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Article

Blue–Green Infrastructure Strategies for Improvement of Outdoor Thermal Comfort in Post-Socialist High-Rise Residential Areas: A Case Study of Niš, Serbia

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Abstract

Urban densification in post-socialist cities has led to the loss of open and green spaces in high-rise housing areas (HRHA), exacerbating urban heat and reducing outdoor thermal comfort (OTC). This study examines the effectiveness of blue–green infrastructure (BGI) interventions in improving OTC within an infill HRHA courtyard in Niš, Serbia, during the extreme summer heatwave of 2024. A 24-hour field campaign conducted on 14 August 2024 provided data on air temperature, humidity, wind speed, and mean radiant temperature, which were used to validate an ENVI-met microclimate model. Four scenarios were simulated: S0 (existing conditions), S1 (grass), S2 (grass + deciduous trees), and S3 (S2 + shallow reflecting pool). The results show that OTC across all open space areas was extremely poor during most of the day, with acceptable conditions only in the early morning hours. Greening and tree-planting measures produced negligible improvements in thermal comfort, while modifications of surface materials demonstrated slightly higher efficiency in reducing heat stress. These findings highlight the limited microclimatic effectiveness of small-scale surface-level interventions and emphasize the importance of integrated urban greening strategies within HRHA regeneration processes.

Keywords: Outdoor Thermal Comfort; Blue–Green Infrastructure; ENVI-met; Physiological Equivalent Temperature (PET); High-Rise Housing areas; Post-Socialist Cities

1. Introduction

The world is experiencing accelerated urbanization: cities currently accommodate 56% of the global population, a share projected to reach approximately 68% by 2050 [1]. This rapid growth intensifies pressure on urban systems, increasing housing demand and expanding densely built environments. These trends amplify both global warming and the urban heat island (UHI) effect, with well-documented implications for outdoor human thermal comfort [2–7]. The UHI—defined as systematically higher temperatures in urban areas relative to their surroundings [8]—has emerged as a critical challenge of the 21st century [9]. Prolonged heat events, driven by the combined influence of climate change and UHI, increasingly threaten public health across Europe [10–12].

Southeastern Europe exemplifies this pattern, with markedly warmer summer conditions recorded during 2024 [13,14]. In Serbia’s lowland cities, summer air temperatures rose by 4–6 °C above the 1991–2020 norm during the record-breaking 2024 European heatwave, while national projections indicate a rise in mean summer maximum temperature of approximately 4–5 °C by 2100

under high-emission pathways [15,16]. On 14 August 2024, Niš registered 41 °C—the highest temperature in Serbia that day [17]. Ensuring favorable outdoor thermal comfort (OTC) in residential environments has therefore become a pressing public-health and planning imperative.

As in other post-socialist countries, Serbia has experienced a pronounced contraction of open spaces (OS) within high-rise housing areas (HRHA) [18,19]. This trend reflects three interrelated forces.

First, intensifying urbanization and densification have replaced permeable, shaded ground with hard, impervious surfaces, increasing runoff, suppressing evapotranspiration, and exacerbating the UHI effect [20]. The result is heightened exposure to heat stress and reduced opportunities for recreation and physical activity, impacts expected to worsen under climate change [21,22].

Second, the transition from state-planned to market-oriented development after 1990 replaced long-range urban strategies with opportunity-led densification and privatization of formerly public land [23,24]. In Niš, green areas within HRHA have frequently been converted into construction land, while post-2000 General Regulation Plans stipulated a minimum of only 10% on-plot greenery [25]. Consequently, many post-socialist HRHA have become predominantly “grey,” with green-space provision dropping to ~1.2 m² per inhabitant—far below both the ~38.6% share recorded in socialist-era HRHA and international norms of 20–40 m² per resident [26].

Third, fragmented development amid prolonged political and economic crises disrupted comprehensive planning reform. Developers often pursued plot-by-plot infill construction, maximizing yield while neglecting public interest and omitting POS [27–31]. In the Municipality of Medijana (Niš), new residential blocks provide only ~0.34 m² of green space per inhabitant (~8.66% of the ground area), falling short of the prescribed 10% minimum [32]. The HRHA on Romanijska Street in Niš—an infill development within the Krivi Vir neighborhood—illustrates this pattern, with most surfaces paved and green coverage limited to ~4.3% of the plot (~0.27 m² per resident). Such conditions create a microclimatic environment conducive to strong UHI expression and thermal stress.

The reduction and fragmentation of vegetation suppress evapotranspiration and latent heat fluxes, elevating air temperature and degrading environmental quality [33–35]. Post-socialist HRHA are especially vulnerable: tall slab buildings, narrow courtyards, and extensive paving reduce the sky-view factor, hinder ventilation, and trap heat. Studies indicate that such morphologies can increase mean radiant temperature (T_{mrt}) by 6–10 °C and push Physiological Equivalent Temperature (PET) into “very hot” (>41 °C) or “extreme heat-stress” (>46 °C) categories on typical summer afternoons [36–40]. Because OTC strongly affects outdoor stay duration, social interaction, and perceived neighborhood quality [41], mitigating heat stress in OS is essential for sustainable housing strategies in post-socialist cities.

Rapid urban transformation after 1990—marked by deindustrialization, suburbanization, illegal construction, and loss of green space—has further intensified ecological pressures, including increased air and noise pollution, stormwater runoff, and UHI intensity [42,43]. Despite substantial Serbian research on these issues, practical frameworks for climate-adaptive open-space design in inherited HRHA remain underdeveloped.

International evidence, mainly from Mediterranean, East Asian, and arid North American contexts, suggests that small-scale Blue Green Infrastructure (BGI) measures (e.g., lawns, tree canopies, shallow water surfaces) can reduce PET by approximately 1–4 °C, even where air-temperature effects are modest [44–47]. The three-dimensional ENVI-met model is widely applied for such analyses, with mean absolute errors typically ≤ 2 °C for PET and ≤ 0.7 °C for air temperature following a 48-hour spin-up. However, field-validated ENVI-met applications in post-socialist infill blocks in the continental Balkans—particularly in Serbia—remain scarce. Consequently, Serbian planning regulations lack microclimate-relevant numerical thresholds for shifting PET from “extreme” to “strong heat-stress” levels in HRHA courtyards.

To address this gap, this study combines a 24-hour field campaign conducted on 14 August 2024—the peak day of the 2024 heatwave—with a validated ENVI-met model of an infill HRHA courtyard on Romanijska Street, Niš. The research aims to:

- (1) quantify air temperature (T_a), mean radiant temperature (T_{mrt}), wind speed, relative humidity, and PET under heatwave conditions;
- (2) test the cooling performance of four incremental surface-cover scenarios—S0 (concrete baseline), S1 (grass), S2 (grass plus deciduous trees), and S3 (S2 plus a ~40 m² shallow reflecting pool); and
- (3) formulate context-specific design recommendations for improving OTC in post-socialist HRHA open spaces.

This study represents, to our knowledge, the first field-validated ENVI-met analysis of a post-2000 Serbian HRHA courtyard conducted during an actual record heatwave. By examining an extreme—yet increasingly typical—density regime and testing stepwise BGI scenarios, it provides evidence-based guidance for mitigating urban heat in dense residential environments. The proposed framework offers planners and designers across the Western Balkans a practical template for embedding microclimate-responsive open-space retrofits within high-rise housing regeneration strategies.

2. Literature Review

2.1. Outdoor Thermal Comfort Indices

OTC in compact OS is determined by the interaction of environmental variables such as air temperature, wind speed, humidity, and solar radiation [48]. Numerous indices have been developed to evaluate OTC in dense urban settings, integrating meteorological, physiological, and environmental factors—most commonly the Predicted Mean Vote (PMV), Universal Thermal Climate Index (UTCI), Standard Effective Temperature (SET), Physiological Equivalent Temperature (PET), and Perceived Temperature (PT) [49–51]. Among these, PET is widely regarded as most suitable for urban applications, as demonstrated across extensive OTC research [39,47,48,50,52, 53].

PET is frequently adopted because it (i) uses the intuitive unit of degrees Celsius; (ii) is valid over a broad temperature range (−10 °C to +50 °C); (iii) requires only standard meteorological inputs; (iv) aligns with perceptible changes in thermal sensation at approximately 2 °C increments; and (v) is grounded in the Munich Energy Balance Model for Individuals, incorporating air temperature, wind, humidity, and radiation while treating personal factors (activity, clothing, age) as constants [39]. Following Hoppe [39], PET is defined as “the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor environment.”

PET became a standard metric for thermal perception studies after 2003 and has been predominant since around 2012. Consistent with Matzarakis’ classification [39], this study interprets PET values above 46 °C as indicating extreme heat stress (Figure 1). Previous research further demonstrates that modifying landscape cover—such as increasing grass or tree canopy—can substantially improve OTC in high-rise urban environments, even during the hottest summer periods.

Building on this empirical evidence, numerous studies have employed microclimate simulation tools, particularly ENVI-met, to quantify the cooling potential of BGI in dense urban settings.

PET (°C)	Thermal Perception	Grade of Physiological Stress Level
< 4	Very cold	Extreme cold stress
4 – 8	Cold	Strong cold stress
8 – 13	Cool	Moderate cold stress
13 – 18	Slightly cool	Slight cold stress
18 – 23	Comfortable	No thermal stress
23 – 29	Slightly warm	Slight heat stress
29 – 35	Warm	Moderate heat stress
35 – 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Figure 1. Ranges of the PET for different grades of thermal perception by human beings and physiological stress on human beings [39].

2.2. Microclimate Simulation on Open Spaces in High-Rise Housing Areas and the Cooling Performance of Blue-Green Infrastructure

A large proportion of OTC assessments in HRHA employ ENVI-met, a three-dimensional microclimate model used to simulate the influence of BGI on thermal conditions [54, 55]. ENVI-met resolves building–vegetation–atmosphere interactions at high spatial and temporal resolution, enabling detailed analyses of how urban configuration and environmental modifications (e.g., radiation environment, wind flow, and surface properties) affect OTC in OS.

ENVI-met has demonstrated robustness across diverse climatic contexts [56–59]. Courtyard validations in mid-latitude settings commonly report RMSE ≤ 0.7 °C for air temperature (T_a) and ≤ 2 °C for PET after a 48-hour spin-up [56]. Recent model developments include refined tree-physiology algorithms and reflective-water modules. For biothermal assessment, the BioMet module computes comfort indices such as PMV, PET, and UTCI; in this study, BioMet was employed to calculate PET following field measurements.

Numerous ENVI-met studies have evaluated strategies for mitigating thermal stress in dense urban morphologies. Mahmoud et al. [60] demonstrated that scenarios combining vegetation and shading (e.g., grass, trees, semi-shaded surfaces) can reduce PET by 13.6–19.1 °C. Vegetation—through canopy shade and evapotranspiration—consistently lowers surface and near-surface temperatures, improving OTC; these benefits have been reported for both tree planting and green roofs [61]. Using ENVI-met, Aydin et al. [62] found that increasing green space and optimizing building layouts can reduce thermal discomfort in high-rise environments. Additional research indicates that reflective materials and expanded tree coverage near tall buildings can decrease local air temperatures and enhance OTC [63]. Tan et al. [64] concluded that tree planting—especially when coordinated with urban form—effectively mitigates daytime UHI effects, with air-temperature reductions up to 1.5 °C. Similarly, Jin et al. [64] reported that tripling tree numbers relative to advisory guidelines lowered average T_a by 0.87 °C, mean radiant temperature (T_{mrt}) by 11.00 °C, and PET by 4.50 °C.

