+0.20 plant)	2,24	leaf 0.95/ soil 0.90	leaf 0.22/soil 0.30

adopted for the as-built (S2) and design of (S3) scenarios (Burgueño and Nardini, 2019).

2.5 Microclimatic simulation, comfort metric, and post-processing

UTCI was computed using the HB UTCI Comfort Map component in Ladybug Tools v1.9. Air temperature and relative humidity were taken from the EPW file, while wind speed was overridden to a constant 0.1 m/s for all scenarios. Solar radiation was used to estimate mean radiant temperature at pedestrian level for each grid point and each simulated hour. Wind speed was fixed at a constant 0.1 m/s across all scenarios to represent near-calm, worst-case heat-stress conditions at pedestrian level and to ensure cross-scenario comparability, thereby isolating the radiative effect of NbS on the outdoor thermal environment. This choice reflects the significant wind attenuation and flow decoupling characteristic of dense, irregular urban fabrics, where meteorological station data (typically referenced at 10 m height) is not representative of sheltered pedestrian-level conditions. The selected value is consistent with "still air" thresholds used in thermal comfort standards (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023). If higher pedestrian-level wind speeds were assumed, absolute UTCI values would be expected to decrease and the magnitude of radiative-driven ΔUTCI to be attenuated, while the direction and timing of inter-scenario differences during peak solar hours would be expected to remain.

In the HB UTCI Comfort Map workflow, surface temperatures for the modeled geometry are obtained via EnergyPlus, while radiative exchange at sensor points is computed using Radiance. Longwave mean radiant temperature is derived by combining EnergyPlus surface temperatures with Radiance-derived spherical view factors between each sensor point and surrounding surfaces; for outdoor sensors, the sky contribution is weighted by each sensor's sky view and EPW sky temperature. Shortwave mean radiant temperature is calculated using a Radiance-based enhanced two-phase method, which resolves direct solar exposure through ray-tracing from each sensor point to the solar position. In this study, the analysis was restricted to outdoor conditions; ground and surrounding context were modeled as thermal zones, enabling the calculation of radiative exchange using their simulated surface temperatures rather than assuming outdoor context surfaces at EPW air temperature.

Simulations were run at an hourly time step between 05:00 and 20:00. Outdoor thermal comfort was evaluated on a regular grid of points covering the footprint of each passageway, generated on the horizontal ground plane with 0.5 m spacing at a height of 1.10 m above ground, consistent with commonly adopted pedestrian-level evaluation heights for thermal-environment characterization (International Organization for Standardization, 1998). Here we report UTCI (°C); Ta and RH were taken from the EPW for each hour, so spatial variability in UTCI across grid points is primarily driven by MRT differences computed from shading/radiative exchange. This resulted in 2,080 points for P01 and 4,208 points for P02. For reporting and cross-scenario comparison, results are presented for 09:00, 12:00, 13:00, 14:00, and 17:00.

Hourly UTCI values (06:00–20:00) extracted at each spatial measurement point were analysed using a linear mixed-effects

TABLE 4 **Optical properties and effective solar transmittance (τ) assigned to NbS vegetation elements across scenarios.**

NbS element	Type	Albedo ρ	Emissivity ε	Effective solar transmittance τ	Where it appears
Existing tree (base vegetation)	Tree canopy (porous shading)	0.15	0.95	0.25	P01: S2 and S3. P02: S2 and S3
New tree (curupí/anacahuita)	Tree canopy (porous shading)	0.15	0.95	0.10	P01: S3 (4.2 in S2; 4.1 + 4.2 in S3) P02: Shown as "4 new tree planting"
Climbers/vine	Vertical greening/vegetated layer	0.22	0.95	0.20	P01: S2 and S3 (includes 6). P02: S2 and S3 (includes 6)
Pergola	Horizontal plane with vegetated layer	0.22	0.95	0.20	P01: S2 and S3 (includes 5). P02: S3 (includes 5)

"Where it appears" refers to the scenario diagrams (P01 and P02) and indicates presence by passageway and scenario.

TABLE 5 **Tree geometry adopted for S2 (as built) and S3 (native species) used in the design.**

Species/Class	Total height (m)	Crown-base height (m)	Crown diameter (m)	Scenario
Anacahuita (small canopy tree)	3.2–6.5	1.2–2.3	1.6–2.5	S2
Bauhinia forficata Pezuña de vaca (medium stature tree)	4.0	1.5	2.5	S2
Curupí (medium stature tree)	10.0	3.0	4.0	S3
Anacahuita (small canopy tree)	7.0	0.5	3.0	S3

For S2, values correspond to observed ranges derived from photographic records and site visits. For S3, values derived from Burgueño and Nardini (2019). Crown diameter refers to the overall crown width used for the simplified canopy geometry.

model (LMM) implemented in R software (R Core Team, 2025). Scenarios, hour of the day, and day type were included as fixed effects, together with their interactions. Inter-scenario differences were evaluated through post hoc pairwise contrasts with Bonferroni correction applied to account for multiple comparisons. For each contrast, the estimated mean differences (ΔUTCI, ˚C), 95% confidence intervals, standard errors and adjusted p-values are reported. The statistical significance was set at 0.05.

3 Results

This section presents the results of the microclimatic simulations conducted for the two analysed passageways in Barrio 20. Using city-scale EPW without site-specific calibration, the analysis prioritises relative differences across scenarios under identical boundary conditions**.** Outdoor thermal comfort outcomes are reported in terms of UTCI values and inter-scenario differentials, allowing for a comparative assessment of both the magnitude and temporal persistence of NbS-induced cooling effects. The hourly statistical significance differences analysed highlight how thermal comfort patterns evolve throughout the day under different design configurations and climatic conditions.

To illustrate these patterns and highlight potential differences between the two urban contexts, Figures 6–8 present the results for Passageway P01, whereas Figures 9–11 focus on Passageway P02.

Figure 6 illustrates the diurnal evolution of UTCI values (˚C) across all measurement points in Passageway P01 for a typical summer day and a heatwave day, comparing the three scenarios. Figure 7 presents the hourly UTCI differences between scenarios and if this difference is statistically significant ($p < 0.05$). Table A (Appendix) shows detailed hourly inter-scenario contrasts, including ΔUTCI values, 95% confidence intervals and adjusted p-values. Figure 8 shows the spatial distribution of UTCI in P01 during different hours of the day.

For the typical summer day, the implementation of NbS leads to a progressive reduction in UTCI from S1 to S3. The maximum temperature reduction under typical conditions occurs at 12:00 (Figure 6). While differences between scenarios are negligible during the early morning and late afternoon, a clear cooling effect emerges between 11:00 and 15:00. During this central period of the day, S2 exhibits UTCI values approximately 0.5 ˚C–1.0 ˚C lower than S1, with statistically significant differences observed for all 5 hours ($p < 0.05$). The mid-term desirable scenario (S3) further amplifies this effect, yielding additional UTCI reductions of approximately 1 ˚C–2 ˚C during the same time window.

