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Microclimate Modeling of UHI Mitigation Scenarios in a Historical Urban District

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Abstract

The study investigates the efficacy of various Urban Heat Island (UHI) mitigation measures within the United Nations Educational, Scientific and Cultural Organization UNESCO-listed historical center of Florence. Increasingly frequent and severe heatwaves during the summer season represent significant challenges for urban sustainability and public health in the outdoor urban environment. Using ENVI-met as a simulation tool, the research assesses the current microclimate conditions of a district within a historical center and simulates alternative mitigation scenarios. It quantifies the benefits in terms of microclimate characteristics (Potential Air Temperature-Ta and Mean Radiant Temperature-MRT) and human comfort indexes (Physiological Equivalent Temperature-PET and Universal Thermal Climate Index-UTCI). The proposed interventions include blue and green infrastructures as well as shading systems installed across the district. Current climate conditions are characterized by an average Ta of approximately 32 °C and MRT exceeding 59 °C; consequently, the analyzed area falls into the very strong heat stress category for both the calculated comfort indexes. All evaluated mitigation measures result in improving microclimate conditions as well as enhancing human thermal wellbeing within the outdoor environment. The most effective district-level intervention is the installation of shading fabrics, which reduces average Ta by 0.2 °C and MRT by up to 14 °C compared to the current scenario. Interventions tailored for the main square significantly reduce both UTCI and PET values, shifting the thermal stress from very strong to strong or even moderate. These findings highlight the potential of localized and tailored interventions to successfully integrate climate mitigation strategies within sensitive historic urban districts.

Keywords: Urban Heat Island (UHI); ENVI-met; UHI mitigation; green and blue infrastructures; shading systems

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1. Introduction

Climate change, rising outdoor air temperatures, and the Urban Heat Island (UHI) effect represent critical challenges for urban sustainability and public health within the city environment. Evidence retrievable in the recent literature suggests that these combined phenomena have led to a significant increase in extreme thermal events and outdoor thermal discomfort during the summer season, especially in densely built urban contexts [1,2]. Characterized by a marked temperature difference between urban and rural environments, the UHI effect is a major atmospheric issue that is further compounded by both the impacts of rapid urban expansion and global warming [3,4]. Multiple factors contribute to exacerbating outdoor thermal stress in large cities, such as anthropogenic heat production, use of low-albedo materials, urban morphology, and the lack of green and blue infrastructures [5]. In particular, the morphological configuration of urban districts strongly influences outdoor air temperature [6]. Beyond thermal discomfort, the UHI phenomenon negatively affects urban air quality [7] and deepens socio-economic challenges such as energy poverty [8].

Heat-related mortality and morbidity in Europe tripled in June 2025 alone [9,10] compared to a hypothetical scenario without heat waves due to a rise in external air temperature. The Mediterranean region is particularly vulnerable to these trends; in Italy, regional capitals have already documented a 1.7 °C rise in average outdoor air temperatures [11], with projections indicating a further increase of 2 °C anticipated by mid-century [12,13]. Recent studies propose innovative methodological approaches to estimate the resilience of densely built urban environments based on hazard, exposure, and vulnerability with the aim of safeguarding inhabitants' health [14].

Beyond health risks, rising temperatures significantly affect buildings' energy consumption for cooling. Sharston et al. [15] analyze 16 different building types located in different climate zones, demonstrating that the UHI affects both cooling and heating demand as well as thermal properties of some envelope components, especially windows. Eurostat data indicate a 25% increase in Cooling Degree Days (CDD) since the 1980s, with projections suggesting a 100% increase by 2050 [16,17]. Given the low resilience of modern built environments and their inadequate adaptive capacity to mitigate these extreme meteorological events, addressing urban heat stress through effective mitigation measures and resilience strategies is essential for safeguarding quality of life, reducing mortality risks, and ensuring urban well-being and livability. A key challenge lies in intervening in historical and heritage-sensitive United Nations Educational, Scientific and Cultural Organization (UNESCO) contexts where climate resilience and mitigation initiatives must be harmonized with rigid cultural preservation mandates and physical constraints.

Recent research highlights that the design and implementation of green infrastructures in dense urban environments play a fundamental role in mitigating the urban heat island effect and improving residents' well-being in outdoor spaces [18,19]. Some studies propose alternative simulation approaches to evaluate multi-risk mitigation in open public space within dense urban environments, showing that the introduction of greenery installation can reduce risks for citizens by up to 27% [20]. Gaur et al. [21] outline the importance of using machine learning methods for multi-temporal evaluation of the UHI phenomenon and possible mitigation measures. Su et al. highlight that the integration of both green and blue infrastructures in a densely urban environment can reduce the average external air temperature by up to 5.34 °C [22]. According to the previous research, Lopes et al. demonstrate that the introduction of green infrastructures in a historical urban environment, when supported by appropriate urban design strategies, effectively reduces air pollution, improving urban resilience to extreme events [23], as also outlined by Seo et al. for an effective resilient urban environment [24]. Cardinali et al. [9] propose a multi-scale method that integrates microclimate simulations and energy evaluations, demonstrating that the introduction of mitigation strategies can lower buildings' energy consumption by up to 22%.

As regards historical contexts, the implementation of nature-based solutions can be challenging to apply due to different factors such as restricted space, funds availability, regulations, and political constraints [25]. Ascione et al. [26] assess the effectiveness of several passive mitigation strategies (cool and green roofs, green facades, and urban vegetation) in reducing temperatures in the densely built historical center of Naples (Italy). They conclude that both urban vegetation at pedestrian level and green facades can significantly reduce mean radiant temperature and positively influence buildings' energy demand for cooling. Dalla Mora et al. propose the use of light-colored, porous, and permeable pavements in the historical center of Venice (Italy), reporting a decrease in average external surface temperature of approximately 2 °C [27]. Furthermore, Battista et al. [28] investigate different mitigation strategies for an urban square located in Rome, concluding that the installation of grass pavers is among the most effective interventions, with a reduction in external air temperature of approximately 1.5 °C. Analyzing other Italian historical contexts, Noro et al. [29] highlight that mitigation scenarios including green ground surfaces or cool pavements can lower outdoor air temperature by 3 °C and 4 °C, respectively. In line with previous findings, Bahadori et al. confirm through an extensive review that the use of high albedo materials is one of the most effective strategies for mitigating the UHI effect [30].

Despite the significant proliferation of research on Urban Heat Island (UHI) mitigation, the current literature lacks comprehensive strategies specifically tailored to Italian and European historical centers. In this context, there is a notable research gap regarding the comparative effectiveness of integrated blue and green infrastructures as single mitigation strategies or combined, with the former frequently remaining under-represented in recent mitigation studies despite its potential cooling benefits. A critical knowledge gap persists regarding the development and empirical validation of strategies tailored for heritage-sensitive, UNESCO-protected centers—limitations that are also acutely evident in the understudied context of Italian and European historical cities characterized by several architectural and technological constraints. In these environments, strict regulatory frameworks and physical constraints preclude the application of conventional interventions, such as extensive green roofs or technological and structural modifications related to building external envelopes.

This study utilizes ENVI-met microclimate simulations to quantify the thermal experience of pedestrians within Florence's historical center and propose different mitigation strategies, including both green and blue infrastructures to be evaluated. The novelty of the paper lies in providing a systematic evaluation of various mitigation strategies within a UNESCO-heritage urban district. Among these, blue infrastructures remain under-investigated in the literature, particularly regarding historical urban contexts; the others are potentially non-invasive and reversible measures, proving their viability in strictly preserved historical areas rather than traditional greenery. Additionally, this work quantifies the synergistic microclimatic benefits resulting from the combination of single mitigation scenarios.

The proposed mitigation measures can also be applied to different European historical areas, given their feasibility and effectiveness in improving microclimate conditions in densely built historical contexts preserving heritage identity.

2. Methodology

A representative sector of Florence′s historic center including Piazza della Repubblica was selected to evaluate pedestrian thermal comfort under typical summer conditions. Due to the site′s significant heritage value, the specific urban morphology and environmental characteristics—which constitute critical constraints for mitigation measures design—are detailed in Section 2.1. Each redevelopment scenario was carefully planned to preserve the historical integrity of the urban district. The spatial dataset was constructed using GIS-based repositories and aerial orthophotography retrieved from the Tuscany Region's Geoscopio open-access portal.

The research methodology is detailed in the following Figure 1.