Designing OS in HRHA is inherently challenging because tall buildings alter shading regimes, modify wind patterns, and trap longwave radiation, collectively intensifying heat stress. ENVI-met facilitates ex-ante testing of interventions such as strategic vegetation placement, surface-material selection, and adjustments in building orientation or spacing. Despite its demonstrated utility, a regional research gap remains: no validated ENVI-met applications have yet been documented for Serbian infill HRHA, leaving uncertainties about model calibration, parameterization, and scenario design in this specific urban context.

Beyond modeling evidence, the thermal effects of vegetation are well established: urban greenery improves microclimate and mitigates UHI by reducing summer temperatures [65], with effectiveness confirmed across multiple regions [66–68]. Recent studies underscore the role of BGI in climate adaptation and OTC improvement [69–71], alongside co-benefits such as air purification,

urban agriculture, and overall microclimate regulation. While large urban parks average approximately 1 °C cooler than surrounding built-up areas—and larger parks exhibit stronger cooling [72]—small-scale interventions (lawns, green roofs, urban gardens, street trees) can also deliver meaningful cooling benefits where land for large parks is limited. Such measures are particularly relevant for HRHA, where high density restricts boundary-layer airflow and ventilation, intensifying heat stress and reducing opportunities for outdoor activity [73,74].

Specific findings on the cooling performance of BGI include:

- **Vegetation.** Meta-analyses suggest that every 10% increase in canopy cover can reduce T_{mrt} by 4–6 °C and PET by 1–2 °C during mid-afternoon [75]. Even modest green areas can cool by 1–3 °C relative to paved surfaces; tree planting consistently reduces maximum air and surface temperatures, achieving average PET reductions of approximately 13% compared with existing vegetation [65].
- **Water features.** During summer, water elements rank among the most effective cooling strategies. Shallow pools (<100 m²) or mist fountains typically provide 0.5–1.2 °C PET relief, while improvements exceeding 2 °C are reported when water areas surpass ~20 m² or include active misting [76,77].
- **Albedo and permeability.** Bright, permeable pavements operate 8–12 °C cooler than asphalt under direct sun; however, their PET impact is secondary when the sky-view factor (SVF) falls below ~0.35. Impervious pavements may reach 12–15 °C higher surface temperatures than adjacent grassed or tree-shaded zones, particularly under dense summer conditions [78].

In addition, building shading can substantially improve OTC in OS by reducing radiant exposure during peak hours [79,80].

Despite these global insights, empirical research remains unevenly distributed, with limited evidence from post-socialist and Western Balkan contexts.

2.3. The Western Balkan Evidence Gap

Since 2000, urban densification in post-socialist cities has markedly reduced public open space per resident, resulting in overcrowding, declining environmental quality, and limited access to green infrastructure [18,81,82]. In the Western Balkans, densification policies have promoted infill construction on formerly communal OS, producing courtyards that are approximately 85–90% impervious and largely treeless. Unlike socialist-era estates—characterized by generous greenery—many new developments leave minimal space for conventional residential OS. Empirical OTC studies, however, remain concentrated in Mediterranean and Asian contexts or focus on public squares in post-socialist cities [83]. To the best of the author's knowledge, only one study [84] has examined inherited socialist blocks, and new-build infill courtyards remain empirically unexplored. Notably, no study has yet paired field measurements with ENVI-met simulations for Serbian infill estates.

As a result, Serbian planners currently lack locally grounded design thresholds—for example, minimum canopy coverage, water-surface ratios, or wind-corridor parameters—together with urban-morphological principles for mitigating heat stress in HRHA across post-socialist European contexts. This study addresses that gap by providing the first measurement-validated ENVI-met assessment of incremental BGI retrofits in a Serbian HRHA infill courtyard, contributing essential evidence for climate-adaptive neighborhood design in the post-socialist Balkans.

3. Materials and Methods

This study combines field measurements, OTC assessment, and microclimate modeling to examine the effects of BGI strategies on OTC in OS within an infill HRHA in Niš, Serbia. The overarching aim is to identify configurations that improve the summer microclimate for residents. The workflow comprised four stages: (1) scoping the study area; (2) conducting a 24-hour field campaign to collect meteorological data; (3) constructing a base ENVI-met model (BM); and (4)

simulating alternative BGI scenarios. Field measurements were complemented with data from the Meteorological Monthly Bulletin for Serbia: August 2024 [85].

3.1. Climate Conditions and Study Area

The city of Niš is located in the southeastern part of the Republic of Serbia (43°19' N, 21°54' E), as shown in Figure 2a [86]. According to the 2022 census, the administrative district (596.73 km²) has a population of 250,648. Niš functions as the macro-regional center of South and East Serbia and serves as the seat of the Nišava Administrative District. The Nišava River traverses the city, while its last major left-bank tributary, the Gabrovačka River, flows through the Krivi Vir and Krive Livade residential areas.

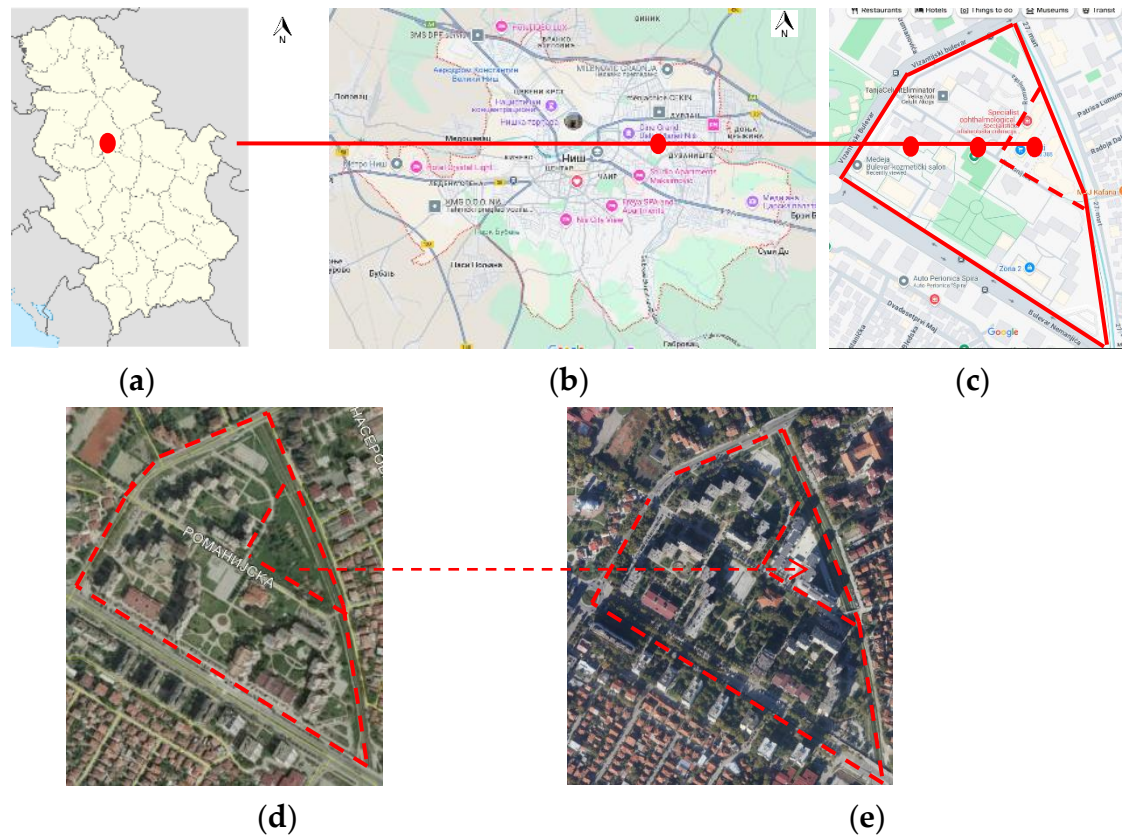


Figure 2. Study area HRHA in Romanijska street, Niš, Serbia (a) Geographical of city of Niš in Serbia; (b) Location of neighbourhood Krivi vir in Niš; (c) Location of Romanijska street HRHA in the neighbourhood Krivi Vir; (d) Location in 2006; (e) Location in 2025. [86,87, 88].

Climatically, Niš exhibits a humid subtropical regime (Köppen classification) influenced by both Mediterranean and continental conditions, resulting in pronounced seasonal variation. The mean annual air temperature is 12.4 °C. Analysis of recent summers (June–August) indicates that the highest temperatures typically occur in July and August [89]. In August 2024, the average daily temperature was approximately 29 °C, nearly 3 °C above the long-term norm, indicating substantial summer heat stress. Serbia experienced five heat waves during the summer of 2024 [87]; the fourth affected the entire country and persisted for eight days in Niš (11–18 August). While average summer temperatures are moderate, extreme daytime maxima reached 41 °C in August 2024, making Niš the hottest city in Serbia on that date. The field campaign for this study was conducted on 14 August 2024, a characteristically extreme hot day in Niš.

3.1.1. Selection of High-Rise housing area for Case Study

A critically important yet under-researched typology in Serbia and across post-socialist Europe is the infill HRHA that proliferated during late socialism and, especially, after 2000. Unlike many

modernist predecessors, numerous post-2000 blocks in Serbia replaced communal green zones with underground garages and paved courtyards. The HRHA on Romanijska Street (Figure 2b, c), situated within the Krivi Vir neighborhood of Niš, was selected to illustrate these conditions.

Krivi Vir, initially developed on the urban fringe in the early 1980s, forms part of the Bulevar Nemanjića residential zone—the city's largest multi-family housing area. The study parcel, bounded by Romanijska Street and the Gabrovačka River, was constructed as an infill development on previously vacant green land between 2007 and 2010 by private investors, substantially reducing greenery within an already dense urban fabric (Figure 2d, e). This makes the site a representative post-socialist infill development in Niš (and in other Serbian cities) and a suitable platform for investigating summertime OTC.

The study area is semi-open and comprises two eight-story residential buildings (R1 and R2; ~27 m in height) and two underground garages (Figure 3a). The original plan envisioned six-story residential buildings with ground-floor commercial facilities and a central communal courtyard featuring playgrounds, gathering areas, and greenery—particularly along the Gabrovačka River frontage. These provisions were not implemented. Instead, eight-story residential buildings were constructed with ground-floor apartments facing the inner courtyard, and two commercial buildings were added within the central OS toward Romanijska Street, partly occupying the previously planned small green zone. Consequently, greenery is extremely scarce, limited to a few planter boxes and a small green patch in the northeastern part of the site (Figure 3a).

The total green area measures approximately 500 m², representing about 4.3% of the building plot—well below the minimum 10% required by the General Regulation Plan (PGR) of the Municipality of Medijana for this location [25]. The remaining 95% of the OS is paved with concrete blocks and asphalt, rendering the courtyard predominantly impermeable.

Key urban-form parameters underscore the extremity of conditions:

- Site coverage index: 0.43 (buildings occupy 43% of the parcel)
- Floor-area ratio (FAR): 3.27 (very high built intensity)
- Population density: extremely high (site-specific figures withheld for confidentiality).