During a heatwave day, both the magnitude and the temporal persistence of the cooling effect increase substantially across scenarios. The maximum temperature reduction occurs at 14:00, reaching up to 6 ˚C between S1 and S3 (Figure 6). Comparisons among the three scenarios reveal not only larger UTCI reductions at each individual hour, but also an extension of the cooling effect over a longer portion of the day, which is particularly pronounced between 10:00 and 16:00. Within this period, S2 shows UTCI values up to 2 ˚C lower than S1, with statistically significant differences across all seven central hours ($p < 0.05$). The S3 scenario further intensifies this cooling, resulting in additional

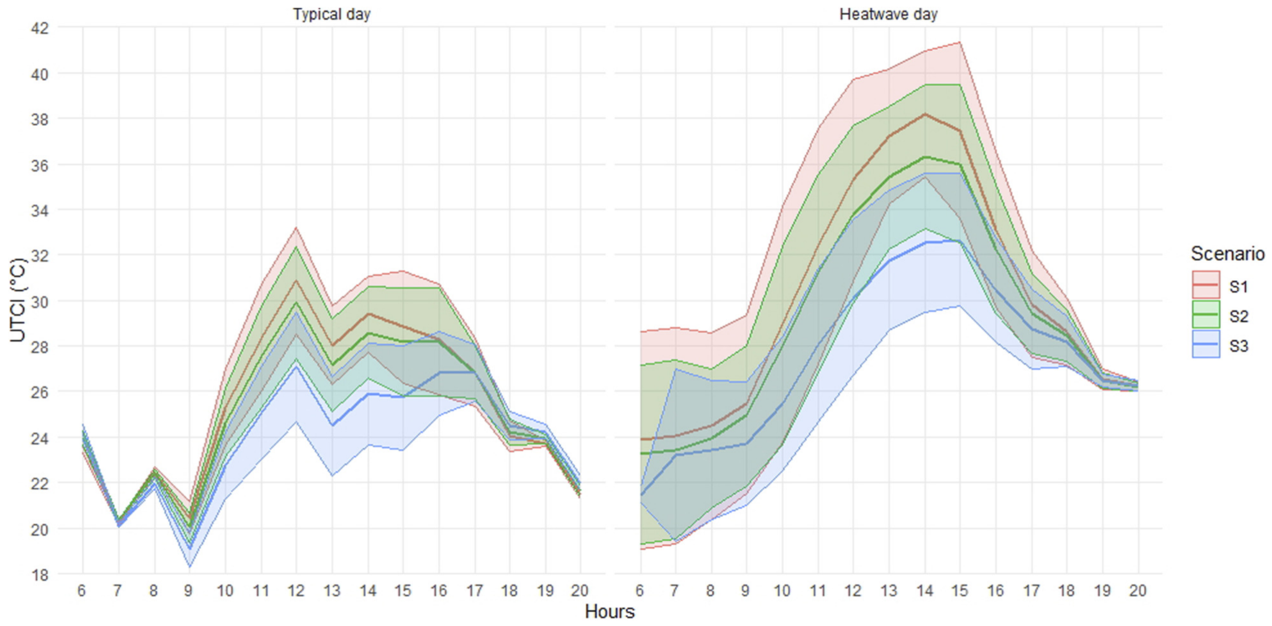

FIGURE 6
Diurnal evolution of UTCI (°C) in P01 for a typical summer day and a heatwave day under the three scenarios.

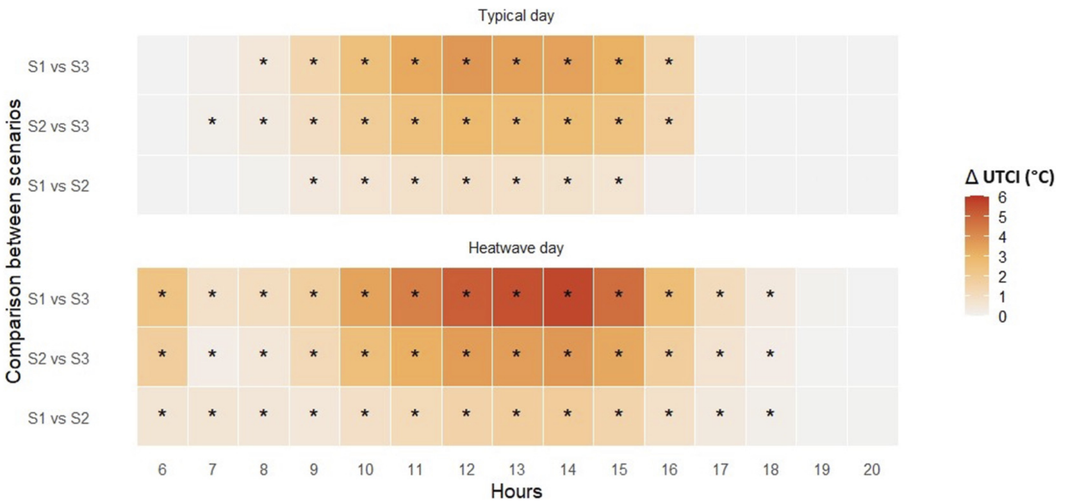

FIGURE 7
Hourly UTCI differences (°C) between scenarios in P01 for a typical summer day and a heatwave day. Asterisks indicate statistically significant differences (p < 0.05).

reductions of approximately 4 °C–6 °C. Consequently, the maximum mean UTCI decreases from 38.1 °C in S1 to 32.4 °C in S3.

Similarly, Figure 9 illustrates the diurnal evolution of UTCI values (°C) across all measurement points in P02 for a typical summer day and a heatwave day, comparing the three scenarios. Figure 10 presents the hourly UTCI differences between scenarios and if this difference is statistically significant ($p < 0.05$). Table B (Appendix) shows detailed hourly inter-scenario contrasts, including ΔUTCI values, 95% confidence intervals and adjusted p-values. Figure 11 shows the spatial distribution of UTCI in P02 during different hours of the day.

In this case, the reduction in UTCI between S1 and S2 is minimal for both day types. However, when comparing S1 and S3, the reduction in UTCI is substantial and statistically significant ($p < 0.05$). The largest reductions occur between 10:00 and 16:00, reaching up to 5 °C on a typical summer day and up to 6 °C on the heatwave day, with peak reductions observed at 13:00 for both day types.