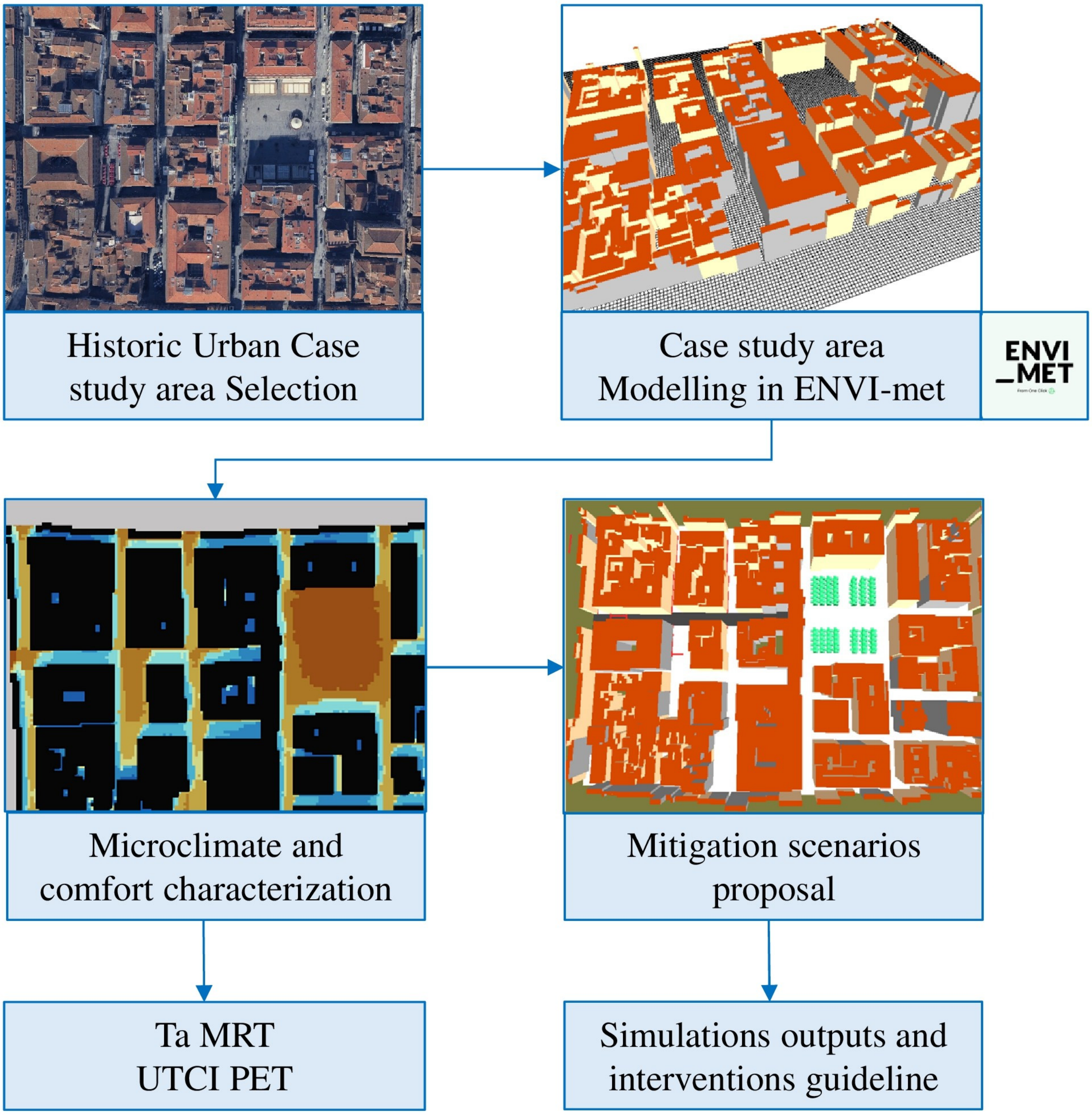

Figure 1. Workflow of the methodology.

2.1. Case Study Area

The city of Florence is characterized by a warm climate classified as Cfa according to the Koppen classification, and it belongs to Italian Climate Zone D, characterized by 2041 Heating Degree Days (HDD). During the summer period in Florence, July represents the most precarious period regarding thermal stress; it is characterized by a significant precipitation deficit (less than 25 mm) and a high frequency of heatwaves, averaging 23 days where temperatures exceed the 28 °C threshold.

The climate characteristics of the urban center are detailed in the following Table 1.

The input climate file (.epw) is a Typical Meteorological Year of the Peretola Airport weather station downloaded from the EnergyPlus database. Both the microclimate and comfort simulations with ENVI-met v.5 and BIO-met, respectively, were performed for 1 July for 4 h starting from 11:00 a.m. July was chosen for the simulations because it is characterized by the highest air temperatures during the summer season over the last decades.

Table 1. Climate data for Florence: HDD Heating Degree Days, Gh Global Horizontal Radiation, Dh Diffuse Radiation, Bn Direct Normal Radiation, Ta Air temperature, Td Dewpoint Temperature and Ws wind speed.

Latitude	Longitude	HDD [K/d]	Gh [kWh/m^{2}a]	Dh [kWh/m^{2}a]	Bn [kWh/m^{2}a]	Ta [°C]	Td [°C]	Ws [m/s]
43.34° N	11.52° E	2041	1447	629	1496	15	7.9	2.8

The urban portion considered in the study covers approximately 0.065 km^2. It is confined by Via dei Medici and Via della Calimala to the east and Via de' Tornabuoni to the west. It is delineated by Via dei Tosinghi to the north and Via Porta Rossa to the south (Figure 2). It is one of the highly dense and oldest areas of the city center, and Piazza della Repubblica represents a pivotal point of the UNESCO heritage site. The study area is almost a pedestrian zone with extremely high pedestrian traffic during the whole year, and it serves as both a vital commercial artery and an immersive open-air museum, also including the Renaissance Palazzo Strozzi and Piazza degli Strozzi. Consequently, this area was selected for microclimate analyses because of the significant population density exposed to potential extreme thermal events during the summer months. The perpendicular grid of narrow streets facilitates a consistent flow of residents and tourists, integrating high-density retail activities and the sight of historical landmarks, thereby remaining a vibrant nexus of contemporary Florentine life with its historical cafés. The area is distinguished by low-albedo finishing materials of public streets with the use of both dark asphalt for driveways and gray Pietra Serena for pedestrian paving. The external envelopes of the buildings are also characterized by the presence of high-heat-absorbing materials.

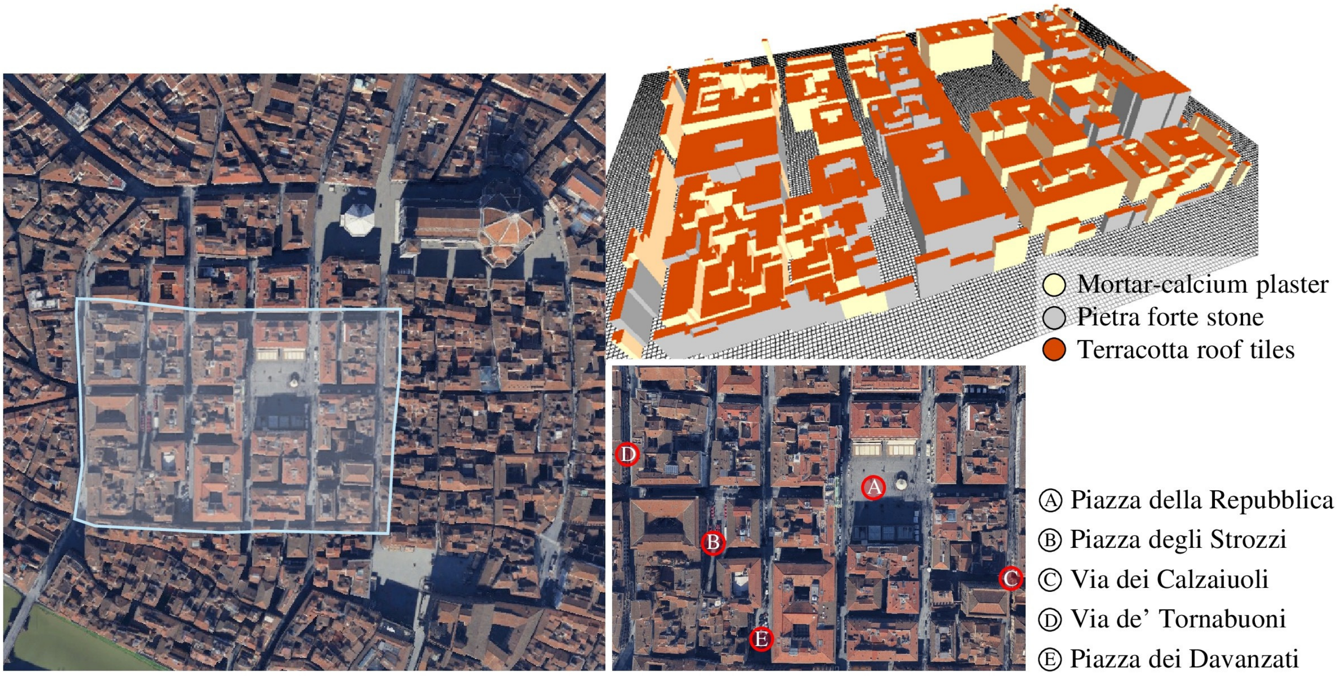

Figure 2. Case study area: aerial view with the identification of the area (340 m × 190 m) (on the **bottom- left**); aerial view of the modeled portion with the indication of the main points of interest (**bottom-right**); model of the area in ENVI-met software (**top-right**). Source: elaboration by the authors from Google Earth aerial view (https://earth.google.com/web/@43.77146108,11.25379937,48.25779528a,509.58441467d,35y,0h,0t,0r/data=CgRCAggBOgMKATBCAggASg0I___________ARAA (accessed on 25 August 2026)).

The findings of the study provide a possible strategic protocol of interventions for UHI mitigation that may be suitable and scalable for other historical, high-density, and densely populated urban districts.

2.2. ENVI-met Set-Up

Microclimatic parameters within the study area were analyzed using ENVI-met, a three-dimensional, grid-based numerical modeling tool.

For the case study area, the geometric model was defined by a grid of 210 cells in the X-direction, 160 in the Y-direction, and 20 in the Z-direction, with a telescoping factor of 20% implemented from 5 m height to reduce computational time while ensuring accuracy in atmospheric conditions at higher levels in the model environment. A fine grid resolution of dx = 2 m × dy = 2 m and a vertical resolution of dz = 1 m was applied to balance refined simulations of climatic characteristics. To reduce modeling time, the buildings' geometry within the case study area was simplified by discretizing the morphologies along the grid. Pitched roofs identified from aerial imagery were modeled as flat roofs, given that thermal modifications at roof level influence the ground-level thermal comfort to a lesser extent [31]. Moreover, boundary areas were scaled relative to the maximum building height to mitigate edge effects.

As for the buildings and external floor finishes, the materials were directly defined through the Database Manager of ENVI-met software. The thermal properties of the materials applied to the buildings modeled in the ENVI-met environment were derived from both the literature on historical constructions and Italian regulations [32–35]. The external pavements were considered as two different types: stone paving characterized by an albedo of 0.30 and asphalt distinguished by a lower one and applied to driveway areas. The detailed properties of the two materials are illustrated in the following Table 2.

Table 2. Outdoor paving materials.

Material	Volumetric Thermal Capacity [J/m^{3}K]	Thermal Conductivity [W/mK]	Albedo
Stone paving	2.35	3.00	0.30
Asphalt	2.25	0.70	0.12

For the outer areas, belonging to the boundary zones and consequently left empty, the default loamy sand soil was assigned, considering the following main characteristics: volumetric thermal capacity of approximately 1.4 J/m^{3}K and null thermal conductivity.

Regarding the construction, for the external walls two different technological solutions were considered as they are the most used in the historical buildings of Florence city center: both are characterized by the presence of "muratura a sacco". One includes an internal cavity and external finish in Pietraforte sandstone, while the other is made of Pietraforte sandstone blocks with external plaster. The main characteristics are reported in the following Tables 3 and 4.