Per-capita open space is approximately 3.45 m²/inhabitant, and per-capita green area is ~0.27 m²/inhabitant—far below the already low average of ~1.2 m²/inhabitant reported for the Municipality of Medijana, and especially below the commonly cited minimum of 9 m² of urban green space per capita in WHO-linked studies [29].

The loss and fragmentation of OS have degraded environmental quality and eliminated a vital buffer against extreme heat, creating a courtyard morphology with strong preconditions for UHI amplification and degraded OTC.



R- residential building; C. Commercial building; p- paved spaces; g-green spaces

Figure 3. Study area: (a) Detailed view of the study area [87]; (b-e): Observation points P1-P4- Measurement instruments locations.

3.2. Field Study, Measurement Indicators, and Instruments

A continuous 24-h on-site campaign was carried out on 14 August 2024, selected based on official meteorological reports [85] identifying August 2024 as the warmest on record at most main stations in Serbia. In Niš, the average monthly air temperature in August 2024 was 26.0 °C, with an anomaly of +2.9 °C and 28 tropical days, marking the warmest August since instrumental records began in 1925. 14 August 2024 was an extremely hot, clear-sky day—the peak of the 2024 Balkan heat wave—with a synoptic $T_{\text{max}} = 40.5$ °C at the Niš Fortress station (WMO 13270).

The field survey comprised two components: (i) outdoor microclimate measurements and (ii) built-environment documentation.

3.2.1. Outdoor Microclimate Measurements

Meteorological variables—air temperature (T_{ar} , °C), relative humidity (RH, %), and wind speed (W , $m\ s^{-1}$)—were recorded using a mobile array of HOBO U23 dataloggers mounted 1.5 m above ground level at representative OS locations (Figure 4). The sensors met the ISO 7726 requirements for thermal-environment measurement and were connected to an Almemo portable data logger. The sampling interval was set to 2 minutes to capture short-term variability.



Figure 4. Mobile meteorological station.

Wind speed was additionally measured with a Lutron AM-4215SD hot-wire anemometer (accuracy $\pm 5\% + 0.1\ m\ s^{-1}$, per product manual). Parallel datasets were obtained from the Niš Fortress Meteorological Station for the same period to support calibration and validation of site-specific measurements. The instrument locations on observation points P1-P4 within the HRHA are shown in Figure 3.

The date 14 August 2024 was selected for simulation and validation because it combined clear-sky conditions, weak winds, and no precipitation during the preceding three days—conditions conducive to strong UHI expression. Initial meteorological inputs for the ENVI-met model were derived from the field campaign and the station records (Table 1).

Table 1. Meteorological data on 14 August 2024.

Weather	Maximum Air Temperature (°C)	Minimum Air Temperature (°C)	Wind Velocity (m/s)	Wind Direction	Realitve Humidity (%)
Sunny	40.5	25.2		South-East	

The ENVI-met simulation covered 00:00–24:00 CET, producing hourly outputs. High-frequency calculations (1-minute internal timestep) were applied during peak daytime hours. The main input parameters are summarized in Table 1, and the calibrated base model is illustrated in Figure 5.

To capture intra-courtyard variability related to geometry, land cover, and use, the study area was partitioned into three functional sub-zones, with four observation points (P1–P4) instrumented (Figure 3b–e; Table 2):

- P1 – Central paved OS above the underground garage (no vegetation or equipment). Located in the geometric center, flanked by 8-story residential blocks on two long sides; the southwest short

side hosts two single-story commercial buildings, while the northeast side remains largely undeveloped. As in many Niš HRHA courtyards, occasional informal parking on the southeast margin further degrades the microclimate (heated vehicle masses, tailpipe emissions).

- P2 – Asphalt parking area (southeast of R2, above the second underground garage). Originally conceived as part of the communal OS connected with the greenery along the Gabrovačka River, the area has been repurposed for parking.
- P3 – The only larger lawn (northeastern sector). A small but critical grassed patch representing the sole sizeable permeable and vegetated surface within the courtyard.
- P4 – Narrow paved corridor between R1, R2, and a commercial unit (no vegetation). A linear, high-aspect-ratio passage with limited sky view, analogous to P1 in its lack of vegetation.

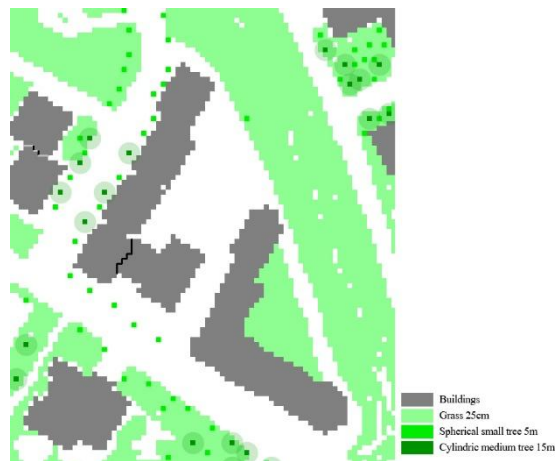


Figure 5. ENVI-met model domain of the Romanijska Street HRHA in Niš, Serbia. The 3D model configuration represents the base case scenario (S0), including building geometry, open space layout, and surface characteristics. Model grid: 30 × 30 × 15, with a grid cell size of 2 × 2 × 2 m.

Table 2. Characteristics of the selected observation points [90].

OP	Surface & setting	Shade regime
P1	Central paved court (concrete)	Full sun 06:30 – 13:00 h; shaded by 27 m south façade thereafter
P2	Asphalt parking, north-east sub-court	Sun-exposed from until 16:00 h; partial shade afterwards
P3	Existing lawn above garage slab	Sun-exposed until 16:00 h
P4	Narrow paved canyon (2 m width)	Sun 08:00 – 13:30 h; shaded by 27 m and 6 m blocks

3.2.2. Built-Environment Documentation

A concurrent survey catalogued vegetation types and conditions, surface materials, and building morphology using direct field observation, measuring equipment, detailed cadastral maps, Google Earth imagery, and plan documentation.

The base case layout consists of a lawn behind one residential block, a small street-edge lawn with planters, and extensive paved surfaces elsewhere.

The collected microclimate parameters were used as input data for ENVI-met 4.3.3 to construct the model. The BioMet submodule of ENVI-met software was employed to calculate thermal comfort indicators, specifically the PET index, for both measured and simulated datasets.

3.3. ENVI-met Model Setup

The existing condition (BM) was simulated using ENVI-met v4.4.5, calibrated against on-site measurements and cross-validated with data from the Niš Fortress Meteorological Station (WMO 13270). The computational domain comprised 30 × 30 × 15 cells with a spatial resolution of 2 × 2 × 2 m. Hourly meteorological forcing for 00:00–24:00 CET on 14 August 2024 was derived from the

station’s hourly dataset. Large-scale wind veered from 190° at 1.5 m s⁻¹ (02:00) to 230° at 2.4 m s⁻¹ (14:00). A 48-hour spin-up period was applied to equilibrate soil and wall heat storage.

Key atmospheric inputs and model settings are summarized in Table 3, which also clarifies the relationship between the station’s synoptic maximum and the hourly forcing maximum used in the model. The BM geometry is shown in Figure 5, and the scenario layouts (S0–S3) in Figure 6.

Table 3. Initial input parameters for the ENVI-met simulation on 14 August 2024 (Niš, Serbia). *Note: The synoptic daily maximum (40.5 °C) differs from the hourly forcing maximum (38.2 °C) due to temporal averaging; see Section 3.3 for calibration details.*

Parameter	Value	Source
Simulation period	14 August 2024, 00:00–24:00	Niš Meteorological Station (WMO 13270)
Daily maximum air temp.	38.2 °C (forcing)	Niš Meteorological Station (hourly series)
Synoptic maximum (reference)	40.5 °C	Niš Meteorological Station (daily synoptic)
Relative humidity (mean)	39 %	Field survey calibration + station data
Wind speed / direction	1.5 m·s ⁻¹ @ 190° → 2.4 m·s ⁻¹ @ 230°	Niš Meteorological Station
Simulation period	14 August 2024, 00:00–24:00	Niš Meteorological Station (WMO 13270)
Daily maximum air temp.	38.2 °C (forcing)	Niš Meteorological Station (hourly series)
Synoptic maximum (reference)	40.5 °C	Niš Meteorological Station (daily synoptic)
Relative humidity (mean)	39 %	Field survey calibration + station data
Wind speed / direction	1.5 m·s ⁻¹ @ 190° → 2.4 m·s ⁻¹ @ 230°	Niš Meteorological Station
Spin-up period	48 h	ENVI-met best practice
Grid dimensions	30 × 30 × 15	Model setup
Grid cell size	2 m × 2 m × 2 m	Model setup
Calculation height for PET	1.4 m	BioMet (ENVI-met build 2025-05-12)
Human parameters	M = 80 W·m ⁻² , clo = 0.6	ISO 7726 standard

Following the parameters listed in Table 3, PET was calculated at 1.4 m height using BioMet (ENVI-met build 2025-05-12) with standard personal parameters: metabolic rate 80 W m⁻², clothing insulation 0.6 clo, and reference air speed 0.1 m s⁻¹. Model outputs (T_a, T_{mrt}, PET, SVF) were archived at hourly intervals across the 24-hour simulation period, with finer internal timesteps inspected during daytime peaks.

The difference between the synoptic maximum (40.5 °C) and the hourly forcing maximum (38.2 °C), as noted in Table 1, reflects temporal aggregation. Calibration aligned modeled diurnal peaks with on-site sensor records within the expected tolerance range.

3.4. Definition of the Project Scenarios

This study evaluates ground-level BGI solutions to improve OTC within the selected HRHA courtyard. The analysis is intentionally confined to interventions at the deck level above the underground garages and adjacent paved areas, reflecting the site’s existing conditions and realistic constructability constraints.

Envelope retrofits (façades and roofs) and full pavement replacement with porous slab systems were excluded, as they lie beyond the scope of this study. As noted in the Introduction, such measures are presently unlikely to be implemented at scale in Serbia under current budgetary and institutional constraints—this remains a contextual assumption rather than a cost-analysis limitation.

In several European cities (e.g., Copenhagen, Berlin, Stuttgart), intensive green roofs over garage decks have successfully converted formerly paved public open spaces into multifunctional

courtyards (lawns, pedestrian paths, play areas, tree plantings) with documented OTC and social co-benefits [91–93]. The scenarios developed here adapt these principles to the Serbian case context.

BGI measures were targeted at P1 and P4 (central and corridor paved areas). No interventions were defined at P2 (vehicular passage near the riverbank) or P3 (existing lawn), the latter serving as a limited green reference. Because the modeled OS areas are predominantly situated above the garage slab, proposed planting typologies were restricted to loads compatible with deck construction. A formal structural-capacity and waterproofing assessment is assumed as a prerequisite for real-world implementation but lies outside the scope of this research.

To test mitigation potential and derive design guidance, four incremental surface-cover scenarios were defined and simulated in ENVI-met (Figures 6a–d). Building geometry, traffic layout, and meteorological forcing were held constant across all runs; only ground-level materials and vegetation/water elements were varied:

- S0 — Base case: Existing condition with continuous concrete/asphalt paving except for a $\sim 420 \text{ m}^2$ lawn above the garage at P3 and a $\sim 30 \text{ m}^2$ lawn in front of commercial building C2.
- S1 — Grass: Replacement of selected paved areas by lawn over the garage deck between and in front of R1 and R2, focusing on P1 and P4.
- S2 — Grass + Deciduous Trees: Scenario S1 plus deciduous canopy trees positioned on the deck (in load-appropriate planting pits), primarily around P1 and P4 and between R1 and R2.
- S3 — S2 + Shallow Reflecting Pool: Scenario S2 augmented with a $\sim 40 \text{ m}^2$ shallow reflecting pool located on the deck near P1.