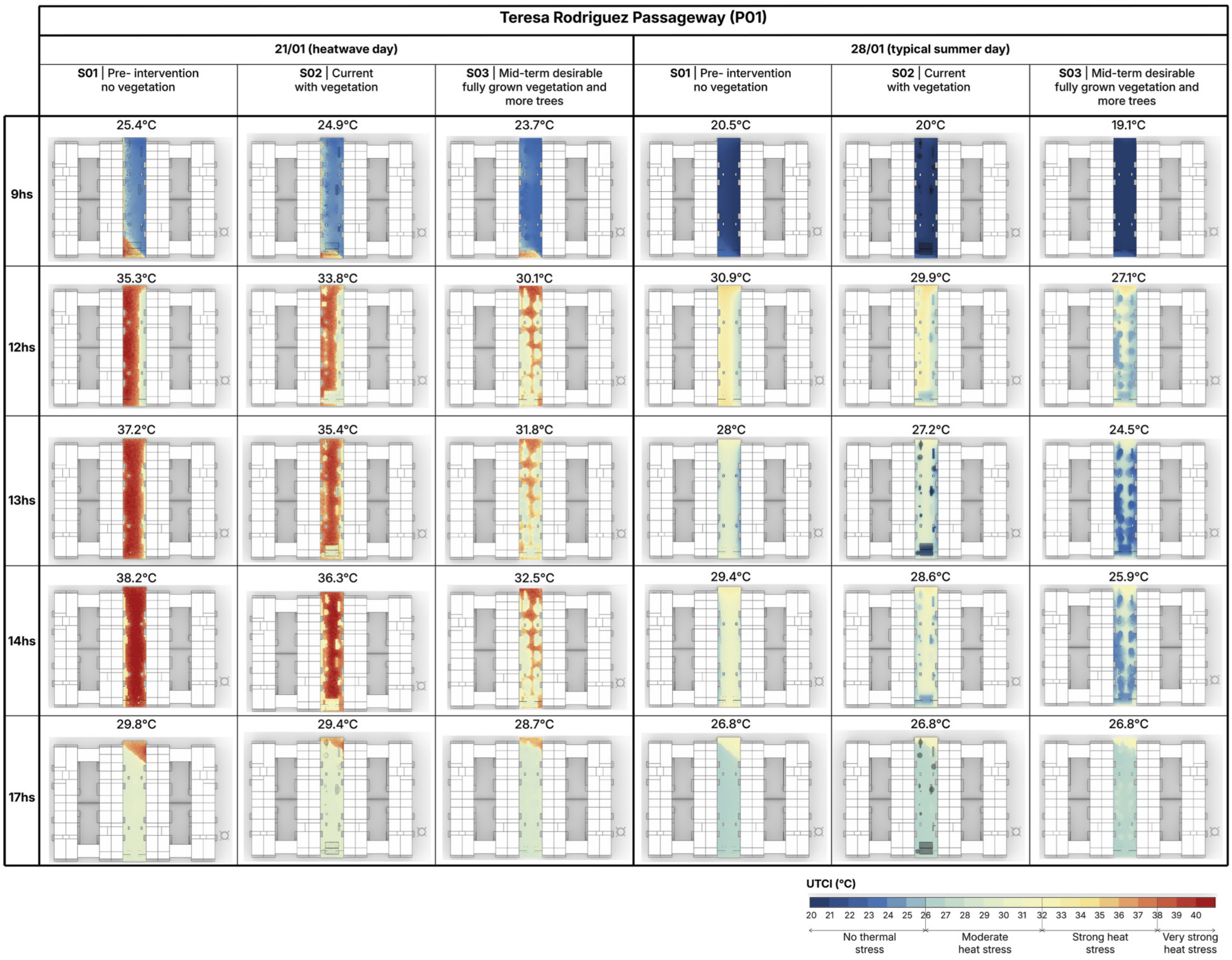

FIGURE 8
Spatial distribution of UTCI (°C) in P01 at selected hours for the three scenarios (S1 - pre-intervention no vegetation; S2 - current state with vegetation; S3 - Mid-term desirable fully grown vegetation and more trees).

A comparative assessment of the two passageways reveals marked differences in both the magnitude and the temporal behaviour of the cooling effects associated with NbS interventions. In P01, the implementation of NbS leads to a clear and progressive reduction in UTCI from the pre-intervention (S1) to post-interventions (S2) and desirable medium-term future (S3) scenarios for both day types. In contrast, P02 shows a different response. The transition from S1 to S2 results in only marginal changes in UTCI for both the typical summer day and the heatwave day, indicating a limited short-term impact of the initial intervention. However, the S3 produces a substantial and statistically significant reduction in UTCI relative to S1, especially during the central hours of the day. Notably, under typical summer conditions, the magnitude of the UTCI reduction in P02 in the S3 is comparable to, or even exceeds, that observed in P01, whereas under heatwave conditions both passageways exhibit similarly strong peak reductions.

For both passageways, UTCI values during the typical summer day are classified as Moderate Heat Stress under scenarios S1 and S2, while during the extreme day they increase to Strong Heat Stress. Between these scenarios, effects emerge under extreme conditions, with relevant reductions only observed in P01 under scenario S2, where UTCI values decrease to ranges close to Moderate Heat Stress. In contrast, scenario S3 shows the strongest and most consistent impact across both passageways: during a typical summer day, UTCI values are reduced to the No Heat Stress category, while during heatwave conditions, scenario S3 achieves a meaningful mitigation effect, lowering thermal stress to Moderate Heat Stress.

4 Discussion

Results are examined in relation to three interrelated dimensions: urban morphology, climatic extremes, and the institutional conditions shaping NbS implementation in dense informal urban environments. By comparing the two passageways under typical and extreme summer conditions, the discussion highlights how design choices, governance frameworks and temporal horizons interact to condition the effectiveness of NbS. It also reflects on the methodological value of microclimatic simulation as a decision-support tool and explores the broader

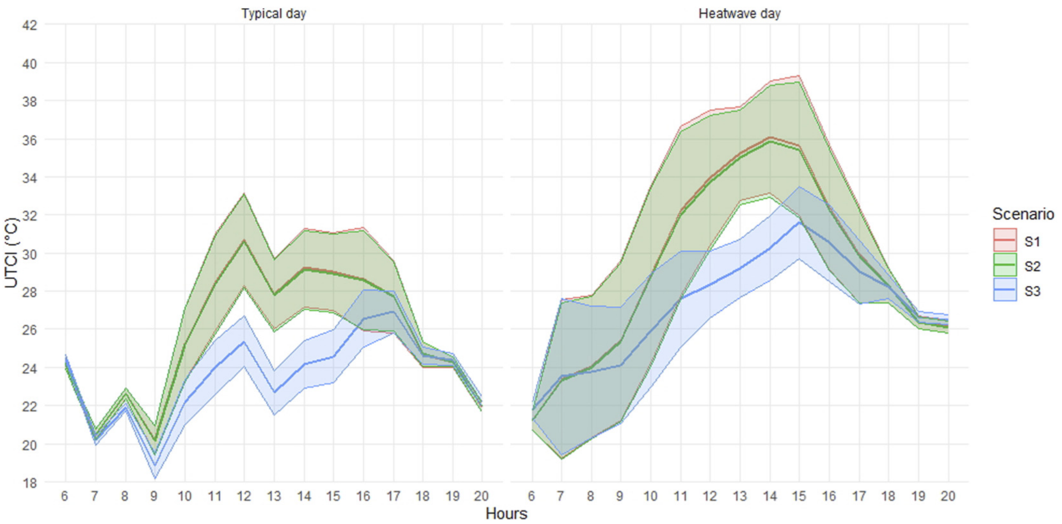

FIGURE 9
Diurnal evolution of UTCI (°C) in P02 for a typical summer day and a heatwave day under the three scenarios (S1 - pre-intervention no vegetation; S2 - current state with vegetation; S3 - Mid-term desirable fully grown vegetation and more trees).

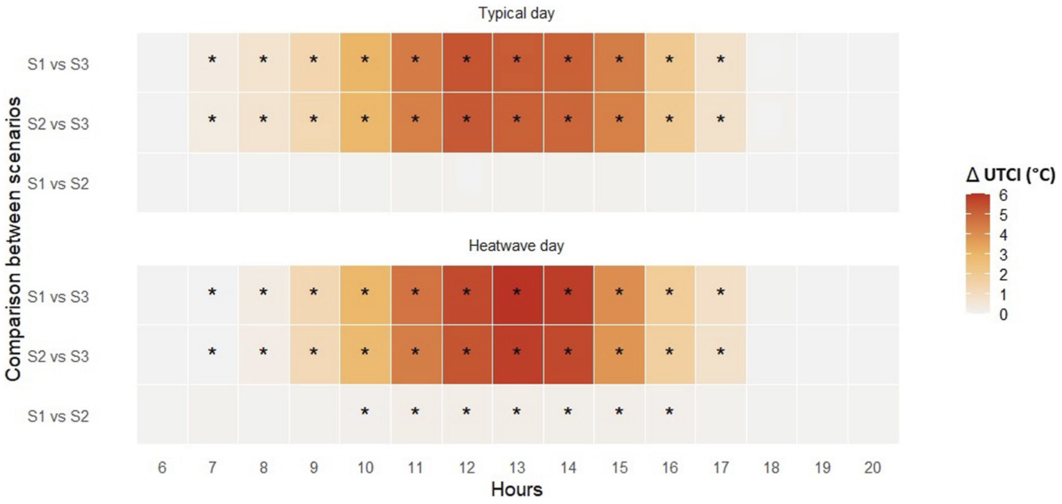

FIGURE 10
Hourly UTCI differences (°C) between scenarios (S1 - pre-intervention no vegetation; S2 - current state with vegetation; S3 - Mid-term desirable fully grown vegetation and more trees) in P02 for a typical summer day and a heatwave day. Asterisks indicate statistically significant differences ($p < 0.05$).

implications of the findings for reurbanization policies, climate adaptation and urban climate justice.

4.1 Differential effectiveness of NbS according to urban morphology

The results indicate that thermal performance of NbS is strongly mediated by the morphological characteristics of the urban space in which they are implemented.

Although the interventions followed similar objectives and principles, contrasting spatial configurations led to markedly different short- and medium-term outcomes between the two passageways. P01, located within a recently formalized urban sector, presents a wider and more regular street section, allowing for the integration of multiple NbS elements–tree canopy, vegetated pergolas and permeable surfaces–due primarily to the shading effect provided by the tree canopy, which drastically reduced the MRT in the canyon (Chàfer et al., 2020; Park et al., 2019). Cooling benefits emerge earlier and are more persistent across scenarios, suggesting a higher immediate sensitivity to NbS implementation.