As regards roof stratigraphy, a timber horizontal slab combined with terracotta roof tiles as finishing layer was applied to all buildings included in the model. The main distinguished characteristics are listed in the following Table 5.

Table 3. Façade stratigraphy 1: Masonry cavity wall.

Material	Thick. [m]	Solar Absorpt.	Solar Reflect.	Emissivity	Specific Heat [J/kgK]	Thermal Conduct. [W/mK]	Density [kg/m^3]
Pietraforte stone	0.20	0.60	0.40	0.90	880	3.00	2700
Inert infill	0.40	0.70	0.30	0.90	880	2.30	2400
Pietraforte stone	0.20	0.60	0.40	0.90	880	3.00	2700

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Table 4. Façade stratigraphy 2: Masonry cavity wall with plaster as external finishing.

Material	Thick. [m]	Solar Absorpt.	Solar Reflect.	Emissivity	Specific Heat [J/kgK]	Thermal Conduct. [W/mK]	Density [kg/m^3]
Mortar-calcium plaster	0.04	0.40	0.60	0.60	1000	0.9	1800
Pietraforte stone	0.20	0.60	0.40	0.90	880	3.00	2700
Inert infill	0.40	0.70	0.30	0.90	880	2.30	2400
Pietraforte stone	0.20	0.60	0.40	0.90	880	3.00	2700

Table 5. Roofing stratigraphy materials.

Material	Thick. [m]	Solar Absorpt.	Solar Reflect.	Emissivity	Specific Heat [J/kgK]	Thermal Conduct. [W/mK]	Density [kg/m^3]
Terracotta roof tiles	0.01	0.70	0.30	0.90	840	1	2000
Pianelle tiles	0.03	0.60	0.40	0.90	800	1	2000

Finally, the microclimate characteristics of the base case and mitigation scenarios were assessed by calculating outdoor air temperature and relative humidity at z = 1.5 m to consider the pedestrian corridor real conditions, and wind speed at the same level. To evaluate the pedestrian comfort in the outdoor environment, the following parameters were calculated, as the most retrievable in the recent literature [36,37]: mean radiant temperature (MRT), Universal Thermal Climate Index (UTCI), and Physiological Equivalent Temperature (PET). The comfort indices characterize human physiological responses to atmospheric factors, specifically air temperature, relative humidity, wind speed, and radiative fluxes [38]. The first represents the overall radiation perceived by a human body based on radiative energy exchange governed by temperature differences and surface emissivity [38]. The second serves as an equivalent temperature metric representing human physiological stress. It is based on energy balance modeling and it incorporates thermoregulatory mechanisms, metabolic heat exchange, and dynamic clothing adaptation in response to ambient temperature [39]. Finally, the calculation of PET derives from human thermal radiation and energy exchange models that include meteorological variables and individual parameters, such as activity level and clothing insulation [40].

The comfort indices are calculated considering the following parameters: for the PET index, a default male with summer clothing (male 35 years, 0.50 clo) is considered as proposed by the BIO-met library, while for the UTCI calculation, the wind speed at 10 m height is considered. Baseline parameters for the PET index follow the standard reference retrievable in the scientific literature, using a normal adult profile to avoid introducing health variables associated with vulnerable people.

2.3. Mitigation Strategies

This paragraph details the mitigation scenarios to be possibly applied to the case study, outlining their compatibility with the historical environment while considering the morphological layout and all the possible existing constraints. Neither green facades nor green roofs are considered viable mitigation strategies due to the significant and inevitable changes that they would cause in the built environment. As for the former, they significantly affect the visual integrity of the external wall finishing, which is primarily characterized by the presence of Pietraforte sandstone, especially for the ground floor. Regarding the latter, the horizontal greenery would increase vertical loads on these types of historical constructions as well as present several issues regarding the installation process and feasibility challenges arising from the numerous constraints of this high-density urban context.

The mitigation strategies chosen for this historical area and their combinations are listed below and illustrated in the following Figure 3:

- Water bodies (SC1) installed directly in the Piazza della Repubblica, planned for 25% of the total surface of the square.
- Implementation of greenery through flowerbeds (SC2) covering 25% of the total surface of Piazza della Repubblica. As for the narrow streets, widths range from 2 m to 8 m, depending on street dimensions, parking availability, and driveway and pedestrian corridors.
- Tree planting (SC3) considering 81 *Citrus* × *aurantium* trees as species planned in Piazza della Repubblica.
- Installation of removable shading systems (SC4–SC4_A) over streets, where possible based on street dimensions, building height, and historical value of construction, especially along Via dei Calzaiuoli and Via Calimala. For the shading systems, two different heights are modeled (12 m and 20 m) to consider the possible effects of the wind speed and direction on comfort parameters along the pedestrian corridors.
- Two different combinations: the first one combines the implementation of flowerbeds and tree planting in Piazza della Repubblica (SC5), and the other includes a removable shading structure at 20 m for streets coupled with water bodies in the main square (SC6). The combined scenarios are considered to evaluate the optimal combination of mitigation strategies between the main square and the surrounding narrow streets.

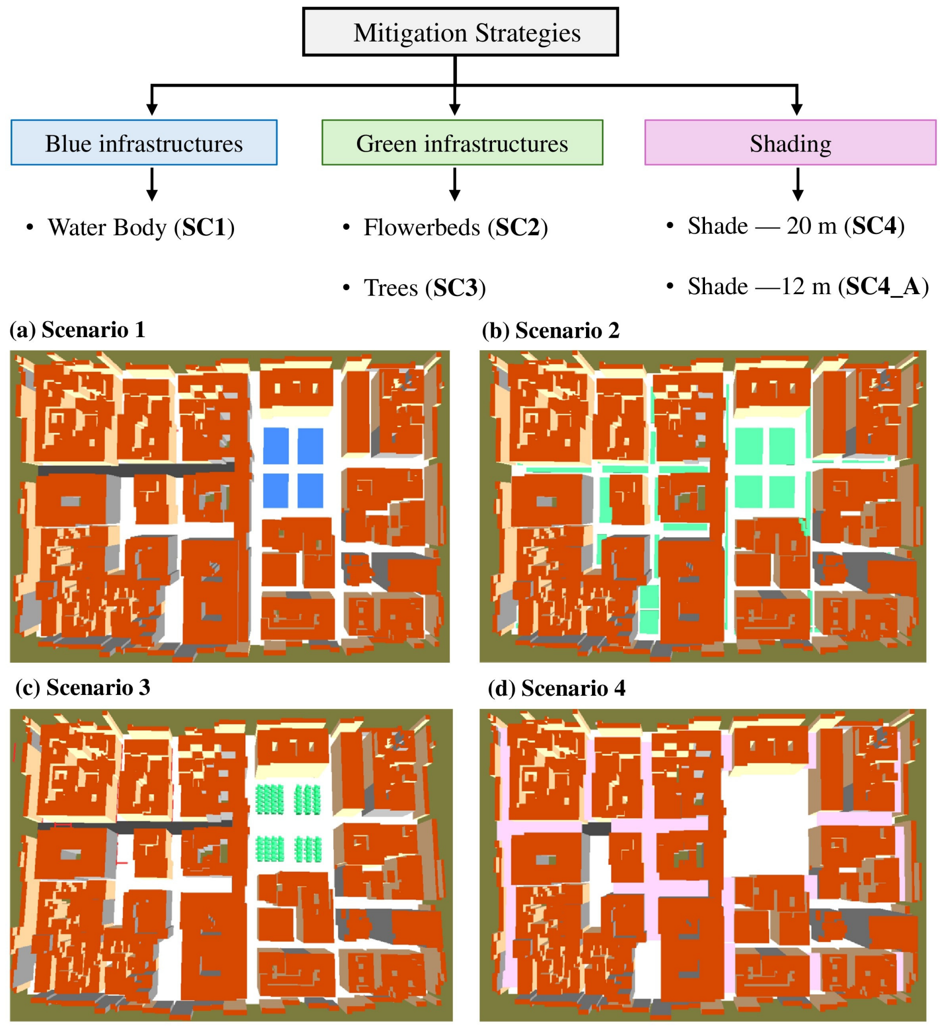


Figure 3. Proposed mitigation scenarios are divided into three different strategies: blue infrastructures, green infrastructures, and shading structures. The figure illustrates the four single different scenarios modeled in the simulation environment. The arrangement of shading systems in scenario 4 (**d**) is the same for both heights.

As for single mitigation measures, SC1 serves as a theoretical baseline scenario designed as a numerical benchmark to evaluate potential microclimate benefits for the historical urban site. The practical feasibility of this implementation must be assessed considering the site-specific regulatory and structural constraints. As for the introduction of flowerbeds (SC2), this constitutes a permanent and invasive redevelopment measure involving the installation of greenery at ground level, and it involves removing the current surface finishes. The final two implementation scenarios (SC3 and SC4) can be considered non-invasive and fully reversible mitigation measures.

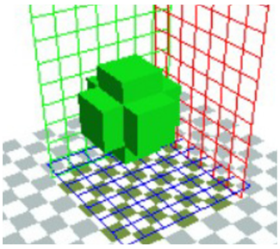
Regarding SC1, the mitigation scenario was modeled and applied exclusively within Piazza della Repubblica. This design choice was dictated by the morphological layout and constraints of the case study area, especially related to the narrow dimensions of the surrounding streets. The square is the only modeled space where it is dimensionally possible to integrate this mitigation strategy while maintaining both the necessary area for proper pedestrian flow and adequate surface for public activities. The water bodies were represented in ENVI-met using the predefined Deep Water Body profile. In the adopted configuration, water depth was not prescribed as an independent geometrical parameter. The corresponding volumetric heat capacity and thermal conductivity were 4.20×10^6 J m^{-3} K^{-1} and 0.6 W m^{-1} K^{-1}, respectively. Regarding SC2, flowerbeds are planned for Piazza della Repubblica as well as for the smaller squares in the model: Piazza degli Strozzi and Piazza dei Davanzati. In the latter two external spaces, the installations feature reduced widths of 8 m and 4 m, respectively, extending across the full length of each square. In Via dei Calzaiouli, a 2 m-wide strip of selective greenery was foreseen in the center of the street in order to maintain an appropriate clearance zone for shops and intensive pedestrian flow. A similar design was proposed in Via dei Tornabuoni, but in this case the greenery is characterized by a width of 4 m. In this scenario, the design involves depaving the existing asphalt material across the non-vegetated area of the street and implementing a new stone pavement with higher albedo (0.3). The parameters for microclimate simulations are detailed in the following Table 6.