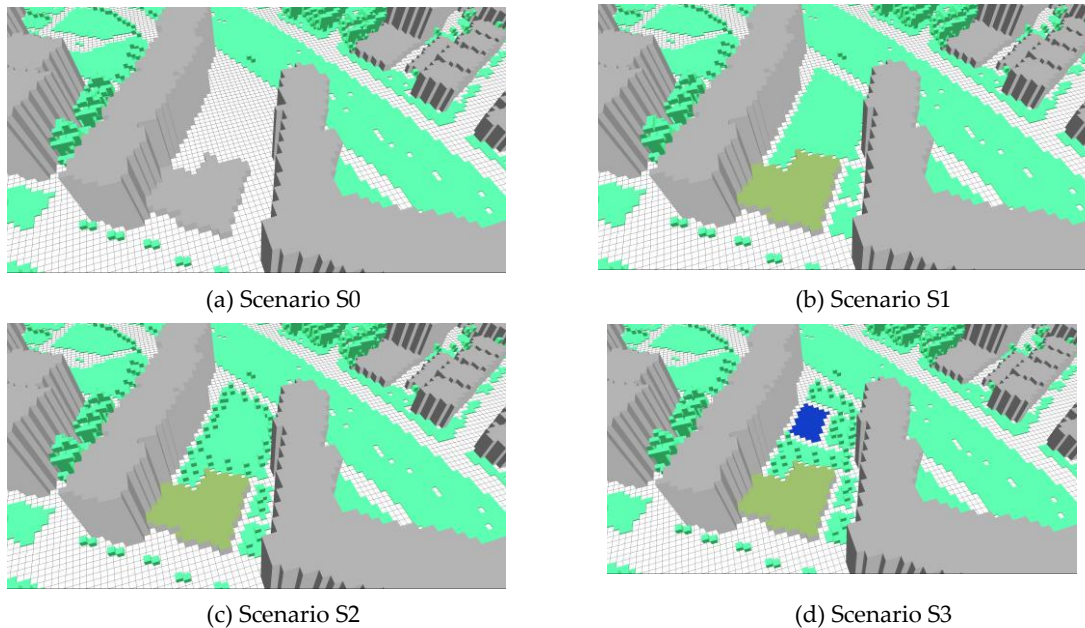


Figure 6. Layout of scenarios; (a) S0; (b) S1; (c) S2; (d) S3.

These scenarios were designed to isolate the stepwise cooling contributions of vegetation cover (grass and trees) and the small water surface, allowing direct comparison of diurnal T_a , T_{mrt} , and PET responses under identical boundary conditions. Results are reported relative to S0 (BM), with spatial emphasis on the monitored points (P1–P4) and key activity nodes within the courtyard.

4. Results

4.1. Validation

A one-day summer field campaign was conducted under clear-sky and calm conditions within the study block. Micrometeorological variables at pedestrian height ($\sim 1.5 \text{ m}$) were recorded using HOBO U23 dataloggers connected to an Almemo portable data logger, while wind speed was

measured with a Lutron AM-4215SD hot-wire anemometer [94]. Concurrent observations from the Niš Fortress Meteorological Station were used both to force and to constrain the ENVI-met simulations (see Table 3 for forcing inputs).

The ENVI-met simulation included a 48-hour spin-up period preceding the analysis window to allow soil and façade heat stores and the radiative–aerodynamic budget to reach a quasi-steady diurnal cycle; only post-spin-up outputs were retained for comparison. Discarding early-hour outputs to avoid initialization artefacts follows standard practice in urban-microclimate validation studies [95,96].

Field time series were time-aligned with model outputs, screened for outliers and spikes, aggregated to the model’s temporal resolution, and harmonized for measurement height and radiative quantities prior to evaluation.

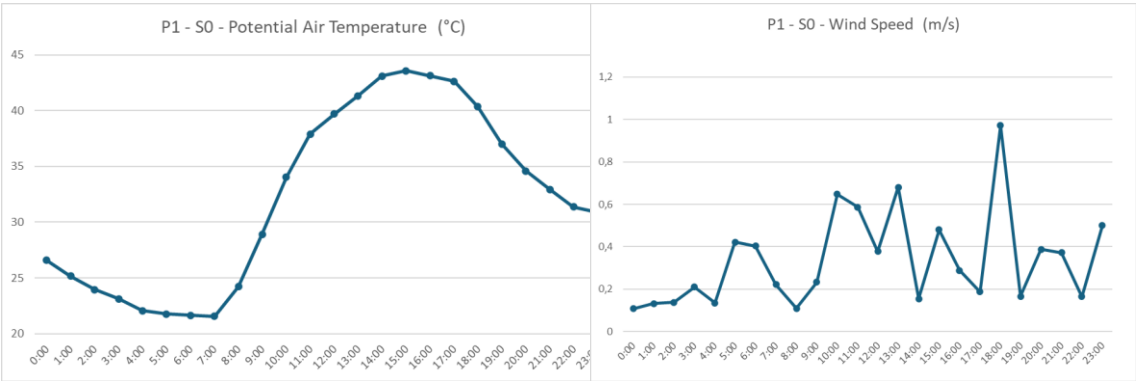
Model–measurement agreement was assessed point-wise at P1–P4 for air temperature (T_a), relative humidity (RH), wind speed (W), and mean radiant temperature (T_{mrt}). PET was computed from model outputs using BioMet, with the same personal parameters specified in Section 3.3. Model performance was quantified using mean absolute error (MAE), root mean square error (RMSE), mean bias error (MBE), and coefficient of determination (R^2), reported both for daytime peak hours and for the full 24-hour period (see figures and tables in the following subsections).

This validation protocol—comprising local meteorological forcing, explicit spin-up, and point-wise comparison for T_a , RH, W , T_{mrt} and PET—is consistent with recent studies demonstrating planning-grade accuracy for ENVI-met v4/v5 in courtyard and dense-urban environments when locally forced and calibrated. Superior agreement has been reported where local forcing and updated radiation schemes are applied [97], with multi-site confirmations in [94,98]. PET calculation followed the ENVI-met BioMet manual.

Because wind and radiation forcing critically influence model skill, these parameters were specified with particular care. Despite improvements in ENVI-met v5, summer T_{mrt} peaks can still be slightly underestimated—a tendency considered in the interpretation of PET patterns and heat-stress class transitions [99,100].

4.2. Overview of microclimatic parameters and PET values of individual parts of OS - Scenario S0 - existing state

For the existing condition (S0), diurnal profiles of Potential Air Temperature (PAT), W , RH, and PET were analyzed at four observation points (P1–P4). Hourly trajectories are shown in Figures 7–10, and the corresponding values and summary statistics are given in Table 4.



a) PAT chart for P1

b) chart W for P1

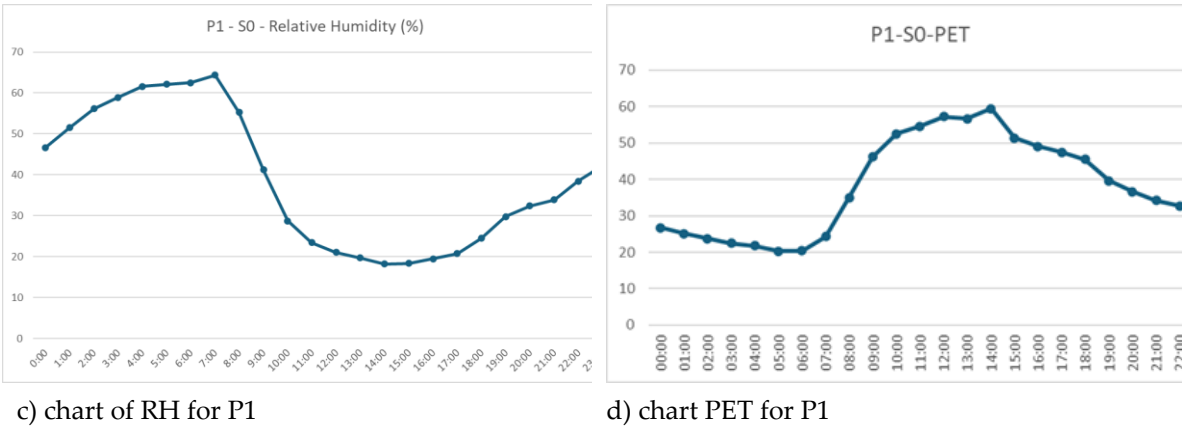


Figure 7. Scenario S0-existing condition: hourly (a) PAT; (b)W; (c) RH; (d) PET hourly at P1.