In contrast, P02 is embedded within the historic core of the informal settlement, characterized by a narrow and irregular canyon with limited sky view. Unlike P01, P02 remains spatially open-ended, as residents continue to open windows and doors. This ongoing condition limited the range of interventions that could be implemented and assessed under S2. Under such conditions–and

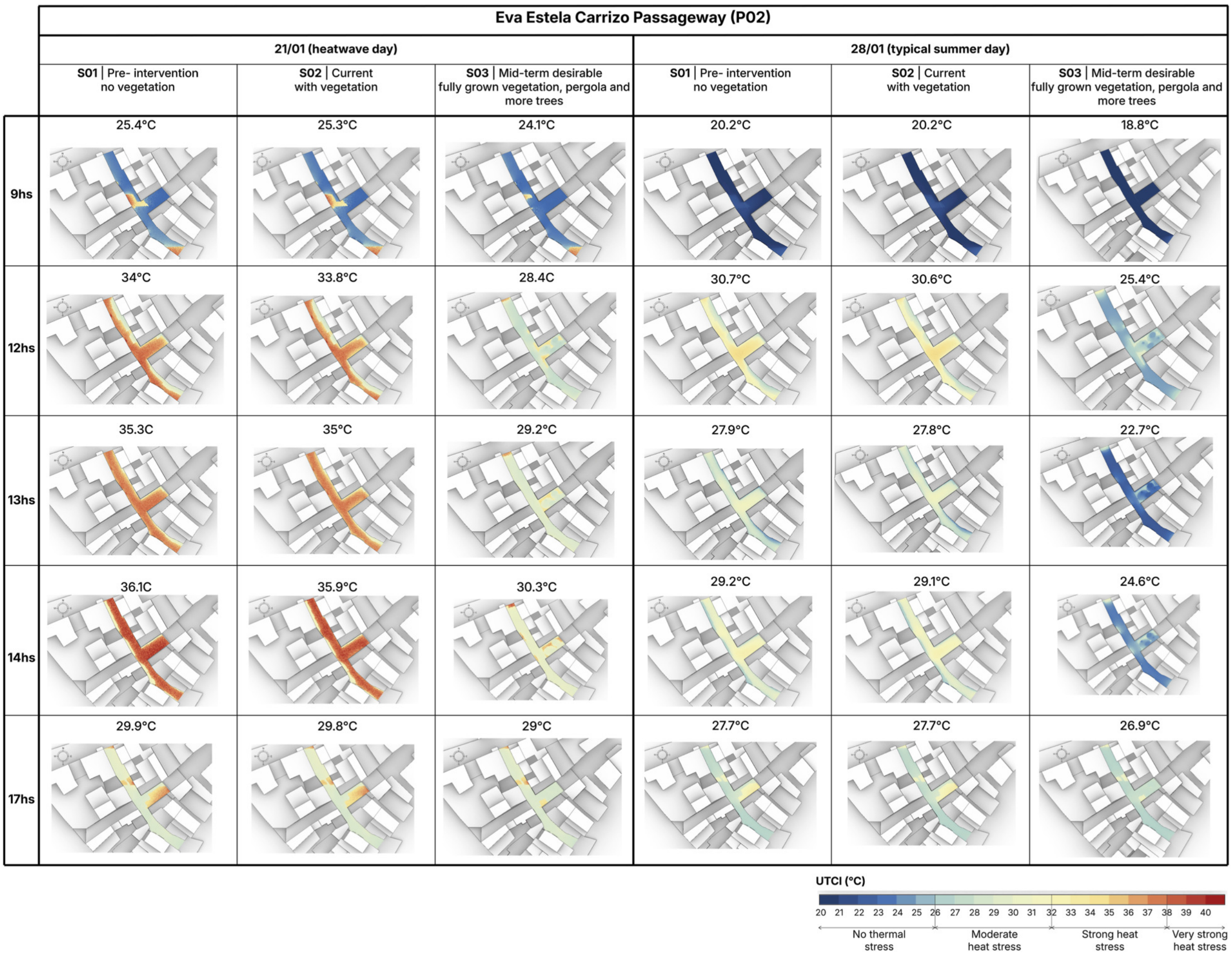

FIGURE 11
Spatial distribution of UTCI (°C) in P02 at selected hours for the three scenarios (S1 - pre-intervention no vegetation; S2 - current state with vegetation; S3 - Mid-term desirable fully grown vegetation and more trees).

the current regulatory framework –, both the availability of space for intervention and the range of feasible NbS are limited, constraining the cooling potential to the contribution of vertical vegetation and small planted areas. Significant improvements are mainly associated with the future scenario, highlighting the importance of vegetation maturation and long-term planning, as well as the need to revisit how vegetation is integrated structurally.

These findings are consistent with previous research demonstrating that the effectiveness of urban vegetation depends not only on its presence but also on its spatial arrangement and interaction with street geometry (Jamei et al., 2016; Pattnaik et al., 2025). In dense urban environments, sufficient spatial volume for tree canopies and continuous shading along pedestrian paths emerges as a critical factor for achieving meaningful reductions in thermal stress. The reviewed literature further indicates that, where the incorporation of tree cover is not feasible, small-scale vegetated interventions combined with lightweight and low-cost shading structures–such as pergolas–can provide comparable shading and thermal benefits. For instance, Oraiopoulos et al. (2026) demonstrated that such systems can achieve levels of solar radiation reduction comparable to those measured in the park's shaded areas. The results therefore reinforce the need to move beyond generic greening targets and towards morphology-sensitive NbS design criteria, particularly in highly constrained environments such as informal settlements.

4.2 Intensification of NbS effects under extreme heat conditions

A key contribution of this study lies in the explicit comparison between typical summer conditions and extreme heat scenarios. Across both passageways, the cooling effect of NbS was consistently stronger during heatwave conditions than on a typical summer day. This effect was particularly pronounced in P01, where UTCI reductions not only increased in magnitude but also persisted for longer periods throughout the day, extending into the afternoon hours.

This non-linear response suggests that NbS provide disproportionate benefits precisely when thermal stress reaches critical levels, reinforcing their role as climate adaptation infrastructure rather than marginal aesthetic improvements. Similar patterns have been reported in other climatic contexts, where vegetation-based interventions exhibit enhanced performance during extreme heat events due to their capacity to attenuate radiant heat loads and buffer peak temperatures (Armson et al., 2012; Ziter et al., 2019). These findings gain particular significance within the aforementioned context of intensifying UHI effects and the unequal distribution of heat-related risks across urban populations.

Within informal settlements–where access to indoor cooling is often limited by energy poverty and housing conditions–the role of outdoor NbS in mitigating peak thermal stress becomes particularly relevant. By reducing exposure during the most critical hours, these interventions may contribute not only to improved outdoor comfort but also to indirect reductions in indoor heat accumulation (Hugo and Sonnendecker, 2023; Li et al., 2020), thereby supporting broader public health and energy resilience objectives. In many informal settlements, including Barrio 20, formal access to electricity remains limited and a significant share of energy consumption occurs through informal connections or highly constrained supply conditions. Under such circumstances, reducing outdoor and indoor heat exposure through shading and vegetation may also contribute to lowering the demand for mechanical cooling and other electricity-dependent coping strategies. Although energy consumption was not directly assessed in this study, a growing body of research indicates that urban greening and nature-based cooling strategies can contribute to measurable reductions in building cooling demand and peak electricity use during hot periods (Santamouris, 2014; Bowler et al., 2010; Wei et al., 2025). In contexts where electricity provision is structurally fragile or unevenly regulated, these indirect energy savings may represent an additional incentive for public agencies and service providers to support NbS-based interventions as part of broader upgrading and climate adaptation strategies.