Table 6. Flowerbeds setting for microclimate simulations.

Greening	Albedo	Emissivity	Plant Height [m]	Roots Depth [m]	Leaf Area Density (LAD) [m^2/m^3]
Grass	0.25	0.95	0.10	0.20	0.30

Regarding the third mitigation scenario (SC3), an evergreen tree species was selected to be implemented in Piazza della Repubblica. This species is well-suited for high-density urban environments, similar to the interventions implemented in Via Cavour since 2024. Specifically, 81 bitter orange trees were proposed as a mitigation strategy specifically designed for Piazza della Repubblica, accounting for the narrow dimensions of the surrounding streets. The trees were arranged to guarantee optimal foliage development. Moreover, this measure represents a reversible mitigation strategy, as the trees can be placed in portable planters and relocated as needed. In this case, a specific modeling assumption was made regarding tree simulation to overcome the intrinsic limitations of the software in directly modelling above-ground planters. In general, ENVI-met does not explicitly represent the finite substrate volume and container geometry of portable planters. Therefore, in SC3 the trees were modeled as planted in natural soil, while the use of portable planters refers to the proposed real-world implementation of the reversible intervention. The main characteristics of the vegetation species are reported in Table 7.

Table 7. Vegetation species characteristics in the ENVI-met model.

Species	ENVI-met Model Geometry	Leaves Albedo at Low-Length Waves	Leaves Transmissivity at Low-Length Waves	Leaf Weight [g/m^2]	LAD [m^2/m^3]
Citrus × aurantium		0.95	0.20	0.20	1

Finally, the last single mitigation scenario (SC4 and SC4A) involves the installation of shading fabrics along the main streets, excluding the squares included in the model and the portion of the model where historical buildings are sited. In ENVI-met, the shading structures were modeled as PVC sails characterized by a high reflectivity equal to 0.7. In this case, the implementation of this mitigation strategy would result in decreasing direct solar radiation in sidewalks as well as ensuring external visual comfort for tourists. In this case, two different heights are considered for the model to evaluate the effect on both external air temperature and comfort indexes. The shading fabrics are installed at 12 m and 20 m through tensioned metal wire systems that can eventually be removed as needed.

3. Results

This section illustrates the primary research results, first focusing on the current microclimate conditions of the area of interest and the corresponding outdoor thermal comfort levels. All numerical data of the presented outputs were extracted from ENVI-met for 21 July at 1:00 p.m., at a height of 1.5 m above ground level to consider pedestrian height.

3.1. Baseline Scenario

Figure 4 illustrates the values of potential air temperature and MRT under current microclimate conditions. An average potential air temperature of 31.65 °C was registered in the study area with a maximum peak value equal to 33.01 °C. As shown in Figure 4, the potential air temperature is relatively uniform throughout the whole urban district; however, minimum values (below 30.52 °C) are found in narrow streets and courtyards due to the shading effects of the surrounding buildings. Piazza della Repubblica is characterized by the highest value of potential air temperatures, ranging between 31.35 °C and 32.45 °C. For this reason, two of the alternative mitigation scenarios are designed specifically for this main square. Additionally, an average external air temperature of approximately 31.4 °C was recorded in the other two squares included in the urban district.

Regarding MRT, the values range between 25.64 °C and 64.09 °C with an average equal to 59.22 °C across the whole urban district. Similarly to the trend of potential air temperature, the lowest MRT values are registered in narrow streets and in a buffer of approximately 1 m from building facades, ranging between 33 °C and 45 °C. As shown in Figure 4, the highest values of this parameter were observed both in the squares, with a peak value in Piazza della Repubblica equal to about 54 °C, and in the center of the main streets. For instance, approximately 50 °C was registered in Via dei Calzaiuoli. These elevated values are attributed to the layout of the urban district, as the geometry of the buildings and the street canyon morphology significantly affect the microclimate conditions. Furthermore, the microclimate conditions are generally affected by paving materials, characterized in this case by low albedo values, as well as by the finishing materials of buildings' external envelopes. For instance, the surface temperature of the paving materials in Piazza della

Repubblica is above 37.50 °C. The significant value of this parameter in the area of interest demonstrates the necessity of mitigation interventions to ameliorate the thermal comfort in this portion of the historical city of Florence.

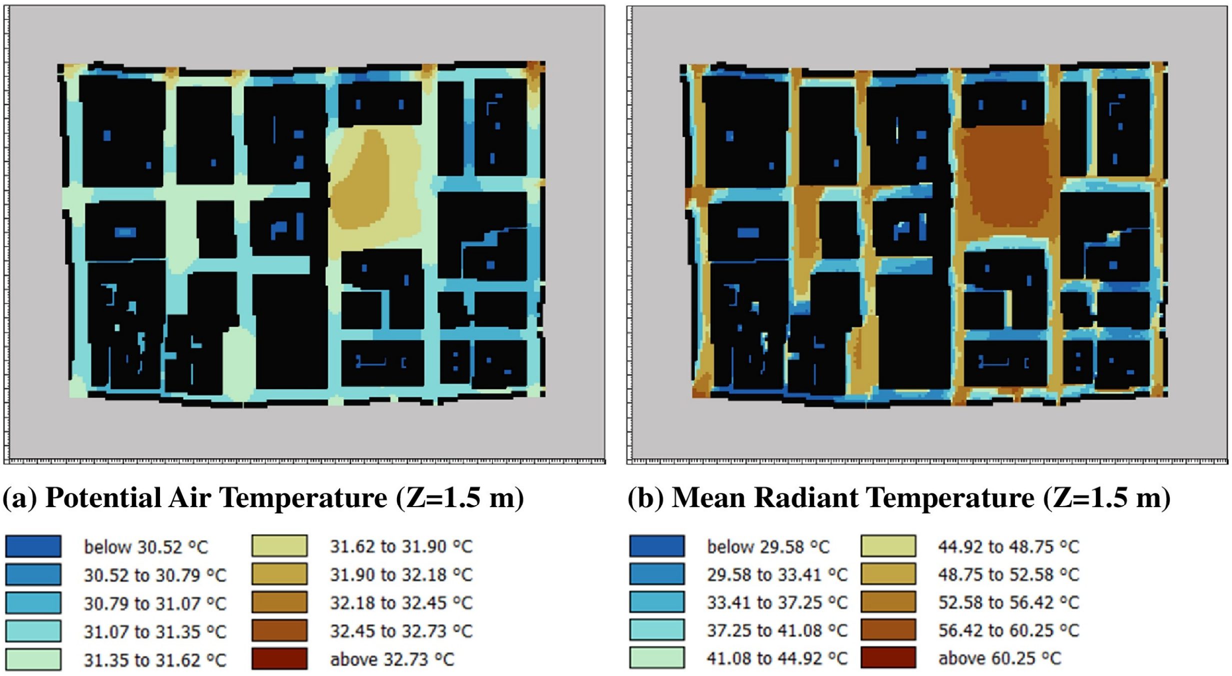


Figure 4. Potential Air Temperature (**a**) and Mean Radiant Temperature (**b**) for the current base case scenario.

In Figure 5, UTCI and PET indices are illustrated. Both represent two essential parameters for evaluating human heat stress in outdoor environments. These results clearly confirm the previous findings and highlight the levels of thermal discomfort within the study area included in the historical center of Florence. The maximum values of the UTCI are registered in the main square (38.14 °C < UTCI < 40.40 °C) and at the crossroads of the secondary streets, for instance between Via dei Vecchietti and Via degli Strozzi. The spatial distribution confirms a uniform thermal environment with perceived temperature for pedestrians ranging between 37 °C and 41 °C and a median value of 39.76 °C. For the case study area, the pedestrians are exposed to very strong heat stress conditions (38 °C < UTCI < 46 °C) according to the European Copernicus assessment scale [41], reflecting the need to introduce possible mitigation measures. In the shaded area, due to the building morphology and height, the UTCI index decreases below 31.5 °C, indicating moderate heat stress. As for PET, the outputs of microclimatic simulations reflect the data of MRT and UTCI parameters with a medium value of the physiological equivalent temperature equal to 50.30 °C within the urban district. The most relevant portion for heat stress is consistently Piazza della Repubblica, where shaded and safety areas are completely missed, and the PET rises to about 52 °C. These results highlight the influence of the mean radiant temperature on both the calculated comfort indices. The three parameters present a similar trend in the selected case study district, underscoring the intrinsic and linear correlation between the radiant heat load and outdoor thermal comfort. The results demonstrate a crucial need to implement targeted mitigation interventions to enhance the pedestrians' well-being in this historical city center; otherwise, during the summer season, the population is likely to be exposed to severe heat stress in open spaces. This poses significant health risks, especially for vulnerable people.

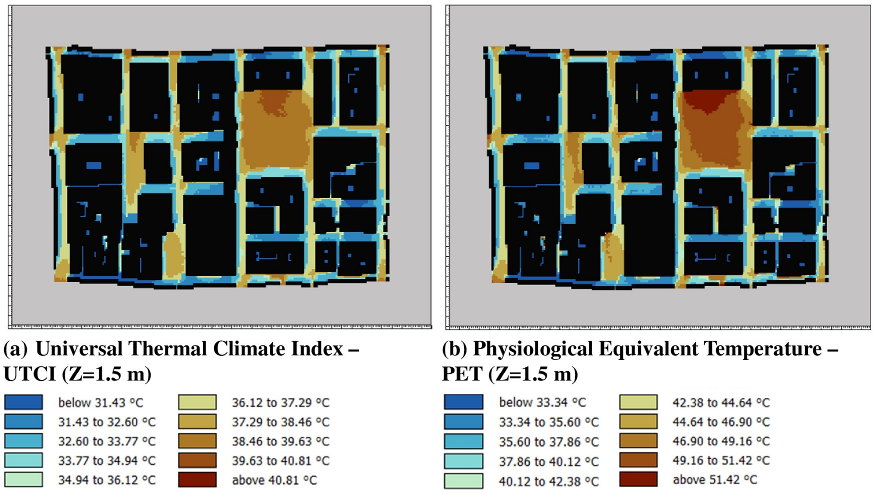


Figure 5. Universal Thermal Climate Index (**a**) and Physiological Equivalent (**b**) for the current base case scenario.