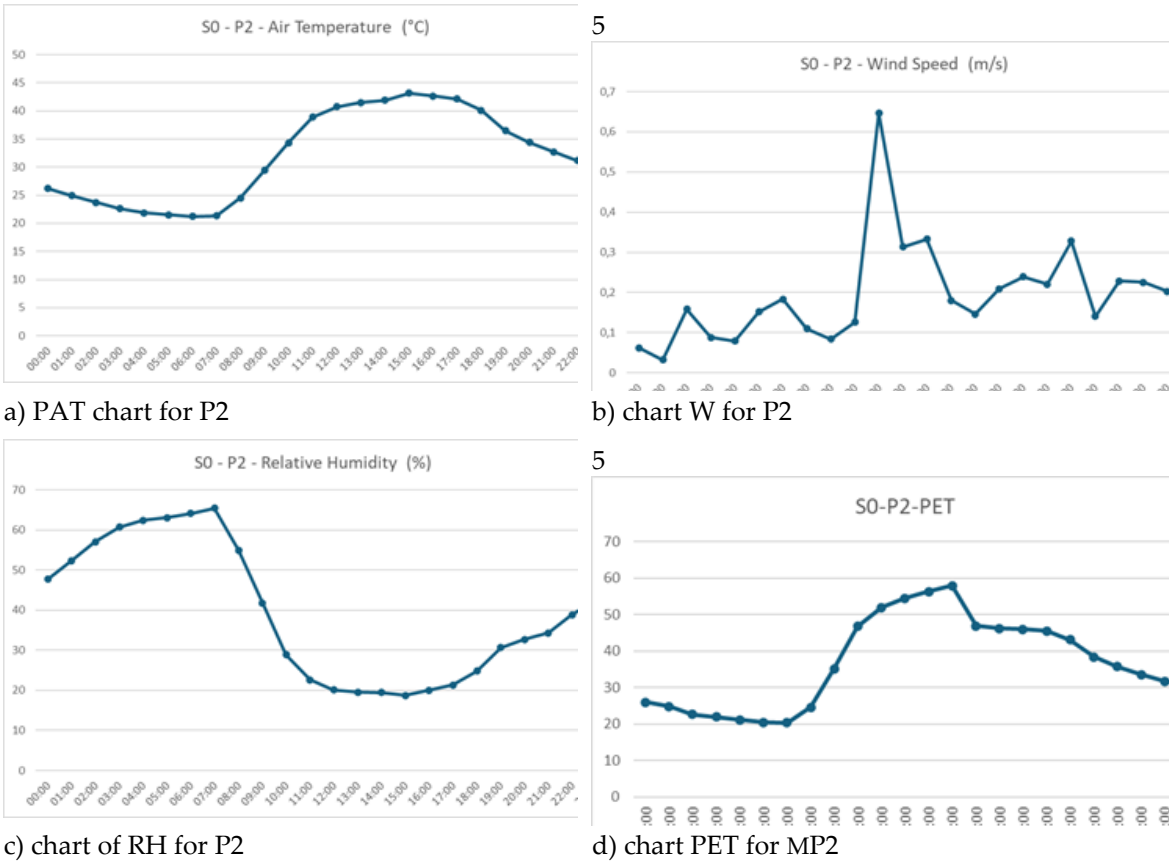
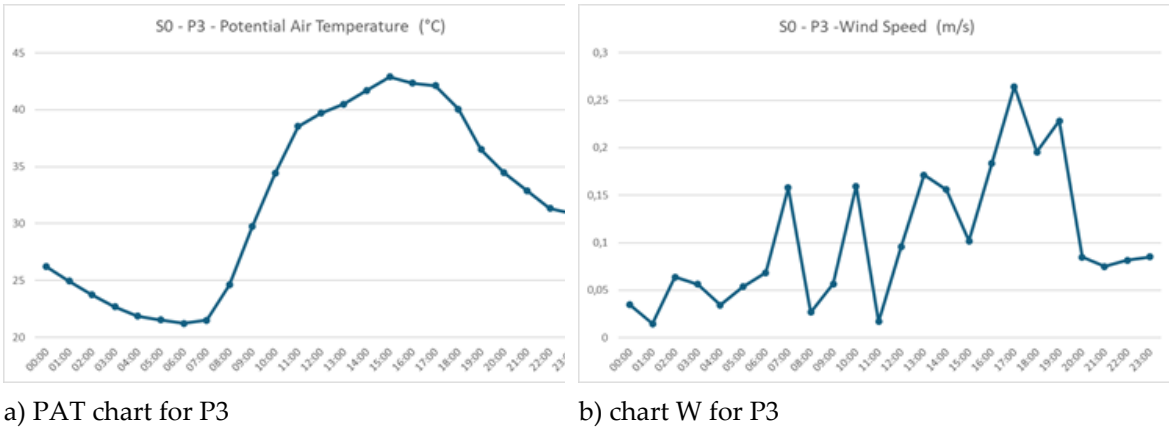


Figure 8. Scenario S0-existing condition: hourly (a) PAT; (b)W; (c) RH; (d) PET hourly at P2.



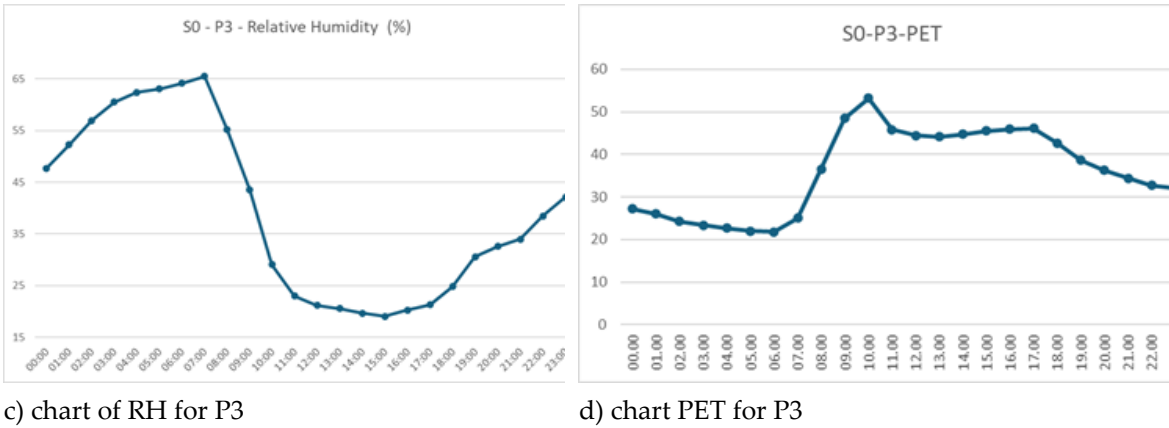


Figure 9. Scenario S0-existing condition: hourly (a) PAT; (b)W; (c) RH; (d) PET hourly at P3.

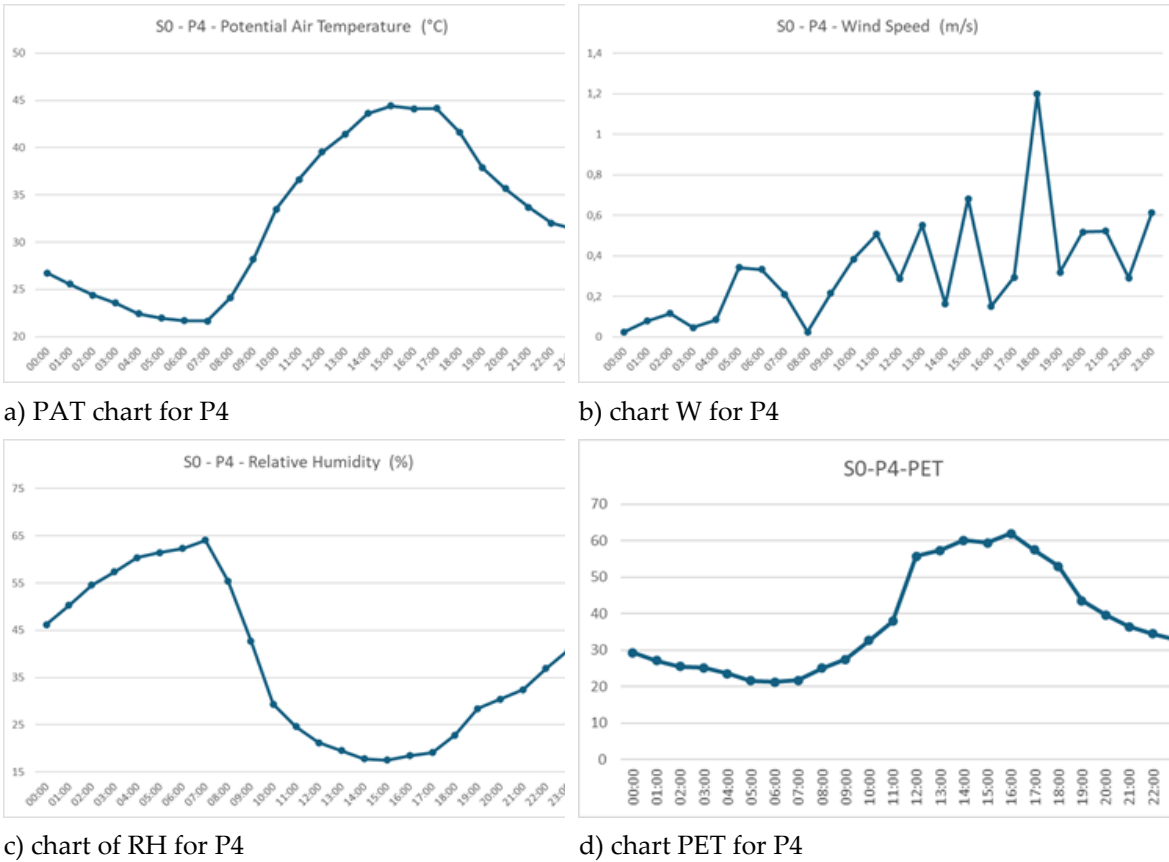


Figure 10. Scenario S0-existing condition: hourly (a) PAT; (b)W; (c) RH; (d) PET hourly at P4.

Table 4. Scenario S0-existing condition: hourly values and summary statistics of PAT, W, RH, and PET at P1–P4.

P1		P2		P3		P4		
Time (h)	PAT (°C)	PET (°C)	PAT (°C)	PET (°C)	PAT (°C)	PET (°C)	PAT (°C)	PET (°C)
1	2	3	4	5	6	7	8	9
0.00								
1.00								
2.00								
3.00								
4.00	Fall on 21.57	Fall on 20,30	Fall on 21.24	Fall on 20.29	Fall on 21.30	Fall on 21.85	Fall on 21.68	Fall on 21.24
5.00								

6.00							
7.00							
8.00							
9.00					Rise on 53.21		
10.00					max		
11.00				Rise on 57.95			
12.00		Rise on		max			
13.00	Rise on 43.57	59.40	Rise on 43.17		Rise on 42.90	Rise on 44.43	Rise on 61.94
14.00	max	max	max		max	max	max
15.00							
16.00							
17.00							
18.00							
19.00							
20.00							
21.00				Fall on 31.10	Fall on 32.04		
22.00	Fall on	Fall on	Fall on 30.80		Fall on 30.87	Fall on 31.36	Fall on 32.73
23.00	30.89	31.23					
- speed W variable and relatively low, from 0.11-0.97 m/s,		- W is pulsating with an interval of usually 2 hours, the speed of W is low, from 0.03-0.64 m/s,		- W of variable intensity but very low speed of 0.048-0.264 m/s,		- W is pulsating with an interval of usually 2 hours, the speed of W is small from 0.024-0.68 m/s,	
- the change in RH approximately follows the decline and growth of PET, but inversely proportionally, from 18.23 to 64.38%.		- RH drops until 03.00 pm (from 47.73 to 18.76%), then rises to 42.32 % at 11 pm, inversely proportional to PAT.		- RH rises up to 07.00 am (from 47.72-65.50 %), then falls to 20.293 at 04.00 PM, then rises again to 42.11 % at 11 PM.		- RH increases until 07:00 a.m. (from 46.24-64.04%), then falls to 17.54% at 03:00 PM, then rises again to 40.88% at 11:00 PM.	

According to the data provided in Table 4, the following results were identified:

- At the observation point P1, representing a paved courtyard enclosed by buildings on three sides, PAT decreased between 00:00 and 07:00 h, then rose to its maximum at 15:00 h. The PET curve generally followed this trend, with the lowest PAT occurring one hour after the most comfortable period. An inverse relationship was observed between PET and RH. Surrounding buildings and paved surfaces re-emitted stored heat, while the lack of ventilation contributed to PET rising from 05:00 h and reaching a relatively high maximum at 14:00 h. Despite façade shading after 15:00 h, thermal relief remained insufficient. Acceptable comfort occurred only between 00:00–03:00 and at 07:00 h, while pleasant conditions were limited to 03:00–06:00 h. By late evening (23:00 h), PET remained around 30.89 °C.
- At the observation point P4, located in a narrow-paved canyon, similar diurnal dynamics of PAT and RH were observed, with minor magnitude differences. The minimum PET occurred one hour earlier, while the maximum PET of 61.94 °C—the highest of all points—appeared one hour later than the PAT maximum. Due to limited air movement and strong heat accumulation caused by the enclosed geometry, OTC remained poor despite shading between 11:00 and 17:00–18:00 h. Pleasant comfort occurred only between 05:00–07:00 h.
- At observation points P2 and P3, Parking and Lawn Areas: PAT decreased between 00:00–06:00 h and peaked at 14:00 h, with negligible differences between these two locations. RH varied inversely with PAT:
 - At P2, PET decreased from 00:00–06:00 h and reached its maximum at 13:00 h—two hours earlier than the PAT peak—due to heat release from dark asphalt.