4.3 Role of spatial design and regulatory constraints

Beyond biophysical factors, the study highlights the decisive influence of spatial design choices and regulatory frameworks on the thermal effectiveness of NbS. In P02, the limited impact observed cannot be attributed solely to unfavorable morphology but also to a set of institutional and social constraints that shaped the final design. Regulations imposed by utility providers–such as minimum clear widths and unobstructed aerial planes–restricted the installation of horizontal shading structures, while residents' concerns about preserving future façade openings led to a reduction in the number of vertical vegetated elements initially proposed during participatory workshops. These constraints are clearly reflected in the modest thermal improvements observed in P02 for scenario S2.

Comparison across scenarios provides further insight into this issue. While Scenarios P01 S2 and P02 S2 represent feasible design options aligned with current regulatory frameworks and negotiated agreements with residents and service providers, Scenarios P01 S3 and P02 S3 correspond to a more ambitious and climatically optimized configuration. These scenarios integrate continuous shading systems and a higher level of vertical and horizontal greening, unconstrained by current minimum clearance requirements or aerial service corridors. Under these conditions, simulations show substantially greater reductions in UTCI (reaching up to 5 °C on a typical summer day and up to 6 °C on the heatwave day), especially during peak heat hours. These findings underscore the strong cooling potential of shading and the cumulative benefits associated with vegetation maturation and the implementation of complementary NbS strategies, particularly when urban regulations and service-related requirements are aligned with microclimatic adaptation goals and the enhancement of thermal comfort. In densely built areas, such as informal urban settlements, these reductions have significant implications for the habitability and use of public space (Kibii et al., 2025; Ribeiro et al., 2021; Uddin et al., 2021). Neighbourhood-scale monitoring in Barrio 20 – the focus of this study–further confirms the combined influence of vegetation presence and surface materials on local temperature and humidity patterns, particularly during heat-wave conditions (UNU, 2025)[5].

These findings suggest that the relatively limited thermal gains observed in the implemented or near-term scenarios should not be interpreted as an intrinsic limitation of NbS in informal settlements. Rather, they reflect an asymmetric regulatory regime, in which service provision standards and spatial restrictions applied to informal neighborhoods are significantly more stringent than those commonly enforced in formal urban areas. Comparable narrow passages in consolidated urban fabrics, including historic centres, often accommodate overhead elements and solar-protection devices without compromising service provision, suggesting that the barriers observed in P02 are not purely morphological but also institutional. Similar tensions have been reported in other informal settlement upgrading processes, where NbS potential is frequently curtailed by rigid standards that are primarily framed around infrastructure maintenance and risk management, constraining the integration of thermal comfort and climate adaptation goals (Castaldo et al., 2025; Hardoy et al., 2022; Kibii et al., 2025). By simulating a desired design scenario, this study makes visible the thermal benefits that could be unlocked through more flexible and context-sensitive regulations. In this sense, S3 functions not as a predictive outcome, but as a strategic reference that reveals the opportunity costs associated with current regulatory constraints and supports evidence-based discussions on how urban standards might evolve to better address extreme heat risks in vulnerable neighborhoods.

The issue is further reinforced by structural deficits in urban green infrastructure. A tree census conducted in Barrio 20 in 2018 recorded 555 trees - approximately one tree per 50 inhabitants compared with a citywide average of roughly one tree per seven inhabitants (Agencia de Protección Ambiental, 2020). Such disparities not only underscore severe inequalities in access to urban vegetation and its associated cooling benefits, but also highlights the limited capacity of existing green infrastructure to

---

[5] Since July 2023, a temperature and humidity monitoring system operates in Barrio 20 as part of Urban Lab data-generation activities, with technical support from the Gerencia Operativa de Generación de Datos Territoriales, Dirección General de Antropología Urbana (Office of Territorial Data Generation, General Directorate of Urban Anthropology) and Gerencia Operativa de Cambio Climático, Dirección General de Política y Estrategia Ambiental (Office of Climate Change, General Directorate for Environmental Policy and Strategy) of the City of Buenos Aires.

buffer the impacts of extreme temperatures and heatwaves. Within this context, it becomes particularly important to explore alternative ways of incorporating vegetation and NbS where tree planting is not feasible, and to promote adaptive regulatory frameworks capable of responding to urban configurations in which more traditional NbS approaches are constrained.

4.4 Methodological contributions and implications for policy, reurbanization and climate justice

From a methodological perspective, this study demonstrates the value of microclimatic simulation as a tool for evaluating and communicating the impacts of NbS in informal urban contexts. The use of a consistent EPW dataset across scenarios and passageways allows for the isolation of morphological and design effects while the scenario-based approach provides insight into the temporal dynamics of vegetation growth and incremental urban transformation. Similar approaches have been highlighted as particularly relevant for capturing the full adaptation potential of NbS, specially increasing heat stress and climatic uncertainty (Cortinovis et al., 2022; Oraiopoulos et al., 2026).

These digital tools play a key role in the technical design of NbS. The constraints inherent to the diverse urban configurations commonly found in informal settlements can be creatively addressed through simulation-based analyses that allow multiple intervention variables to be tested and their impacts anticipated. Such models support the identification of thermally critical areas, the comparison of alternative design options, and the selection of NbS strategies best suited to specific spatial contexts. This approach not only enables the exploration of long-term impacts, but also facilitates a detailed assessment of design parameters, such as installation heights, orientations, spatial layouts, and dimensions, thereby supporting informed design decisions and resource optimisation in contexts where resources are often limited.

Likewise, in settings where empirical microclimatic data are scarce and urban form is highly heterogeneous, simulation tools offer a flexible and relatively low cost means of exploring alternative design strategies and visualizing their potential benefits. Importantly, when embedded within participatory processes, as in the Urban Laboratory for Barrio 20, these simulations can function as mediating devices that translate abstract climate risk into tangible spatial outcomes, supporting collective decision-making and fostering shifts in mindsets among residents, technicians and policymakers.

At the policy level, the findings have direct implications for informal settlement upgrading and climate justice agendas. The results show that even small-scale, distributed NbS interventions can yield meaningful improvements in outdoor thermal comfort, provided that spatial design and regulatory frameworks are aligned with microclimatic adaptation goals. Conversely, the contrast between feasible and optimal scenarios highlights how rigid urban standards and service regulations may limit the effectiveness of NbS, disproportionately affecting populations already exposed to higher thermal risks. This aligns with broader evidence indicating that climate adaptation benefits are unevenly distributed and strongly conditioned by governance structures and planning norms (Amorim-Maia and Olazabal, 2025; Anguelovski et al., 2016).

Overall, this study contributes methodological and empirical evidence to ongoing debates on equitable urban climate adaptation. By linking microclimatic performance, participatory design processes and regulatory constraints, it illustrates how simulation-based approaches can inform more just and context-sensitive reurbanization strategies, particularly in cities of the Global South facing increasing frequency and intensity of extreme heat events.

5 Conclusion

This study assessed the extent to which NbS, primarily through added vegetation, can improve outdoor thermal comfort in dense informal-settlement upgrading contexts, using two pedestrian passageways in Barrio 20 (Buenos Aires) as case studies. By combining UTCI-based microclimatic simulations with a scenario approach (pre-intervention baseline, current post-intervention and a climatically enhanced medium-term desired future), the paper provides evidence on (i) the magnitude of potential improvements in thermal comfort, (ii) when benefits are most significant throughout the day and under different summer conditions and (iii) why outcomes differ across urban configurations and implementation settings.

Across both passageways, results confirm that NbS can deliver meaningful reductions in thermal stress, particularly during peak heat hours. In the wider and more regular passageway (P01), current post-intervention conditions (S2) already generate measurable UTCI reductions during the central hours of the day and these benefits expand substantially under the future scenario. Peak reductions reach up to 6 °C on a heatwave day, with the maximum mean UTCI decreasing from 38.1 °C (S1) to 32.4 °C (S3). In the narrower and more irregular passageway (P02), short-term improvements between the baseline (S1) and the current scenario (S2) remain limited, but the future desired scenario (S3) indicates substantial latent cooling potential, with reductions of up to 5 °C on a typical day and up to 6 °C on a heatwave day, concentrated between 10:00 and 16:00. Taken together, these findings show that NbS performance is highly context-dependent, shaped by baseline thermal exposure, spatial capacity for shading and the feasibility of design solutions at the micro-urban scale.