The following paragraph illustrates the positive effects of the proposed mitigation measures on both microclimate conditions and comfort indices. First, considering the intervention concentrated in the main square (Figure 6), followed by the scenarios related to the whole urban district (Figure 7).

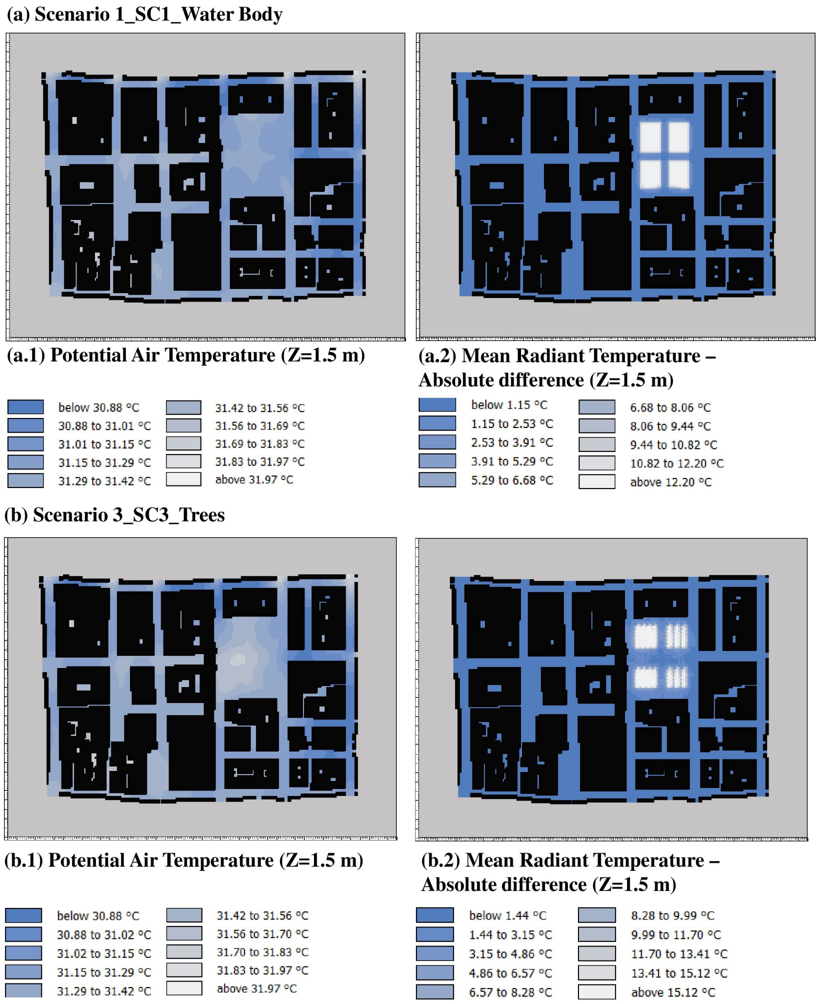


Figure 6. Potential air temperature and MRT Absolute difference compared to base case scenario for SC1 and SC3.

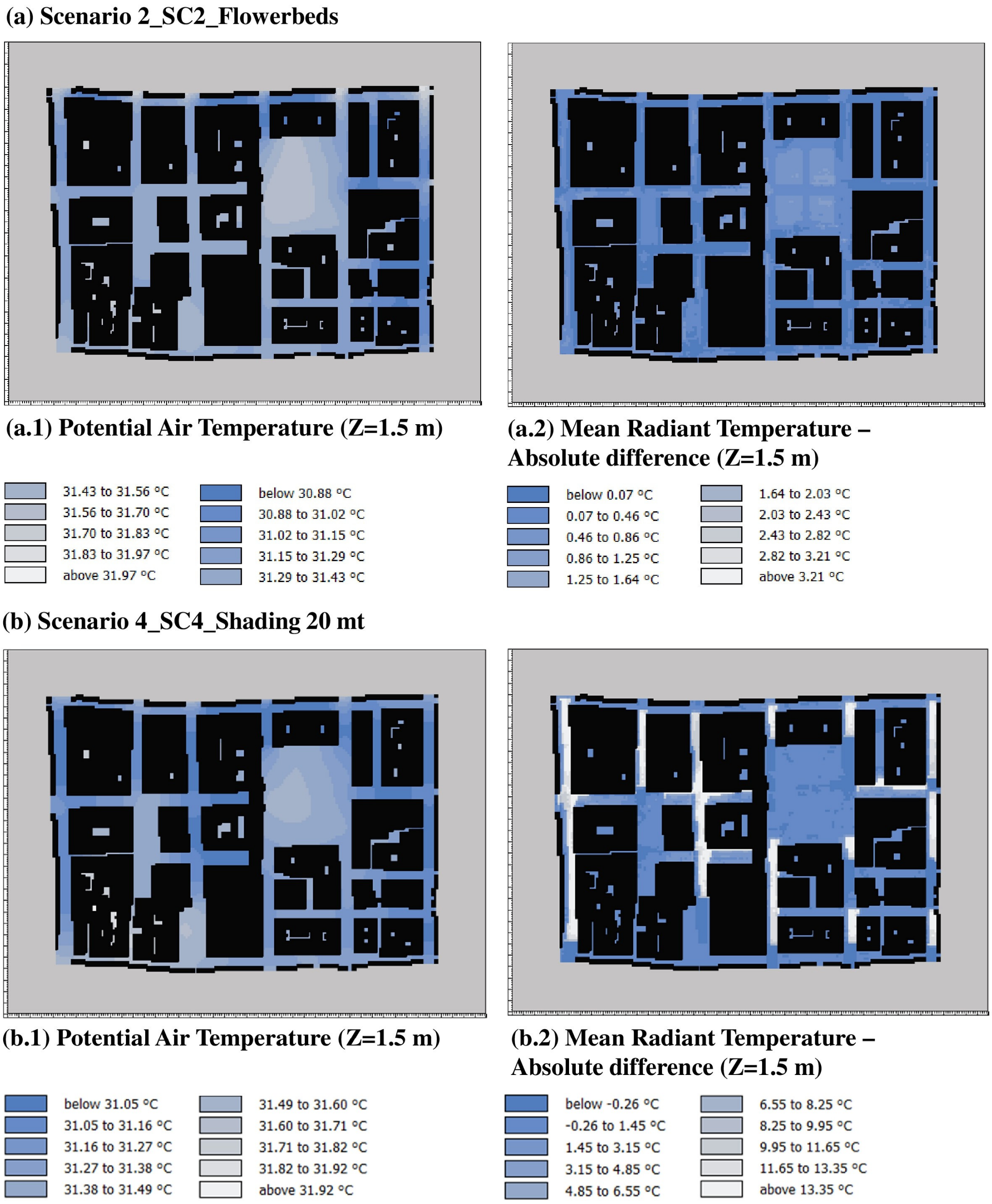


Figure 7. Potential air temperature and MRT Absolute difference compared to base case scenario for SC2 and SC4-20 mt.

3.2. Blue and Green Infrastructures

The introduction of water bodies (SC1) in Piazza della Repubblica results in a decrease in the value of the potential air temperature in the square of about 0.6 °C; however, although this mitigation strategy (SC1) is targeted to the main square, it also influences the whole urban district to a lesser extent with a reduction in the average value of the potential air temperature of 0.2 °C. As regards MRT, an absolute difference of 12.20 °C is calculated in the main square where the water bodies are installed. The value of this temperature ranges between 39 °C and 46.5 °C in Piazza della Repubblica. As for the comfort index UTCI, the main square experiences a reduction of about 3 °C, and the parameter ranges from 35.42 °C to 38.34 °C. Consequently, an evident improvement in thermal comfort conditions is achieved in this outdoor open space without shaded areas. As for the SC3 scenario, related to the other redevelopment intervention for the main square, involving tree planting, the average external air temperature across the whole district decreases by 0.15 °C, demonstrating that the installation of *Citrus × aurantium* has a limited influence at district scale. By contrast, a significant reduction in MRT is observed in the main square, approximately equal to 15 °C, due to the elevated number of trees planted and the direct shade on pedestrians and surfaces provided by the canopies. By contrast, at district scale, the absolute difference in MRT is lower than 1.44 °C. This last result highlights the localized effectiveness of the tree-planting redevelopment, proving that the choice of targeted mitigation measures in public squares could be a viable solution for reducing heat-related health risks, even within historical urban centers. The improvement of outdoor comfort conditions is evident, observing the reduction in UTCI and PET in the main square, which decreases by 4 °C and 7 °C, respectively, again outlining the cooling effect of this mitigation strategy. The area was downgraded from the "very strong" heat stress category to the "strong" heat stress category (32 °C < UTCI < 38 °C), suggesting an amelioration of outdoor comfort conditions and reduction in prolonged heat waves experienced by pedestrians.

As for scenarios involving the whole district, SC2 foresees the adoption of flowerbeds both in the main squares and along the narrow streets. The average potential air temperature decreases by 0.15 °C within the district, and a reduction in medium relative humidity of 1% is registered. At district scale, this mitigation measure is comparable with the SC3 scenario because of the influence of buildings' shade in the narrow street grid on the results. Otherwise, in this case, the absolute difference in MRT compared to the current climatic conditions reaches a peak equal to 3.60 °C achieved in the squares. The positive effect of this mitigation strategy is registered in the UTCI comfort index with an absolute difference of 3.73 °C compared to the current conditions mainly observed in the squares included in the urban district. While the reduction in microclimatic and outdoor comfort parameters appears modest in this scenario, these results are primarily attributable to the predominant shading provided by buildings within the narrow streets and are strictly related to the geometrical layout of the case study district. It is worth noticing that for the main square, the adoption of this mitigation strategy results in a 1.7 °C reduction in MRT and 1.2 °C in Ta.