2. At P3, PET also decreased from 00:00–06:00 h and peaked at 53.21 °C at 10:00 h, which is 4–6 °C lower than the maxima at P1 and P2. This early peak reflected the dry, east-oriented lawn lacking shade, with relatively low RH and weak ventilation (low W). Pleasant comfort occurred between 04:00–06:00 h, and acceptable comfort was confined to 00:00–04:00 h and at 07:00 h.

Across all OS areas, OTC conditions were predominantly unfavorable, with acceptable levels observed only during the early morning hours.

4.3. Overview of microclimate parameters and PET values of scenarios of individual parts of open space

For scenario comparison, diurnal series of PAT, W, RH, and PET were evaluated for two representative observation points—P1 (central paved courtyard) and P4 (narrow paved canyon)—across all simulated scenarios (S0–S3). Hourly profiles are shown in Figures 11–12, with detailed hourly values in Tables 5 and 6.

Based on ENVI-met outputs, as well as Figures 11 and Tables 5, the following observations can be made for the observation point P1:

- In Scenario S1, PAT followed a similar trend as in S0, being up to 1.2 °C lower in early morning and up to 0.9 °C higher at midday. PET values were slightly reduced—by less than 1.67 °C—compared to S0. Neither the presence of lawn nor façade shading after 15:00 h substantially improved thermal comfort, which remained pleasant or acceptable only from 00:00–07:00 h, as in S0.
- In Scenario S2, PAT, RH, and W differed negligibly from S0, with PET reduced by about 1.2 °C only during early morning hours—insufficient to improve daytime comfort. Pleasant or acceptable comfort persisted only from 00:00–07:00 h.
- In Scenario S3, PAT and W differed minimally from S0, RH varied by up to 3.65%, and PET values were slightly lower—by up to 2.68 °C at 10:00 h. As in S0, shading after 15:00 h failed to bring conditions to acceptable levels; comfort remained confined to early morning hours (00:00–07:00 h).

Therefore, the applied surface-level modifications had a negligible effect on the OTCat P1, indicating limited microclimatic efficiency under the given conditions.

Table 5. Observation point P1: hourly values and ΔPET per scenario.

Time (h)	S0			S1			S2			S3		
	PAT (°C)	PET (°C)	ΔPET (°C)	PAT (°C)	PET (°C)	ΔPET (°C)	PAT (°C)	PET (°C)	ΔPET (°C)	PAT (°C)	PET (°C)	ΔPET (°C)
1	2	3	4	5	6	7	8	9	10	11	12	13
0.00												
1.00												
2.00												
3.00												
4.00		Fall on			Fall on	(0.5h)	Fall on	Fall on	(0.5h)		Fall on	(0.5h)
5.00		20,30			19.10	-1.20	20.94	19.10	-1.20		19.10	-1.20
6.00	Fall on			Fall on						Fall on		
7.00	21.57			20.98						20.93		
8.00												
9.00												
10.00												
11.00												
12.00		Rise on			Rise on			Rise on			Rise	
13.00		59.40			59.21	(14 h)		59.20	(14 h)		on	
14.00	Rise on	max		Rise on	max	-0.19	Rise on	max	-0.20		58.84	(14 h)
15.00	43.57						44.01			Rise on	max	-0.56
16.00												
17.00												

18.00											
19.00											
20.00											
21.00	Fall on		Fall on	Fall on	(23 h)	Fall on	Fall on	(23 h)	Fall on	Fall on	(23 h)
22.00	30.89	Fall on	30.74	30.26	-0.96	30.73	30.25	-0.98	30.73	29.83	-1.40
23.00		31.23									

- speed W variable and relatively low, from 0.11-0.97 m/s,

- the change in RH approximately follows the decline and growth of PET, but inversely proportionally, from 18.23 to 64.38%.

- speed W is relatively small, close to W as in S0,

- RH slightly higher than S0,

- PET lower than S0 by less than 1.67 °C.

- the speed W differs negligibly from the value in S0,

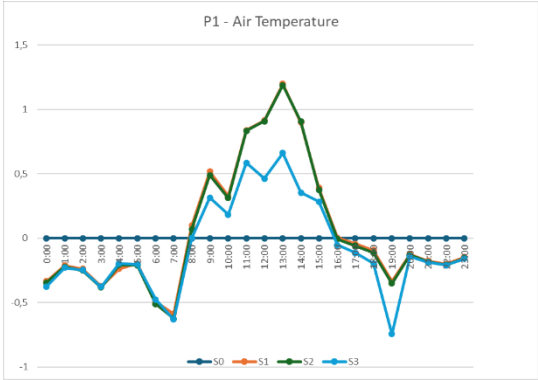
- RH is slightly different from the value in S0, up to 3%,

- PET less than the value at S0 by 0.10 (at 15 h)-1.92 °C (at 7.0 h).

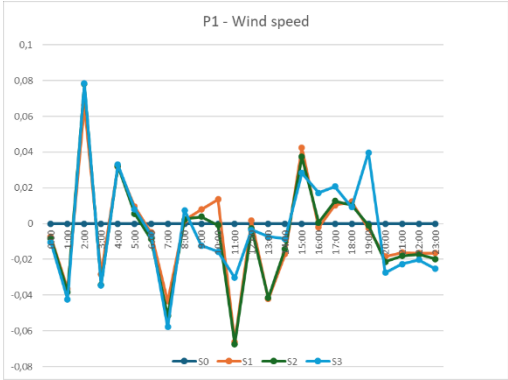
- the speed W differs negligibly from the value in S0

- RH is slightly different from the value in S0, up to 3.65%

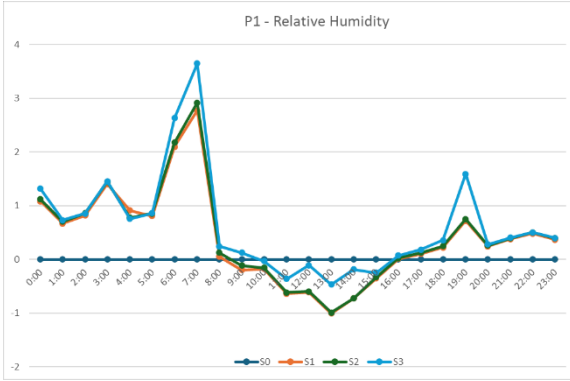
- PET less than the value at S0 up to 2.68 °C in 10 h.



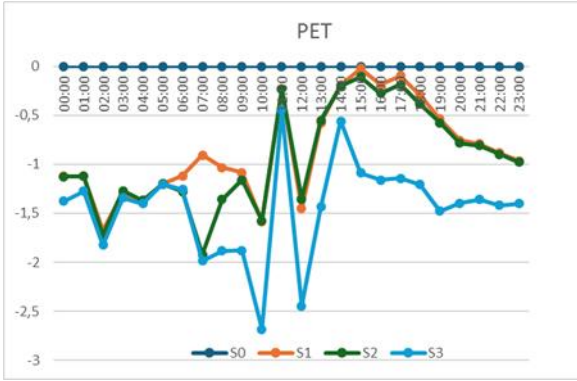
a) PAT chart for P1



b) chart W for P1



c) chart of RH for P1



d) chart PET for P1

Figure 11. Observation point P1: hourly (a) PAT, (b) W, (c) RH, and (d) PET in the base case (S0) and Scenarios S1–S3.

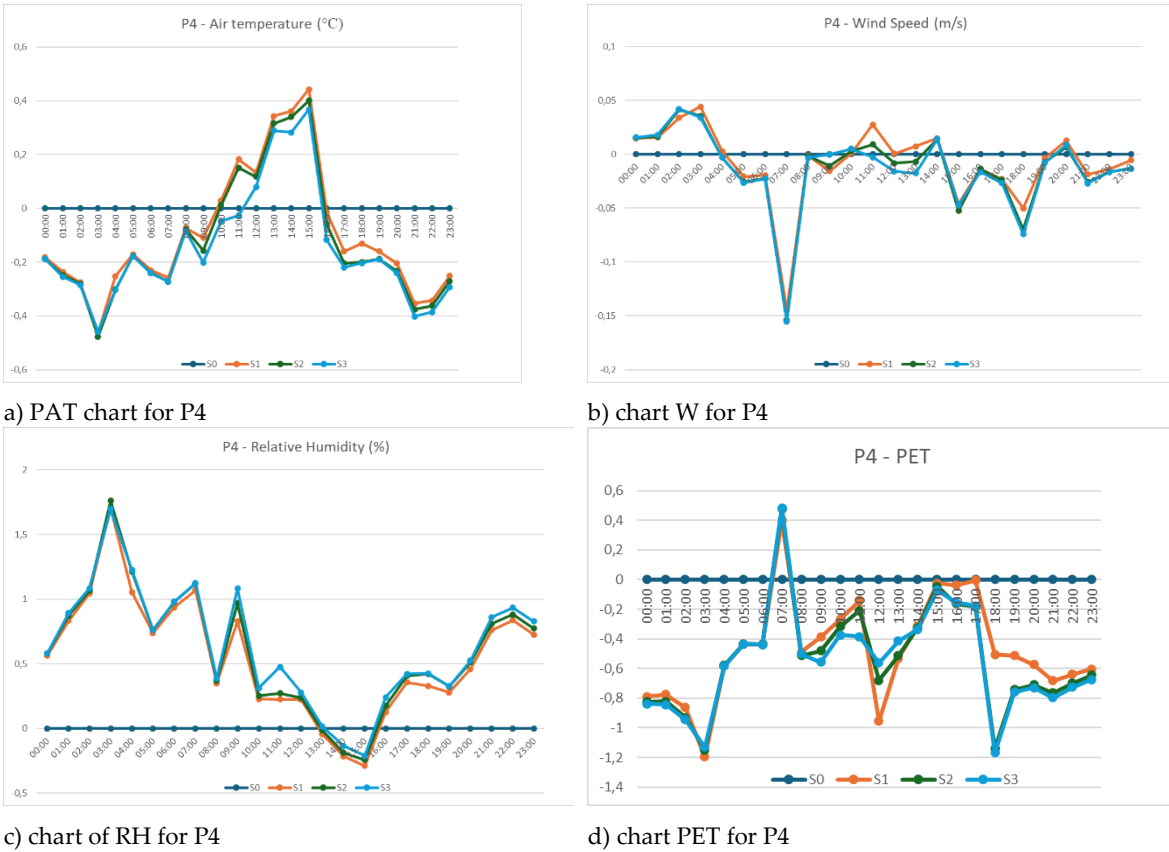


Figure 12. Observation point P4: hourly (a) PAT, (b) W, (c) RH, and (d) PET in the base case (S0) and Scenarios S1–S3.

Table 6. Observation point P4: hourly values and ΔPET per scenario.