A second main conclusion is that NbS impacts intensify under extreme heat conditions. Cooling effects are systematically stronger during heatwave scenarios than during typical summer conditions, both in magnitude and temporal persistence. This non-linear response under extreme heat exposure supports the role of NbS as adaptation infrastructure with particularly high value during critical heat exposure periods.

A third conclusion concerns the decisive role of institutions and regulation in shaping the realised performance of NbS. The limited short-term effect observed in P02 is not only a consequence of constrained morphology, but also the outcome of regulatory and negotiated design conditions that reduced the scope of shading and vegetation initially envisioned. Importantly, these constraints may reflect uneven standards of service provision, whereby requirements applied in informal-settlement contexts can be more restrictive than those commonly accepted in formal areas. The contrast between Scenarios 2 and 3 therefore has strategic value beyond the microclimatic results, with S3 operating as a proof of concept for what becomes possible when regulations and maintenance logics are aligned with microclimatic adaptation goals. In addition, early interventions can act as catalysts for learning and broader uptake, making more ambitious NbS proposals increasingly viable once pilot projects have been implemented and experienced locally. In this sense, this scenario exercise makes visible the opportunity costs of rigid frameworks and supports evidence-informed adjustments to upgrading standards in the face of rising heat risk.

A fourth conclusion highlights the enabling role of implemented interventions (Scenario 2). Although the transition from S1 to S2 results in only modest improvements in UTCI for P02 under both typical summer and heatwave conditions, its significance lies elsewhere. Scenario 2 functions as a critical channel for collaboration, learning and shifts in mindset, enabling stakeholders to understand and engage with pathways that accelerate the transition from existing conditions (S1) and a mid-term desirable scenario (S3). In informal urban contexts, where uncertainty, incremental change, and spatial constraints are inherent, such tangible intermediate interventions are essential for rendering future possibilities visible and actionable. From a methodological and policy perspective, parametric microclimatic simulation can support decision-making in upgrading processes by quantifying thermal benefits, identifying thermally critical locations and comparing design alternatives. When embedded within participatory processes, these simulations can help visualise future scenarios and communicate the potential benefits of interventions, supporting collective deliberation and connecting scientific evidence with community planning. Integrating climate action into the transformation of popular neighbourhoods is essential for more just and transformative urban transitions (Hardoy et al., 2022).

As limitations, simulations were driven by a city-scale EPW (TMYx) without site-specific calibration; absolute UTCI magnitudes are therefore presented as indicative, and the analysis focuses on inter-scenario differences (ΔUTCI). Wind speed was held constant at 0.1 m/s; under higher pedestrian-level wind speeds, absolute UTCI values would decrease and the sensitivity of UTCI to Tmrt (and therefore the magnitude of shade-driven ΔUTCI) would be reduced. In addition, vegetation processes were simplified: above-ground elements were represented as porous shading using an effective solar transmittance to capture radiative effects (without modeling evapotranspiration/plant–air exchanges for tall vegetation), and permeable ground in S2–S3 was represented using an EnergyPlus vegetated-ground formulation that captures simplified moisture-related surface behaviour rather than a fully coupled vegetation microclimate model.

Future research could strengthen these findings through calibration with local measurements and by testing additional public-space typologies and implementation conditions. Overall, the evidence supports a clear practical takeaway: in dense informal settlement upgrading, NbS can produce substantial thermal comfort gains, especially under extreme heat, when design is morphology-sensitive and when regulatory frameworks evolve to enable continuous shading and meaningful vegetation coverage at the pedestrian level.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

GG-G: Investigation, Writing – review and editing, Data curation, Methodology, Visualization, Project administration, Conceptualization, Writing – original draft, Formal Analysis. NF: Writing – review and editing, Project administration, Visualization, Writing – original draft, Methodology, Conceptualization, Investigation. AA-R: Conceptualization, Writing – original draft, Formal Analysis, Methodology, Data curation, Visualization, Investigation. SG-A: Conceptualization, Methodology, Writing – review and editing, Investigation, Writing – original draft. MG: Project administration, Conceptualization, Methodology, Visualization, Writing – original draft. JH: Funding acquisition, Writing – original draft, Conceptualization, Resources. FA: Conceptualization, Writing – original draft, Funding acquisition, Resources. DK: Writing – original draft, Supervision, Project administration, Conceptualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The research leading to these results is part of the project ‘Transformative Urban Coalitions (TUC): Catalysing Urban Partnerships to Drive Systemic Transformation towards Sustainability’ funded by the International Climate Initiative (IKI) of the German Federal Government. Project number: 21_I_377. Duration: 01/2021–12/2026. The funding organization played no role in the design of the study, collection, analysis and interpretation of data, or the writing of this manuscript. In addition, MG received financial support from the European Union (NextGenerationEU), the Ministry of Universities of Spain, and the European Recovery, Transformation and Resilience Plan through the Margarita Salas Grant RD289/2021, which supported her postdoctoral activities during the implementation of the interventions in Barrio 20. The preparation and writing of this manuscript were supported by a postdoctoral fellowship from the National Scientific and Technical Research Council of Argentina (CONICET). NF and GG are supported by doctoral fellowships from CONICET, the latter co-funded with the National Parks Administration of Argentina. SG was supported by her university (University of Valladolid). AA’s academic stay was funded through a mobility grant from the University of Deusto.

Acknowledgements

The authors are very grateful to all Urban Lab members who have made possible the implementation of interventions in Barrio 20. We also acknowledge the Habitat and Energy Research Center of the Faculty of Architecture, Design and Urbanism, University of Buenos Aires (CIHE-FADU-UBA); the CONICET; the University of Valladolid; and the University of Deusto, where parts of this study were carried out.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1800415/full#supplementary-material

References

Agencia de Planificación (2017). "Resolución No. 26/2017," in *"Criterios de Intervención en Construcción de Infraestructura y Operación del Servicio de Agua y Saneamiento en Barrios Populares/Urbanizaciones Emergentes"*. Buenos Aires: Agua y Saneamientos Argentinos Sociedad Anónima (AySA). Available online at: https://www.boletinoficial.gob.ar/detalleAviso/primera/171742/20171003 (Accessed October 15, 2025).

Agencia de Protección Ambiental (2020). *Caracterización de microclimas urbanos del Barrio 20 – ciudad de Buenos Aires. Informe de resultados de mediciones de temperatura 13/02/2020*. Buenos Aires: Gobierno de la Ciudad de Buenos Aires.

Aké Turriza, K. A., and Rivera-Arriaga, E. (2025). Artículo de revisión: Islas de calor urbanas bajo escenarios de cambio climático. *JAINA Costas Mares el Cambio Climático* 7 (1), 67–94. doi:10.26359/52462.0705

Akinsanola, A. A., Singhai, P., Taguela, T. N., Folorunsho, A. H., Adeyeri, O. E., Morakinyo, T. E., et al. (2025). A review of urban resilience to weather and climate extremes. *City Built Environ.* 3 (1), 24. doi:10.1007/s44213-025-00063-6

Almansi, F., Motta, J. M., and Hardoy, J. (2020). Incorporating a resilience lens into the social and urban transformation of informal settlements: the participatory upgrading process in Villa 20, Buenos Aires (2016–2020). *Environ. & Urbanization* 32 (2), 407–428. doi:10.1177/0956247820935717

American Society of Heating, Refrigerating and Air-Conditioning Engineers (2023). *ANSI/ASHRAE Standard 55-2023: thermal environmental conditions for human occupancy*. Peachtree Corners, GA: ASHRAE.