3.3. Shading

Finally, regarding the last single redevelopment scenarios (SC4 and SC4_A), a notable finding is the significant reduction in external pavement temperature directly beneath the shielding systems, which fell below 21.50 °C. In contrast, the average paving temperature remained approximately 30.5 °C, with peak values recorded in the open squares. The installation height affects the paving temperature value to a lesser extent, with a difference of about 1 °C between the two configurations. These two mitigation strategies also influence the wind speed, causing a reduction in the mean value of 0.20 m/s. A decrease in the potential air temperature equal to 0.20 °C is calculated for both configurations. The value of the MRT significantly decreases directly beneath the shading structure, registering values below 39 °C, with a maximum difference of approximately 14 °C compared to the current scenario. These results confirm an improvement in thermal comfort conditions with PET and UTCI average values of 49.53 °C and 39.34 °C, respectively. In the evaluation of these comfort parameters, the different heights do not affect the results. Beyond these averages, the most significant results are the values registered directly beneath the shielding structures, where PET ranges from 31.29 °C to 38.08 °C and UTCI varies from 30.60 °C to 34.44 °C. The distribution of the UTCI across the analyzed district confirms the effectiveness of this strategy in reducing discomfort and lowering perceived temperatures throughout the outdoor analyzed environment. The majority of the case study area now falls into the "moderate heat stress" category (26 °C < UTCI < 32°C), with UTCI achieving values below 31.56 °C, reaching a minimum of 30.60 °C. Extreme heat conditions are markedly reduced with this intervention. High-albedo shading fabrics demonstrate clear efficacy in significantly cooling the district as well as mitigating health risks related to severe summer heat waves. Despite the performance of these materials as a mitigation strategy, their deployment in heritage-protected areas requires a sensitive design approach to safeguard the aesthetic and architectural integrity of the urban landscape while ensuring thermal benefits. It is worth noticing that the variation in the height between the two configurations affects the results in terms of microclimate characteristics and comfort conditions to a lesser extent. Consequently, the feasibility of installing shading structures as a mitigation strategy mainly depends on the geometric configuration of the buildings, the historical significance of the facilities, and the availability of anchoring points.

3.4. Strategies Combinations

Figure 8 illustrates the findings of the combined scenarios. The mitigation scenario (SC5) integrates tree planting with flowerbeds. This configuration results in a modest reduction in average potential air temperature approximately equal to 0.15 °C, mirroring the findings observed in the tree-planting scenario SC3. In this case, the combination of the two strategies does not alter the spatial distribution of the potential air temperature compared to the individual interventions, yielding a similar average temperature decrease across the urban district. However, on the maximum value of the potential air temperature, a reduction of 1 °C was registered. The real effectiveness of this mitigation is evidenced by MRT, which decreased by an average of 0.8 °C across the study area. Notable localized reductions exceeding 13.30 °C—with peaks reaching 14.82 °C—were registered in the main square. In the narrower streets, the decrease ranges from 2.71 °C to 4.22 °C due to the presence of flowerbeds. Furthermore, the installation of horizontal greenery effectively mitigates pavement surface temperatures, improving microclimate conditions in adjacent pedestrian areas. As far as UTCI is concerned, the findings confirm the previous results related to the single redevelopment scenario. The peak reduction is registered in the main square (with the presence of the trees), while the flowerbeds influence the comfort parameter to a lesser extent (reduction of approximately 3 °C).

Finally, as for the mitigation scenario—which combines water bodies in the main square and the shading fabric structures installed at a height of 20 m (SC6)—the average value of the potential air temperature is reduced by 0.2 °C, with a 1 °C reduction in the maximum value. Conversely, a slight increase (~0.7 °C) in the minimum value of this microclimate parameter is detected in certain portions of the urban district. This is primarily caused by the presence of shading structures in the narrower streets and potential variation in the wind speed within this configuration. The results in terms of potential air temperature are comparable with those obtained for the previously proposed combination (SC5). An absolute difference in the maximum value of the MRT higher than 13.43 °C is calculated in the main square and directly beneath the shielding structures. This reduction is comparable with the one obtained considering the single mitigation strategy (SC4) in the narrow streets' layout (13.35 °C). In this first combined configuration, the installation of shading structures along the main streets improves the overall distribution of the MRT compared to the mitigation scenario SC1, which was primarily limited to the main square of Piazza della Repubblica. Consequently, this combination proved effective for the study area, ensuring a significant enhancement of the microclimate characteristics across the urban district as well as reducing the urban heat island effects. The installation of shading fabrics in narrow streets could be a viable strategy for mitigating the UHI phenomenon in high-density built environments, particularly where other alternative interventions, such as vertical greenery or tree planting, may be difficult to implement.

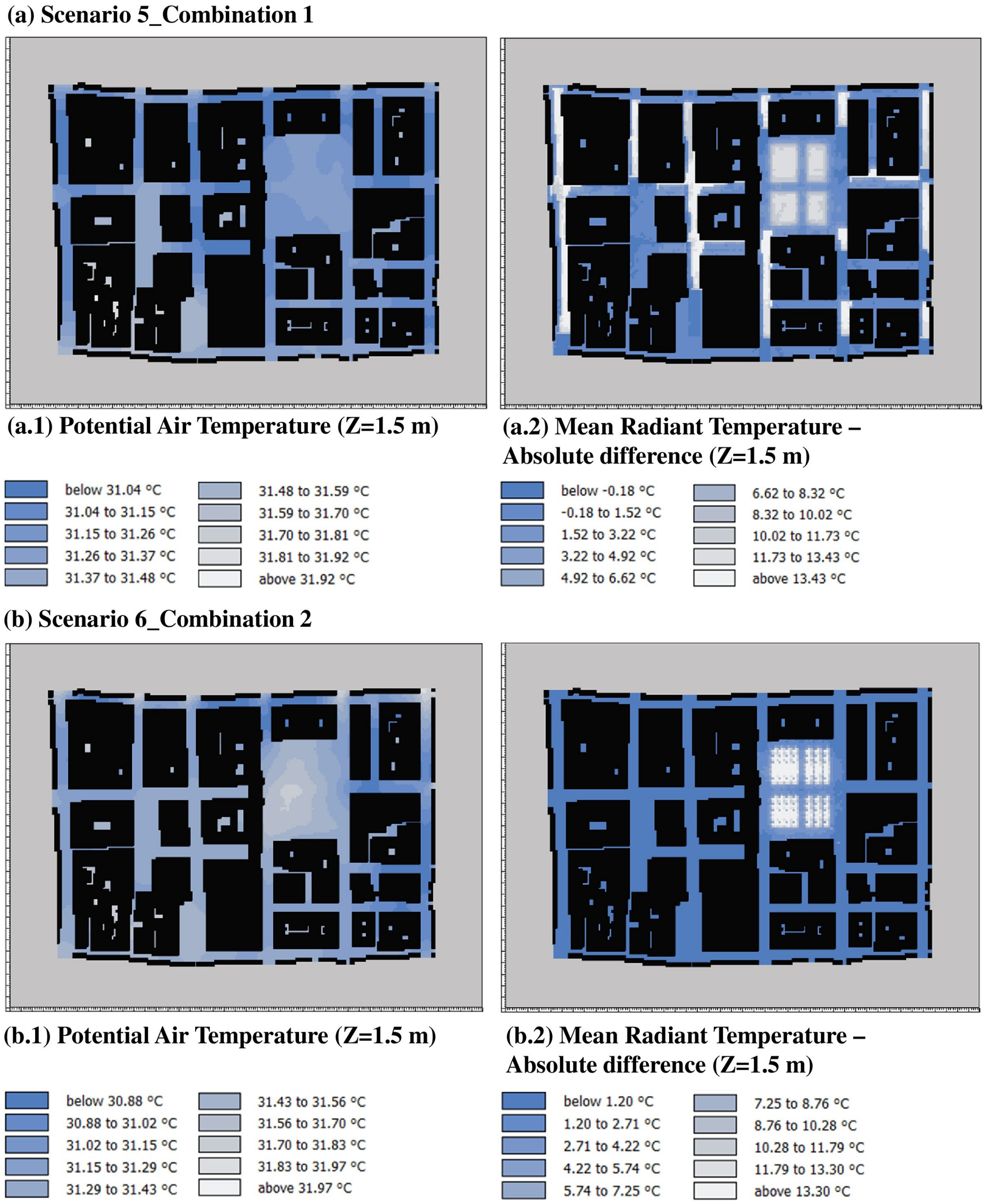
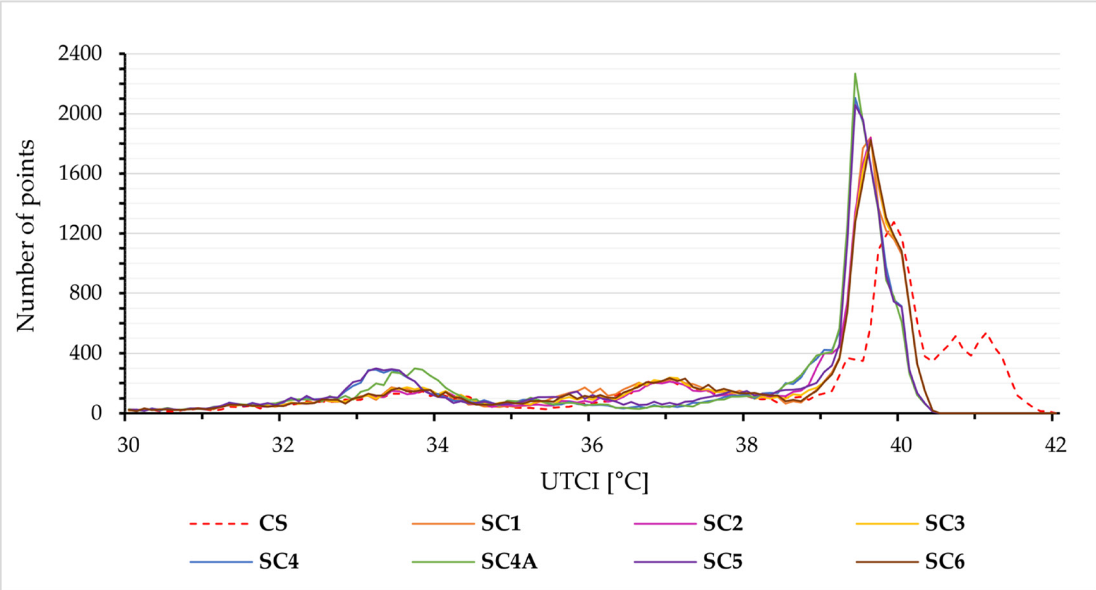


Figure 8. Potential air temperature and MRT Absolute difference compared to base case scenario for SC5 and SC6.