Time (h)	S0			S1			S2		
	PAT (°C)	PET (°C)	ΔPET (°C)	PAT (°C)	PET (°C)	ΔPET (°C)	PAT (°C)	PET (°C)	ΔPET (°C)
1	2	3	4	5	6	7	8	9	10
0.00									
1.00									
2.00									
3.00									
4.00		Fall on			Fall on	(0.6h)		Fall on	(0.6h)
5.00	Fall on	21.24		Fall on	20.80	-0.436	Fall on	20.80	-0.436
6.00	21.68			21.42			21.41		
7.00									
8.00									
9.00									
10.00									
11.00									
12.00	Rise on			Rise on 44.88			Rise on		
13.00	44.43	Rise on		max	Rise on		44.84	Rise on	
14.00	max	61.94			61.91	(16.0h)	max	61.78	(16 h)
15.00		max			max	-0.037		max	-0.163
16.00									
17.00									
18.00									
19.00									
20.00	Fall on	Fall on		Fall on	Fall on	(23 h)	Fall on	Fall on	(23 h)
21.00	31.36	32.73		31.11	32.13	-0.602	31.09	32.09	-0.643

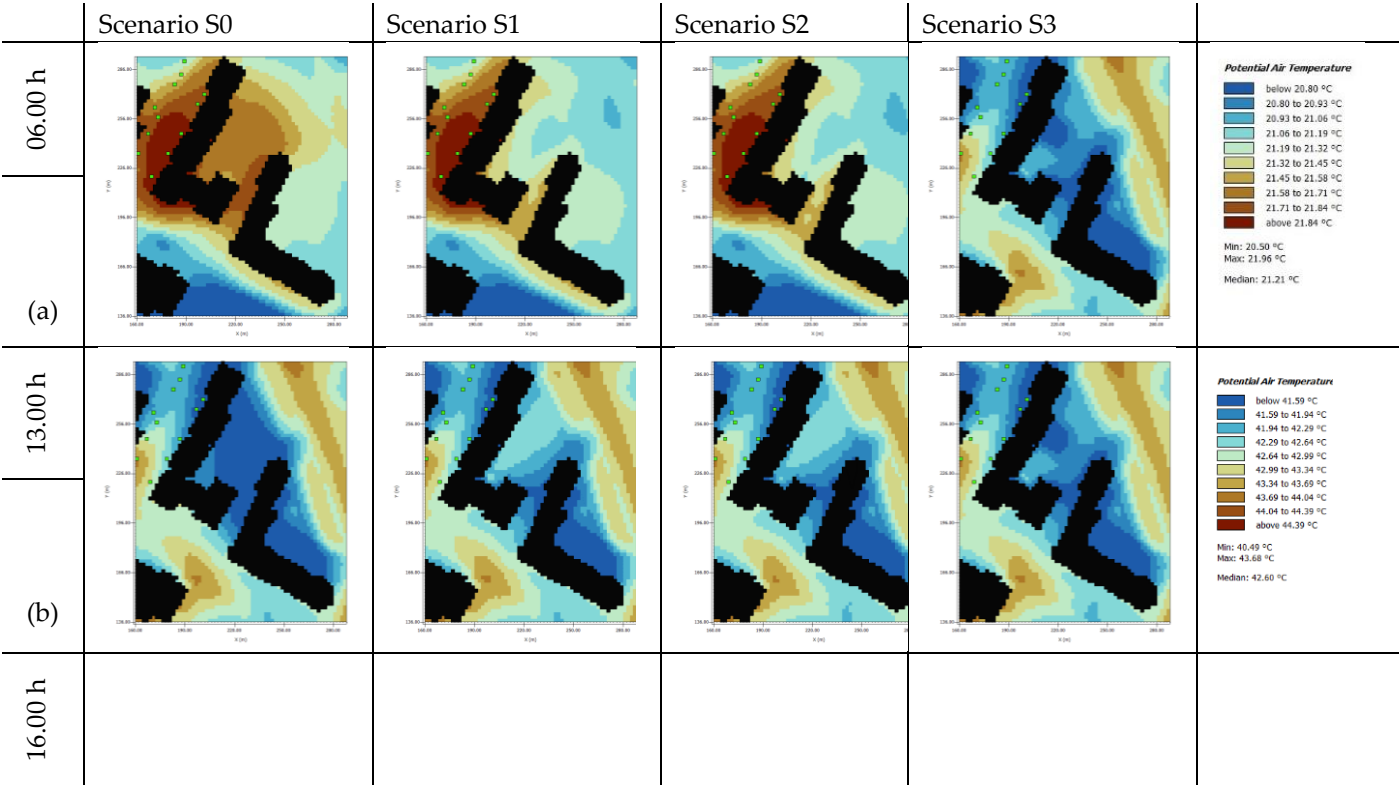
22.00			
23.00			
	- W is pulsating with an interval of usually 2 hours, the speed of W is small from 0.024-0.68 m/s, - RH increases until 07:00 h (up to 64.04%), then falls to 17.54% at 15,00 h, then rises again to 40.88% at 23,00 h.	- W pulsating with an interval of usually 2 hours, low speed, as with S0, with a negligible difference, - the change in RH approximately follows the decline and rise in PAT and PET, inversely proportional, with a negligible difference compared to S0.	- the speed W differs negligibly from the value in S0 -RH changes as in S0 with small differences.

ENVI-met outputs, supported by Figure 12 and Table 6, indicate the following results for observation point P4:

- In the base case (S0), PAT and PET both decreased during early morning hours (07:00 h and 06:00 h, respectively). PET began rising one hour earlier and declined one hour later than PAT. The maximum PET of 61.94 °C occurred at 16:00 h, coinciding with minimum RH. Pleasant thermal comfort occurred only between 05:00–07:00 h, and acceptable comfort between 01:00–04:00 h and 07:00–09:00 h.
- In Scenarios S1 and S2, all parameters differed negligibly from S0. PET reductions were below 1 °C, and building shading in the morning did not improve OTC to acceptable levels.
- In Scenario S1, OTC was pleasant from 04:00–07:00 h and acceptable from 00:00–04:00 h and 07:00–09:00 h.
- In Scenario S2, pleasant OTC occurred from 04:00–07:00 h and acceptable from 00:00–04:00 h and 08:00–10:00 h.

These results indicate that greening and tree planting had no statistically significant effect on improving OTC at point P4.

Figures 13 show the spatial distribution of PAT and PET, respectively, for 06.00, 13.00, 16.00, and 22.00 h across all scenarios (S0–S3), using identical color bands from 20–45 °C.



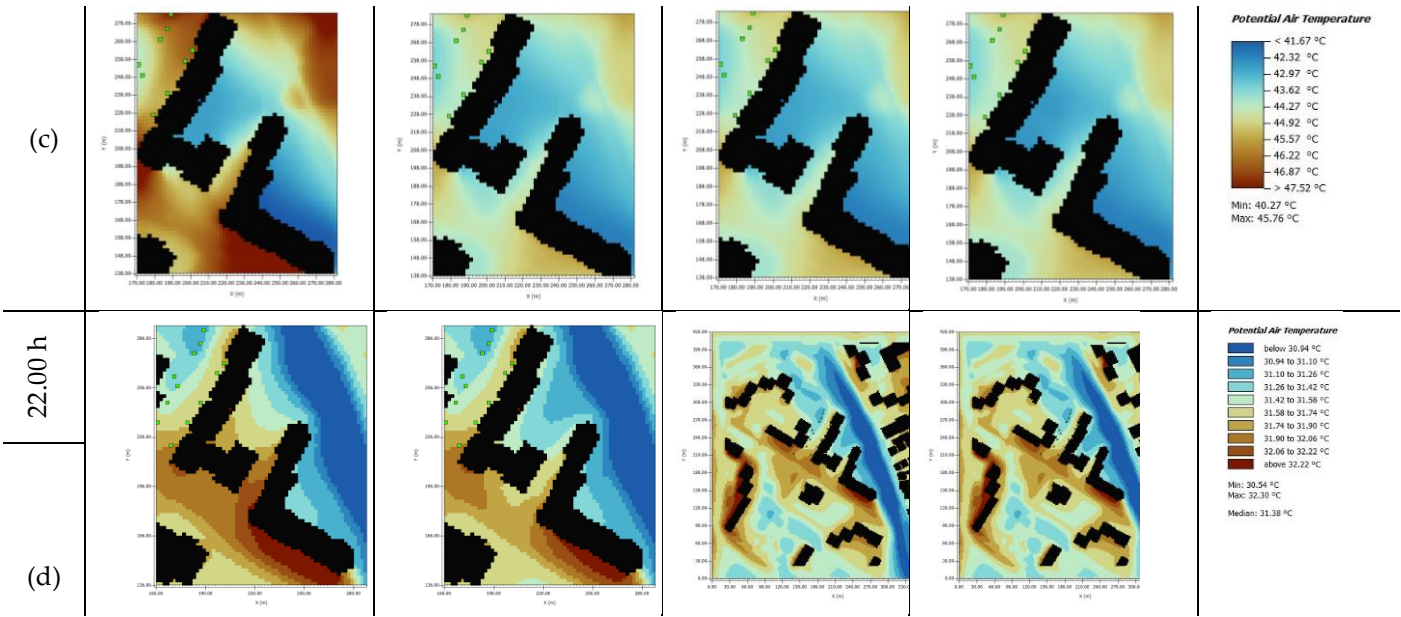
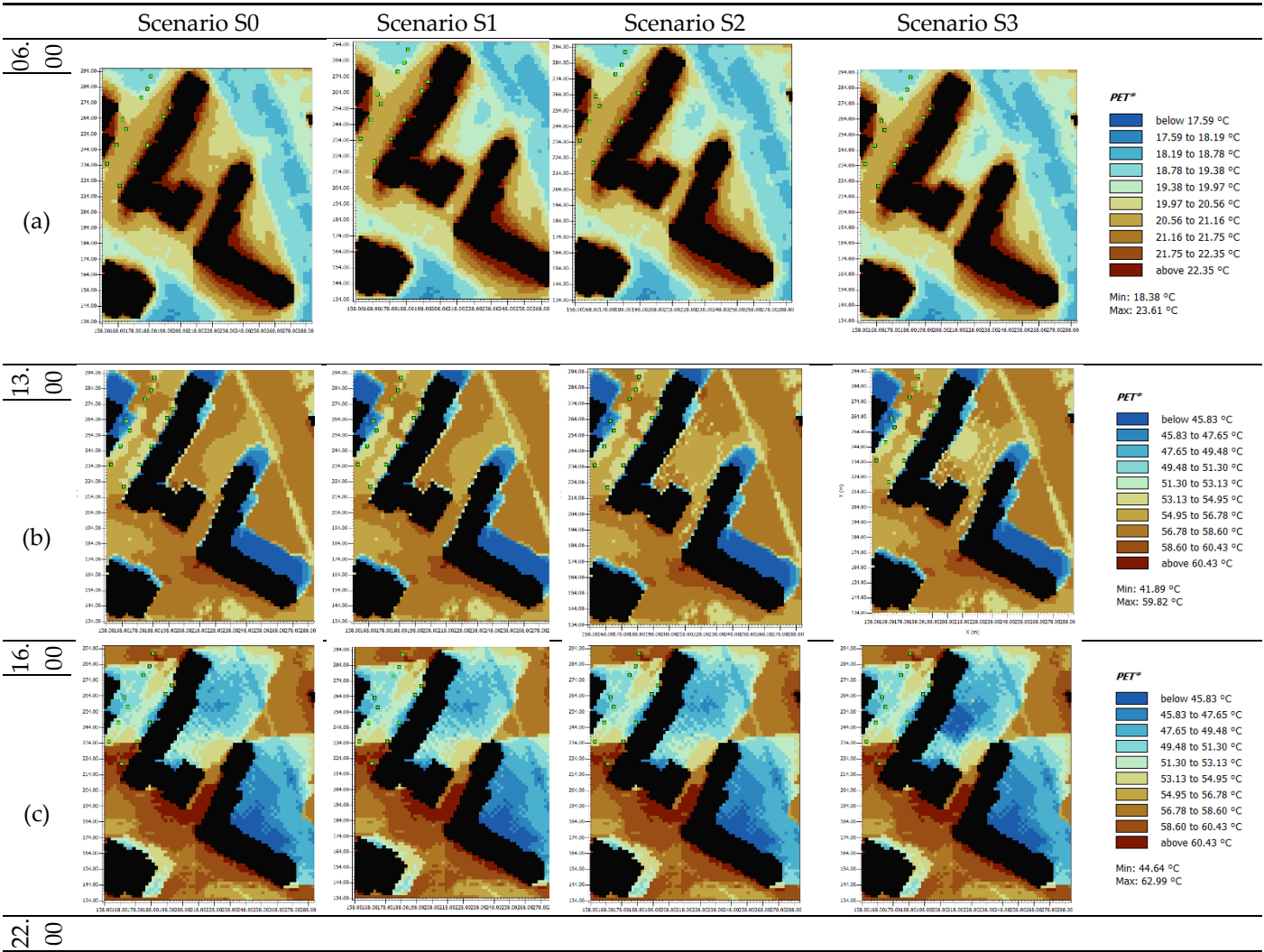


Figure 13. Spatial representation of PAT in in the base case (S0) and Scenarios S1, S2, S3 in (a); 6 h (b); 13 h (c); 16 h (d); 22 h.