Amorim-Maia, A. T., and Olazabal, M. (2025). Beyond adjustment: a new paradigm for climate change adaptation in a complex world. *Glob. Environ. Change* 93, 103027. doi:10.1016/j.gloenvcha.2025.103027

Anand, J., Sailor, D. J., and Baniassadi, A. (2021). The relative role of solar reflectance and thermal emittance for passive daytime radiative cooling technologies applied to rooftops. *Sustain. Cities Soc.* 65, 102612. doi:10.1016/j.scs.2020.102612

Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., et al. (2016). Equity impacts of urban land use planning for climate adaptation: critical perspectives from the global north and south. *J. Plan. Educ. Res.* 36, 333–348. doi:10.1177/0739456X16645166

Armson, D., Stringer, P., and Ennos, A. R. (2012). The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban For. & Urban Green.* 11 (3), 245–255. doi:10.1016/j.ufug.2012.05.002

Arrar, H. F., Kaoula, D., Santamouris, M., Foufa-Abdessemed, A., Emmanuel, R., Elhadi Matallah, M., et al. (2024). Coupling of different nature base solutions for pedestrian thermal comfort in a Mediterranean climate. *Build. Environ.* 256, 111480. doi:10.1016/j.buildenv.2024.111480

Arrighi, J., Izquierdo, K., Korodimou, M., Monasso, F., Pereira Marghidan, C., and Singh, R. (2025). *Through the eyes of the Most vulnerable: perceptions and pathways to action. Geneva: International Federation of Red Cross and Red Crescent Societies (IFRC).* Available online at: https://www.ifrc.org/document/heat-through-eyes-most-vulnerable-perceptions-and-pathways-action (Accessed November 18, 2025).

Bajšanski, I. V., Milošević, D. D., and Savić, S. M. (2015). Evaluation and improvement of outdoor thermal comfort in urban areas on extreme temperature days: applications of automatic algorithms. *Build. Environ.* 94, 632–643. doi:10.1016/j.buildenv.2015.10.019

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* 5, 180214. doi:10.1038/sdata.2018.214

Błażejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., and Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *Int. J. Biometeorology* 56, 515–535. doi:10.1007/s00484-011-0453-2

Błażejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., et al. (2013). An introduction to the Universal Thermal Climate Index (UTCI). *Geogr. Pol.* 86 (1), 5–10. doi:10.7163/GPol.2013.1

Bowler, D. E., Buyung-Ali, L., Knight, T. M., and Pullin, A. S. (2010). Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landsc. Urban Plan.* 97, 147–155. doi:10.1016/j.landurbplan.2010.05.006

Bröde, P., Błażejczyk, K., Fiala, D., Havenith, G., Jendritzky, G., Kuklane, K., et al. (2013). The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment. *Ind. Health*, 51, 16–24. doi:10.2486/indhealth.2012-0098

Burgueño, G., and Nardini, C. (2019). "Plantas nativas rioplatenses para el diseño de espacios verdes: Introducción al paisaje natural (Parte II)," in *Ciudad Autónoma de Buenos Aires: orientación Gráfica Editora*.

Castaldo, A. G., Nocentini, M. G., Lemes de Oliveira, F., and Mahmoud, I. H. (2025). Nature-based solutions and urban planning in the Global South: challenge orientations, typologies, and viability for cities. *Land Use Policy* 150, 107439. doi:10.1016/j.landusepol.2024.107439

Chàfer, M., Pisello, A. L., Piselli, C., and Cabeza, L. F. (2020). Greenery System for cooling Down outdoor spaces: results of an experimental Study. *Sustainability* 12, 5888. doi:10.3390/su12155888

Cortinovis, C., Olsson, P., Boke-Olén, N., and Hedlund, K. (2022). Scaling up nature-based solutions for climate-change adaptation: potential and benefits in three European cities. *Urban For. & Urban Green.* 67, 127450. doi:10.1016/j.ufug.2021.127450

Costadone, L., and Zhang, S. (2025). Integrated valuation of the ecological, social and economic benefits provided by a multifunctional nature-based solution. *Nature-Based Solutions* 8, 100256. doi:10.1016/j.nbsj.2025.100256

Dobbs, C., Escobedo, F. J., Clerici, N., De la Barrera, F., Eleuterio, A. A., MacGregor-Fors, I., et al. (2019). Urban ecosystem Services in Latin America: mismatch between global concepts and regional realities? *Urban Ecosyst.* 22 (1), 173–187. doi:10.1007/s11252-018-0805-3

European Environment Agency (2020). *Thermal comfort indices – universal thermal Climate Index, 1979-2019*. Copenhagen: European Environment Agency. Available online at: https://climate-adapt.eea.europa.eu/en/metadata/indicators/thermal-comfort-indices-universal-thermal-climate-index-1979-2019 (Accessed December 3, 2025).

Gertner, G., and Goytia, C. (2025). Equitable energy transitions in informal urban settlements: lessons from energy audits in the City of Buenos Aires. *J. City Clim. Policy Econ.* 4 (3), 589–616. doi:10.3138/jccpe-2025-0022

Hardoy, J., Motta, J. M., Kozak, D., Almansi, F., Reverter, T., and Costello, M. (2022). Exploring the links between the use of NbS, mindshifts and transformative urban coalitions to promote climate resilience within an ongoing re-urbanization process. The case of Villa 20, Buenos Aires. *Front. Sustain. Cities* 4, 962168. doi:10.3389/frsc.2022.962168

Hugo, J. M., and Sonnendecker, P. W. (2023). Ground-level documentation of heat stress exposure and response strategies in informal settlements in Tshwane, South Africa. *Smart Sustain. Built Environ.* 13 (5), 1177–1193. doi:10.1108/sasbe-10-2022-0229

Instituto de Vivienda de la Ciudad (IVC) (2016). Informe Final Censo 2016 Villa 20. *Buenos Aires: Departamento de Estadísticas y Censos, Gerencia Operativa de Intervención Social y Hábitat, Gerencia de Desarrollo Habitacional*.

Intergovernmental Panel on Climate Change (IPCC) (2023). *Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental Panel on climate change*. Geneva, Switzerland. doi:10.59327/IPCC/AR6-9789291691647

International Organization for Standardization (1998). *ISO 7726:1998 ergonomics of the thermal environment—Instruments for measuring physical quantities*. Geneva: International Organization for Standardization (ISO).

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M., and Jamei, Y. (2016). Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renew. Sustain. Energy Rev.* 54, 1002–1017. doi:10.1016/j.rser.2015.10.104

Jendritzky, G., de Dera, R., and Havenith, G. (2012). UTCI—Why another thermal index? *Int. J. Biometeorology* 56, 421–428. doi:10.1007/s00484-011-0513-7

Ji, L., Gaur, A., Voogt, J., and Krayenhoff, E. S. (2025). Strategic deployment of urban trees to achieve thermal resilience in a Canadian community. *Build. Simul.* 18, 1231–1250. doi:10.1007/s12273-025-1261-7

Kibii, C., Guerra, F., Bonera Bananayo, P., and Sandholz, S. (2025). Nature-based solutions for climate change adaptation and resilience in urban informal settlements: insights from Kibera, Kenya and Villa 20, Argentina. *Nature-Based Solutions* 7, 100216. doi:10.1016/j.nbsj.2025.100216

Knight, T., Price, S., Bowler, D., Hookway, A., King, S., Konno, K., et al. (2021). How effective is 'greening' of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the 'urban heat island effect'? An updated systematic review. *Environ. Evid.* 10 (12), 2–38. doi:10.1186/s13750-021-00226-y

Konarska, J., Lindberg, F., Larsson, A., Thorsson, S., and Holmer, B. (2014). Transmissivity of solar radiation through crowns of single urban trees—application for outdoor thermal comfort modeling. *Theor. Appl. Climatol.* 117 (3–4), 363–376. doi:10.1007/s00704-013-1000-3

Kozak, M., and Lipecki, T. (2025). The impact of green walls on outdoor thermal comfort in residential areas under warm weather conditions: a case study. *Urban Clim.* 62, 102541. doi:10.1016/j.uclim.2025.102541

Lawrie, L. K., and Crawley, D. B. (2022). Development of global typical meteorological years (TMYx). *Clim. OneBuilding.Org*.