A quantitative analysis was conducted through an evaluation of the number of points of the ENVI-met grid registered at a specific temperature for the MRT, UTCI, and PET within the case study area, directly exported from the ENVI-met environment. The primary findings concerning the UTCI are illustrated in the following Figure 9. It is worth highlighting that compared to the current conditions, all intervention measures shift the UTCI parameter toward lower values, demonstrating the effectiveness of the proposed scenarios in improving outdoor thermal comfort. The number of points in the highest temperature interval (40 °C to 42 °C) was significantly reduced by the installation of high albedo shading fabrics (SC4 and SC4_A) as well as by combination 1 (SC5). These scenarios reduce the share of points in the highest interval by approximately 30%. Furthermore, they recorded values of 16%, 15%, and 16% respectively within the 32 °C to 34 °C range. For all proposed scenarios, most points fall within the 38 °C to 40 °C range. For the lowest temperature range (30 °C to 32°C), the scenarios are comparable (number of points < 6%).

(a) Number of points_UTCI



(b) Share of points_UTCI

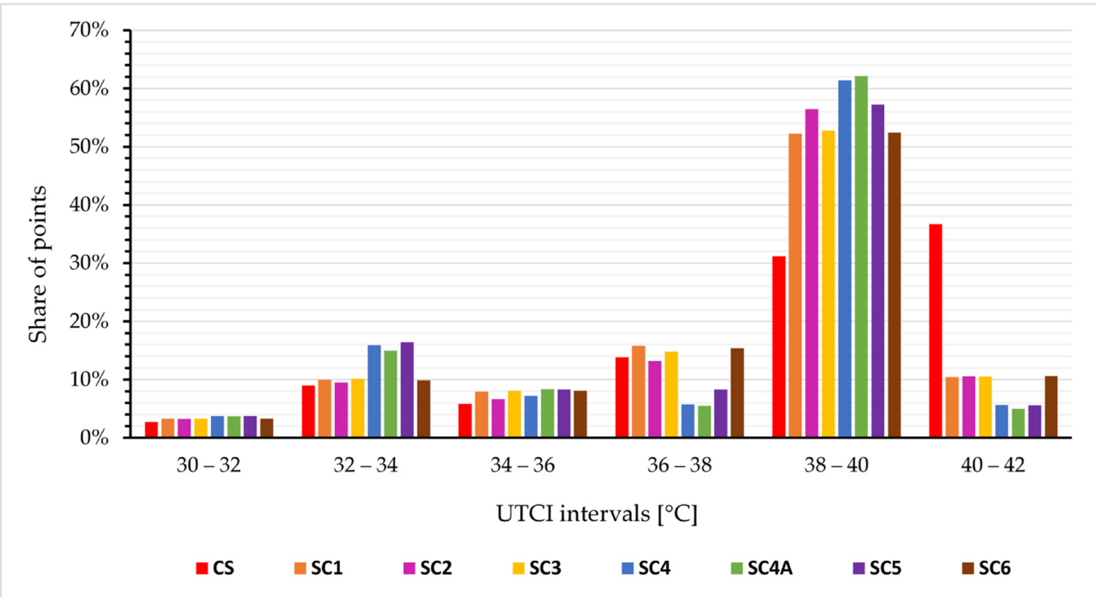
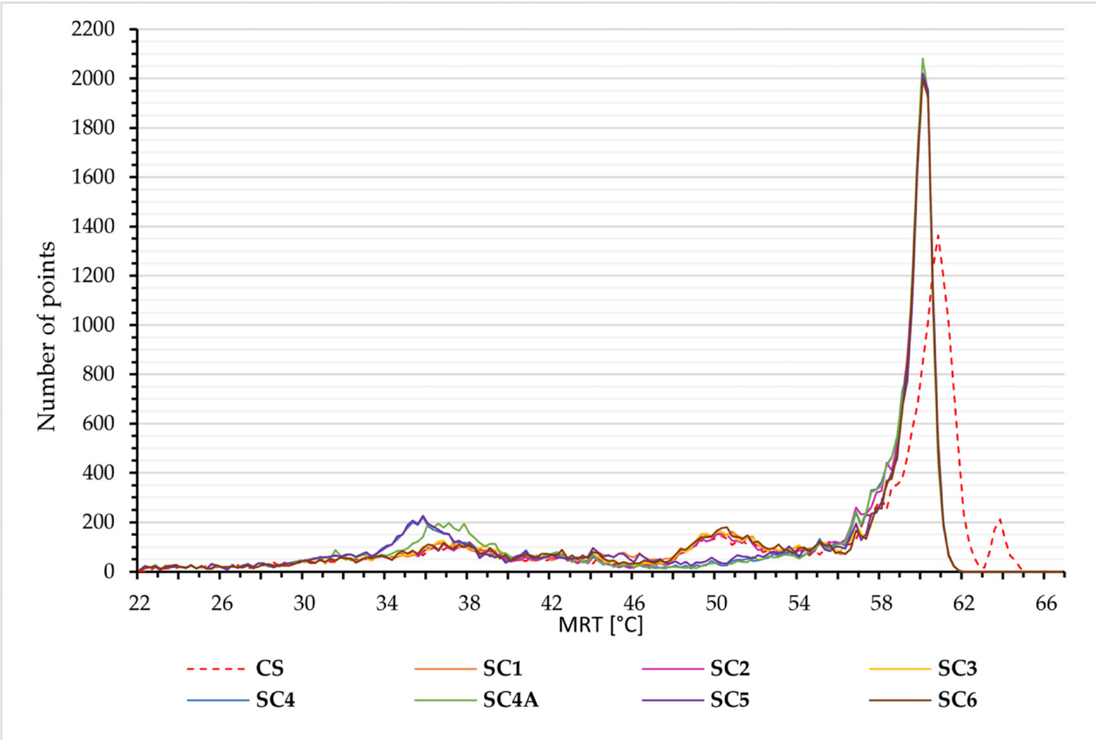


Figure 9. Analysis of data exported from ENVI-met for the evaluation of the impact of various mitigation scenarios in terms of comfort index UTCI [°C]. (**a**) Number of points for the Universal Thermal Climate Index and (**b**) share of points. The case study (CS) represents the current microclimate conditions (red dashed line—(**a**) and red column chart (**b**)).

Finally, Figure 10 illustrates the number of data points for MRT Figure 10a and PET Figure 10b, comparing the base-case scenario (indicated by red dashed line in both graphs) with the various mitigation interventions. Notably, for both these thermal indices, the findings demonstrate a potential reduction in the number of points within the highest temperature intervals. While the various mitigation scenarios have a smaller effect on the average MRT value across the urban district, the number of points at peak values is effectively lowered. Similar to the UTCI trend, the solutions with shielding structures (SC4 and SC4_A) and combination 1 show a significant share of points in the 34 °C to 38 °C range. Regarding PET, the combinations 1 and 2 significantly influence the results, lowering PET values across the urban district to a range of 42 °C to 48 °C and showing a substantial percentage of data points between 35 °C and 38 °C, thereby underscoring their robust cooling effectiveness.

(a) Number of points_MRT



(b) Number of points_PET

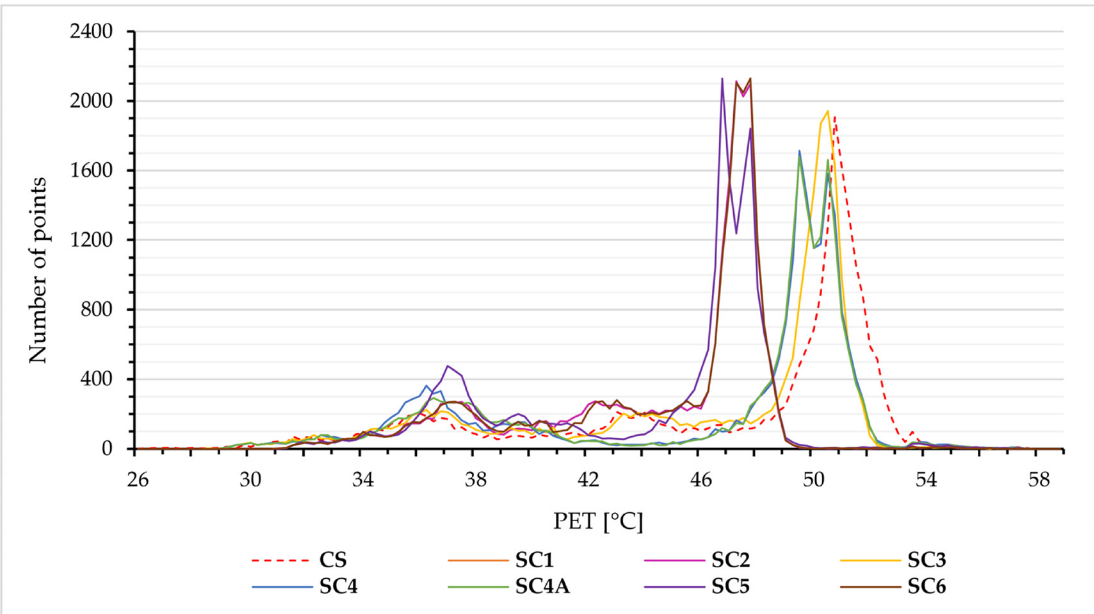


Figure 10. Analysis of data exported from ENVI-met for the evaluation of the impact of various mitigation scenarios in terms of comfort index UTCI [°C]. (**a**) Number of points for the Mean Radiant Temperature and (**b**) Number of points for the Physiological Equivalent Temperature. The case study (CS), used as the baseline case, is represented by a red dashed line.