In the Figure 14 (a-d) the spatial representation of PET is shown in 4 selected hours: 6 h, 13 h, 16 h and 22 h for the base case (S0) and scenarios S1-S4.



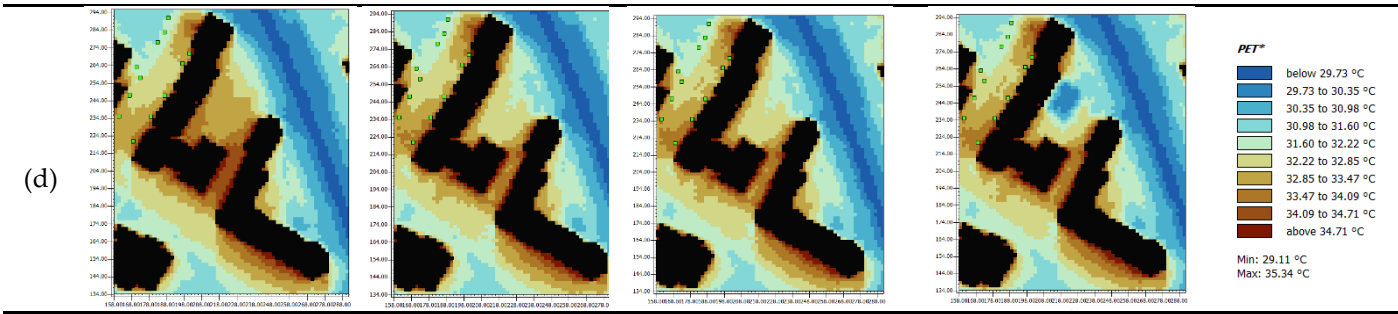


Figure 14. Spatial representation of PET in the base case (S0) and Scenarios S1, S2, S3 in (a); 6 h (b); 13 h (c); 16 h (d); 22 h.

5. Discussion

5.1. Synthesis of key findings

Based on field data collected in the open spaces of densely built HRHA along Romanijska Street in Niš, Serbia, model validation demonstrated high reliability ($R^2 = 0.92$; RMSE = 1.1 °C for PAT; $R^2 = 0.88$; RMSE = 3.5 K for PET).

Across all four observation points (P1–P4), PET values remained well above the “strong” and “extreme” heat-stress thresholds throughout most of the day, particularly in the afternoon. Consequently, OTC was highly unfavorable, except for a few early-morning and late-night hours—periods largely irrelevant for residents’ outdoor activity. These findings are consistent with previous research conducted in comparable urban environments [33,34,41].

The proposed retrofitting scenarios at P1 and P4 produced only modest improvements. At P1, PET decreased by 1.2 °C during minimum PAT periods across all scenarios, and by 0.2 °C (S1 and S2) or 0.56 °C (S3) during maximum PAT hours. The largest PET reduction (2.68 °C) occurred at 10:00 h in S3. At P4, PET decreased by only 0.436 °C during minimum PAT periods and by a mere 0.037–0.163 °C during peak temperatures.

These marginal improvements failed to alleviate thermal discomfort. The main reason lies in the morphological enclosure and radiative trapping of heat. The height-to-width (H/W) ratio of approximately 0.87–2.7 promotes longwave radiation accumulation and restricts ventilation, sustaining high PAT and PET even after midday. The highest PET (61.9 °C) was recorded in the narrow paved canyon (P4), defined by tall façades and limited width.

The analyzed block—typical of many Serbian HRHA—shows an extremely high built-up intensity ($SC \approx 0.43$; $FAR \approx 3.27$), small open-space area per capita ($\approx 3.45 \text{ m}^2/\text{person}$), a very low greenery share relative to net block area ($\approx 4.3\%$, with $\approx 95\%$ impervious surfaces), and minimal green area per inhabitant ($\approx 0.27 \text{ m}^2/\text{person}$). This value is below the city average of $1.2 \text{ m}^2/\text{person}$ and far below international recommendations. Current Serbian planning regulations require a minimum building separation (for NW–SE orientation) of 1.5 H; in the P4 courtyard, this would require 46.5 m, whereas the actual spacing is only 31 m, significantly impeding ventilation and promoting heat entrapment across all scenarios.

At P1, shallow soil above the underground garages and scarce vegetation reduce evapotranspiration, resulting in only minor PAT decreases while PET remains high. Pleasant or acceptable OTC occurs only from 00:00–07:00 h. The massive concrete slab stores and re-emits heat, counteracting daytime cooling (Figures 11–12; Tables 5–6). Although previous studies have documented substantial benefits of vegetation and shading [65,75], the present results confirm that in dense blocks with low sky-view factors and poor ventilation, such measures yield only marginal improvements. PET remains high, and thermal comfort is restricted to early morning hours.

The timing of shading further constrains mitigation. In S2–S3, tree canopies cast shade only later in the day, failing to mitigate peak heat stress between 13:00 and 16:00 h, when heat loads are maximal. Consequently, overall mitigation remains limited (Figures 11–12; Tables 5–6). The shallow

reflecting pool (40 m²) in S3 reduced PET by 2.68 °C at 10:00 h (P1), but this effect did not translate into improved daytime comfort, as radiative storage within façades quickly offset the cooling. This outcome supports previous findings that small water features provide limited benefits unless integrated within larger BGI systems [101–103].

In summary, small-scale, ground-level interventions are insufficient to mitigate heat stress in dense post-socialist HRHA. Effective adaptation demands integrated strategies combining morphological regulation, canopy expansion, permeable surfaces, ventilation corridors, and vertical or roof greening.

5.2. Suggestions for planning and design

The results of this research show that small-scale interventions on OS (lawn + individual trees + shallow water) in deep, semi-enclosed HRHA courtyards cannot provide a significant mitigation of PET values, i.e. improvement of OTC.

At the block scale, the following measures are recommended:

1. Urban Planning Regulation:
 - Limit building height and plot coverage.
 - Define a minimum open-space area per inhabitant.
 - Ensure adequate spacing based on orientation to enable ventilation.
2. Vegetation Planning:
 - Define minimum canopy coverage and tree spacing along pedestrian corridors.
 - Ensure continuity between courtyards and larger green networks.
 - Prescribe minimum open-sky water surface ratios per capita and improve visibility or use dynamic sprinkling in enclosed areas.
3. Ventilation Design:
 - Introduce continuous ventilation corridors within block layouts.
4. Integrated Greening:
 - Combine ground-level greenery with green roofs, vertical greening, and lightweight shading.
5. Surface Materials:
6. Employ permeable and light-colored pavements to minimize heat storage.

These strategies should be included in future urban plan revisions and supported by the Global Environmental Fund of Serbia within the national Green Transition framework.

5.3. Future Research Directions

Future research should:

- Identify optimal morphological parameters of open spaces (H/W ratios, SVF, permeability).
- Conduct multi-seasonal monitoring of climatic parameters to capture variations in humidity, radiation, and wind.
- Apply parametric analyses of different sky-view factors (SVF) and greenery percentages to define performance thresholds.
- Utilize advanced computational fluid dynamics (CFD) to model the behavior of dynamic water elements.
- Incorporate user-behavioral data (e.g., dwell time, movement patterns) to link microclimate improvements with tangible health-risk reductions.

6.0. Conclusion

This study assessed OTC in the OS of HRHA containing residential buildings (P+8) in Niš, Serbia, constructed in the post-socialist period. Climatic parameters were obtained through direct field observations and ENVI-met simulations during an extreme heatwave on 14 August 2024. Four scenarios (S0–S3) and four observation points (P1–P4) were analyzed to evaluate the influence of

different BGI configurations on OTC. The existing condition (S0) exhibited extremely high PET values, confirming that thermal stress was severe or extreme for most of the day at all locations. These results indicate that the built morphology and surface characteristics of dense infill HRHA are the dominant drivers of overheating.

The three proposed retrofit scenarios—grass (S1), grass with trees (S2), and grass with trees and a shallow reflecting pool (S3)—produced only minor temperature and PET reductions. Even the most favorable scenario (S3) achieved a maximum PET reduction of 2.68 °C, insufficient to meaningfully improve thermal comfort. The findings reveal that in deep, semi-enclosed courtyards typical of post-socialist housing blocks, small-scale surface-level measures cannot substantially mitigate heat stress during summer heatwaves. Morphological enclosure, low sky-view factor, limited ventilation, and extensive impervious surfaces prevent significant cooling, even when vegetation or shallow water elements are introduced.

To achieve sustainable usability of open spaces, a comprehensive, integrated approach is required. The measures proposed in Section 5.2—limiting building height and coverage, ensuring adequate spacing for ventilation, increasing canopy cover, introducing continuous green corridors, and employing light, permeable materials—should be prioritized in urban plan revisions. These measures need institutional support through national programs such as the Green Transition of Serbia and the Global Environmental Fund framework.

Beyond regulatory reform, implementation should combine ground-level greenery with vertical greening, green roofs, permeable pavements, dynamic water features, and shading networks at the neighborhood scale. Such multi-layered strategies can achieve measurable microclimate improvement and support social use of outdoor spaces during extreme heat.

The research provides a quantitative and qualitative basis for improving urban plans, design guidelines, and regeneration programs for HRHA in Serbia and across Southeast Europe, where similar morphological and climatic conditions prevail. Future work should focus on identifying optimal spatial configurations, applying multi-seasonal monitoring, and integrating CFD modeling and user-behavioral data to link microclimate improvements with public health and livability outcomes.

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Abbreviations

The following abbreviations are used in this manuscript:

UHI – urban heat island; OTC-outdoor thermal comfort; OS—open spaces; POS—public open space; HRHA- high rise housing areas; PET -Physiological Equivalent Temperature; BGI - Blu Green Infrastructure, PAT—potential air temperatures; BM—base model.

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