Li, J., Zheng, B., Chen, X., Qi, Z., Bedra, K. B., Zheng, J., et al. (2020). Study on a full-year improvement of indoor thermal comfort by different vertical greening patterns. *J. Build. Eng.* 35, 101969. doi:10.1016/j.jobe.2020.101969

Majidi, A. N., Vojinovic, Z., Alves, A., Weesakul, S., Sanchez, A., Boogaard, F., et al. (2019). Planning nature-based solutions for urban flood reduction and thermal comfort enhancement. *Sustainability* 11, 6361. doi:10.3390/su11226361

Mansoldo, M. D. C., de Luca, C., and Balzan, M. V. (2024). Exploring the potential for nature-based solutions to cool the streetscapes of a densely urbanised Mediterranean city. *Nature-Based Solutions* 6, 100177. doi:10.1016/j.nbsj.2024.100177

Nicholson, S., Nikolopoulou, M., Watkins, R., Löve, M., and Ratti, C. (2024). Data driven design for urban street shading: validation and application of ladybug tools as a design tool for outdoor thermal comfort. *Urban Clim.* 56, 102041. doi:10.1016/j.uclim.2024.102041

Oraiopoulos, A., Wieser, M., Verdiere, M., Lambert, R., Fennell, P., and Ruyssevelt, P. (2026). Improving habitability in informal settlements in the Global South: exploring the impact of community urban green infrastructure on outdoor heat stress. *Build. Environ.* 287, 113787. doi:10.1016/j.buildenv.2025.113787

Park, C. Y., Lee, D. K., Krayenhoff, E. S., Heo, H. K., Hyun, J. H., Oh, K., et al. (2019). Variations in pedestrian mean radiant temperature based on the spacing and size of street trees. *Sustain. Cities Soc.* 48, 101521. doi:10.1016/j.scs.2019.101521

Pattnaik, N., Rahman, M. A., and Pauleit, S. (2025). Urban vegetation structure and composition influence pedestrian thermal comfort in public spaces: a case study in Munich. *Urban For. & Urban Green.* 114, 129162. doi:10.1016/j.ufug.2025.129162

Pérez, G., Coma, J., Martorell, I., and Cabeza, L. F. (2014). Vertical Greenery Systems (VGS) for energy saving in buildings: a review. *Renew. Sustain. Energy Rev.* 39, 139–165. doi:10.1016/j.rser.2014.07.055

R Core Team (2025). *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/ (Accessed March 2, 2026).

Reverter, T., Costello, M., Molinari, R., and Llul, L. (2023). Derecho a la ciudad. Transferencia de dominio en el proceso de reurbanización de Villa 20, Ciudad Autónoma de Buenos Aires. *Medio Ambiente Y Urban.* 98 (1), 187–218. Available online at: https://www.ingentaconnect.com/content/iieal/meda/2023/00000098/00000001/art00010 (Accessed October 22, 2025).

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., et al. (2014). "Urban areas," in *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral Aspects. Contribution of Working Group II to the fifth assessment report of the intergovernmental Panel on climate change*. Editors C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Cambridge: Cambridge University Press), 535–612.

Ribeiro, A. P., Bollmann, H. A., de Oliveira, A., Rakauskas, F., Cortese, T. T. P., Rodrigues, M. S. C., et al. (2021). The role of tree landscape to reduce effects of urban heat islands: a study in two Brazilian cities. *Trees* 37, 17–30. doi:10.1007/s00468-021-02230-8

Sabrin, S., Karimi, M., and Nazari, R. (2023). The cooling potential of various vegetation covers in a heat-stressed underserved community in the deep south: birmingham, Alabama. *Urban Clim.* 51, 101623. doi:10.1016/j.uclim.2023.101623

Sadeghipour Roudsari, M., Pak, M., and Viola, A. (2013). "Ladybug: a parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design," in Proceedings of Building Simulation, 2013 *(IBPSA)*. doi:10.26868/25222708.2013.2499

Sanjuán, M. Á., Morales, Á., and Zaragoza, A. (2022). Precast concrete pavements of high albedo to achieve the net "zero-emissions" commitments. *Appl. Sci.* 12 (4), 1955. doi:10.3390/app12041955

Santamouris, M. (2014). Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* 103, 682–703. doi:10.1016/j.solener.2012.07.003

Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with global climate change. *Energy Build.* 207, 109482. doi:10.1016/j.enbuild.2019.109482

Sen, S., and Roesler, J. (2019). Thermal and optical characterization of asphalt field cores for microscale urban heat island analysis. *Constr. Build. Mater.* 217, 600–611. doi:10.1016/j.conbuildmat.2019.05.091

Servicio Meteorológico Nacional (SMN) (2018). Listado de Estaciones Meteorológicas del SMN. Available online at: https://www.datos.gob.ar/dataset/smn-listado-estaciones-meteorologicas-smn (Accessed January 27, 2026).

Smith, P., and Henríquez, C. (2019). Perception of thermal comfort in outdoor public spaces in the medium-sized city of Chillán, Chile, during a warm summer. *Urban Clim.* 30, 100525. doi:10.1016/j.uclim.2019.100525

Sodoudi, S., Zhang, H., Chi, X., Muller, F., and Li, H. (2018). The influence of spatial configuration of green areas on microclimate and thermal comfort. *Urban For. Urban Green.* 34, 85–96. doi:10.1016/j.ufug.2018.06.002

Soltanifard, H., and Amani-Beni, M. (2025). The cooling effect of urban green spaces as nature-based solutions for mitigating urban heat: insights from a decade-long systematic review. *Clim. Risk Manag.* 49, 100731. doi:10.1016/j.crm.2025.100731

Tapia, M. (2022). Islas de calor urbanas. *Crítica Urbana Rev. Estud. urbanos Territ.* 5 (26), 12–15. Available online at: https://criticaurbana.com/islas-de-calor-urbanas (Accessed September 25, 2025).

Uddin, A. S. M. S., Khan, N., Islam, A. R. M. T., Kamruzzaman, M., and Shahid, S. (2021). Changes in urbanization and urban heat island effect in Dhaka city. *Theor. Appl. Climatol.* 147 (3-4), 891–907. doi:10.1007/s00704-021-03872-x

UN-Habitat (2024). *World cities report 2024: cities and climate action*. Nairobi: United Nations Human Settlements Programme (UN-Habitat). Available online at: https://unhabitat.org/sites/default/files/2024/11/wcr2024_-_full_report.pdf (Accessed January 27, 2026).

UNU (2025). *Analytical report: data analyst for climate monitoring. IKI-TUC project barrio 20 urban lab – Buenos Aires, Argentina*. Bonn: United Nations University Institute for Environment and Human Security (UNU-EHS).

U.S. Department of Energy. (2022). EnergyPlus™ Version 22.1.0 documentation: engineering Reference

Wei, H., Bai, X., Lu, Q., Wu, J., Su, F., Hong, T., et al. (2025). Urban cooling and energy-saving effects of nature-based solutions across types and scales. *Nat. Cities* 2, 1194–1204. doi:10.1038/s44284-025-00349-0

Wu, Y. C., Lu, C. L., and Lin, T. P. (2025). Evaluating the effectiveness of tree canopy and building shade in urban heat mitigation using solar radiation transmittance. *Urban Clim.* 62, 102522. doi:10.1016/j.uclim.2025.102522

Zheng, Z., Fong, C. S., Aghamohammadi, N., and Law, Y. K. (2026). A systematic review of Urban Heat Island (UHI). Impacts and mitigation: health, equity, and Policy. *Systems* 14 (1), 82. doi:10.3390/systems14010082

Ziter, C. D., Pedersen, E. J., Kucharik, C. J., and Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proc. Natl. Acad. Sci.* 116 (15), 7575–7580. doi:10.1073/pnas.1817561116