4. Discussion

The microclimate simulations performed for the case study area demonstrate that during the summer season, the urban heat island represents a real and significant issue and poses severe risks for the population in open public spaces. The average potential air temperature is approximately equal to 32 °C, with MRT values peaking at 54 °C in the main square, Piazza della Repubblica. Evola et al. [42] similarly calculate high values of microclimate parameters by modeling in ENVI-met environments the downtown area of Avola (Italy). This microclimate condition results in severe outdoor discomfort for citizens in the outdoor environment, with UTCI reaching the "very strong" heat stress category in some portions (especially open spaces) and PET ranging from 31.08 °C to 53.68 °C. This is mainly attributed to low-albedo surface materials used in open-space finishes and paving, the lack of shaded areas, the reduced dimensions of the narrow streets, and the geometrical layout of the urban district, as well as the lack of green infrastructures. Similar findings regarding the spatial configuration of UTCI in historical centers can be retrieved in the current literature. Lai et al. [43] demonstrate that for middle and deep canyons, outdoor comfort for pedestrians is potentially improved by the presence of shaded areas due to building height during peak hours compared to open spaces. Within this context, the implications of the adopted roof-geometry simplification should also be discussed to better understand the possible influence of this geometrical simplification. Representing pitched roofs as horizontal surfaces neglects slope- and aspect-dependent variations in solar exposure and roof surface temperature. However, existing evidence on roof-level thermal modifications suggests that these thermal perturbations are attenuated toward the pedestrian level for building heights comparable to those considered in this research. For instance, Botham-Myint et al. [44], found that for 15.2 m high, four-storey buildings with H/W = 2, a 20 °C modification in roof surface temperature results in an air-temperature change of less than 0.1 °C at 2 m height. Similarly, Feng et al. [45] report an average daytime pedestrian-level temperature shift of only 0.05 °C for 18 m high buildings. Recent research studies highlight the effectiveness of blue and green infrastructure in mitigating UHI and managing stormwater [46,47] as well as in improving thermal comfort in outdoor spaces [48]. Water-based technologies can be a viable strategy to mitigate the urban heat island phenomenon in high-density districts, as concluded by Santamouris et al. [49]. The findings outline the effective advantages of introducing water bodies (SC1) as a targeted mitigation measure for the main square. A decrease in the MRT value equal to 12.20 °C was calculated, and a reduction in the UTCI value was registered (3 °C). Similar studies conclude that with water spray systems and water nebulization, it is possible to obtain a decrease in the UTCI value up to approximately 8 °C [50] in historical cities. Furthermore, Chatzidimitriou et al. outline that water bodies lower PET by up to 15% when considering the water evaporation phenomenon studied in Thessaloniki (Greece) [51]. Taleghani et al. [52] observed a reduction in MRT value comparable to the study presented in the paper, equal to about 15 °C, with the introduction of water bodies in a campus courtyard that can be considered as an open space, similar to an urban square.

Tree canopies can be considered one of the most promising green mitigation strategies when properly designed [53]. In the results presented in the paper, the tree-planting measure led to external temperature reductions ranging from 0.30 °C to 0.52 °C, which are comparable with the findings obtained by Aboelata et al. [54] for the historic city of Cairo. Those authors conclude that introducing green trees into high-density urban areas reduces daily air temperature by 0.4 K. Furthermore, the results related to the thermal comfort index are consistent with previous research; specifically, it is worth noticing that PET within Piazza della Repubblica decreased by approximately 7 °C and 9 °C. This aligns with research conducted by Behzad et al., which demonstrates that trees in a square can lower PET by up to 8 °C [55]. Alexandrou et al. [56] observed a 5.1 °C reduction in UTCI value following the introduction of trees in a portion of the city of Cairo, a result comparable to the ~4 °C reduction observed in Piazza della Repubblica for the tree-planting scenario.

The installation of flowerbeds (SC3) results in a reduction in the potential air temperature of about 0.15 °C. This aligns with the findings concluded by Santamouris et al. [49], who stated that the use of grass pavers can effectively reduce the ambient temperature by 0.1 K to 1 K. This value is further supported by other authors in the current literature, who demonstrate that flowerbeds can decrease potential air temperature in a courtyard by up to 1.1 °C [52]. Similar results are also obtained by Su et al. [57] in Beijing Old City, with a reduction in the average value of potential air temperature equal to approximately 0.2 °C and a peak average PET value equal to 38.18 °C, achieved with traditional greenery. Battista et al. [28] reported a peak reduction in a square located in Rome of 2.11 °C, which is comparable to the decrease observed in Piazza della Repubblica (~1.2 °C).

Regarding the SC4 and SC4_A scenarios, a significant reduction in both PET and UTCI was demonstrated directly beneath the shading structures. The effectiveness of textile shielding systems in decreasing thermal stress for pedestrians was also highlighted in the research conducted by Corticos et al. in Évora (Portugal) [58]. Furthermore, a decrease in the potential air temperature equal to 0.20 °C across the urban district was registered; this is comparable to the 0.32 °C reduction obtained by Necira et al. [59] in a site characterized by a hot desert climate, and it aligns with the findings by Abedrabboh et al. [60], who highlight a slight reduction in the potential air temperature across the urban district ranging from 0.1 °C to 0.2 °C. The shading fabrics affect the value of the external air temperature to a lesser extent. A decrease in MRT equal to 14 °C can be registered in these configurations with shading fabrics. As suggested by some authors in the recent literature, this favorable condition may result from both the removal of direct solar radiation and lower surface temperature [36,61].

Comparing all the mitigation scenarios modeled and analyzed, it is worth highlighting that all proposed interventions positively affect both the microclimate parameters and the comfort indexes. The most encouraging results are certainly obtained for the open squares included in the historic urban district; however, measurable improvements can also be achieved in the narrower streets of the study area. This suggests that tailored mitigation measures can also be adopted in street canyons, even if characterized by restricted dimensions.

The most promising solution is the adoption of district-wide shading structures (SC4 or SC4_A) and the implementation of tree-planting (SC3) or water bodies (SC1) in the main square (Piazza della Repubblica). In this specific location, heat stress falls into the "very strong" category. The previously cited strategies led to a substantial decrease in thermal stress as measured by both UTCI and PET. Improving thermal comfort in outdoor environments for tourist-oriented cities like Florence is essential to safeguard visitors during the summer season and significantly reduces the vulnerability of residents to heat-related risks. Summer heat waves and associated discomfort in outdoor spaces can be considered a serious threat to tourism in Mediterranean cities [62].

A key advantage of the proposed mitigation alternative is adaptability and replicability. Two of the six proposed scenarios involve portable trees or removable textile structures, which can be deployed or rearranged according to seasonal requirements or urban needs. The intervention with flowerbeds installed across the district affects the microclimate parameters and comfort indexes to a lesser extent. Furthermore, the performance of the combined strategies strictly depends on the efficacy of their single components; the tested combinations yield comparable improvements. This study demonstrates the adequate performance of both green and blue infrastructures as well as shading systems in enhancing comfort in the outdoor environment, even within dense-built historic urban layouts. However, the research presents some limitations and needs further investigation to deepen the results obtained. On-site investigation campaigns should be performed to obtain accurate microclimate files and refine data with on-site measurements to effectively validate the microclimate model in ENVI-met. Additionally, due to the high computational time, this study focuses on the central hours of the day. Future analyses should implement 24 h simulations, also including nighttime evaluations, to further demonstrate the validity of mitigation interventions also in other times of the day or other days of the year (i.e., shoulder seasons). Furthermore, conducting 24 h microclimate simulations yields more comprehensive results by accounting for the thermal behavior of materials. This is significant for those characterized by high thermal inertia, whose contribution cannot be adequately evaluated within a 4 h simulation window. A further limitation concerns the representation of the tree-planting scenario (SC3). Although portable planters are proposed as a reversible solution for real-world intervention, the trees were represented in ENVI-met as planted in natural soil. This modeling assumption may influence the simulated cooling performance of SC3. Indeed, restricted rooting conditions in containers can limit root development and modify water availability compared with unrestricted soil conditions [63]. Experimental evidence also shows that containerized and ground-planted trees may exhibit different soil-temperature, soil-moisture, and transpiration responses, with the magnitude and even direction of these differences depending on the tree species and container configuration [64]. This aspect is particularly relevant for *Citrus aurantium*, as water stress has been shown to reduce stomatal conductance and transpiration in sour orange [65]. Therefore, the SC3 results should be interpreted as the cooling potential obtained under the adopted ENVI-met soil–vegetation representation.

Finally, future developments should explore different mitigation measures and their combinations, also deepen the integrability with the specific morphological layout, and include a cost–benefit analysis to assess the viability and feasibility of these kinds of strategies in sensitive historical contexts.

5. Conclusions

This study assessed the effectiveness of various UHI mitigation measures, including green and blue infrastructures and shading fabrics, within a historical district in the center of Florence. The microclimate simulations were performed using ENVI-met software. First, the microclimate characteristics of the current-state scenario (Ta and MRT) and comfort indices in the outdoor environment (UTCI and PET) were calculated. Then, six mitigation scenarios (SC1–SC6) were proposed to evaluate potential improvements over the existing conditions. Notably, two of the six redevelopment scenarios involve removable or portable measures for flexible urban arrangements based on specific needs. During the peak summer season, the analyzed district exhibits an average Ta of approximately 32 °C and an MRT of about 59 °C, falling into the “very strong” heat stress category according to the Copernicus classification. This poses significant risks for public health. The most critical hotspot identified in the study area is the main square, Piazza della Repubblica, where citizens and tourists can experience severe thermal stress. For this reason, two of the proposed mitigation scenarios are specifically tailored to the main square. Water bodies (SC_1) decreased MRT by up to 12.20 °C, reducing UTCI by 3 °C. The implementation of trees (SC_3) lowered MRT by about 15 °C in the main square, with UTCI and PET decreasing by 4 °C and 7 °C, respectively. Consequently, under the simulated conditions, tree canopy integration proved to be the most effective measure to be used in open spaces like Piazza della Repubblica. The site-specific measures for the main square affect the microclimate characteristics across the urban district to a lesser extent. As regards the broader district level, mitigation strategies foresee the shading structure solution (SC4) appears to be the most viable and effective option compared to the flowerbeds (SC2) scenario by blocking incident direct solar radiation. Shading fabrics successfully reduced the heat stress category to “moderate” directly beneath the structures. Furthermore, these are temporary structures and non-invasive for an historical context, overcoming legislative and regulatory constraints as well as representing an adequate trade-off between microclimate mitigation and heritage conservation.

The implementation of tailored microclimate-aware mitigation strategies should be integrated into near-future urban planning of historic cities, and planners should design solutions beyond isolated greenery projects. These findings demonstrate the feasibility of improving mitigation strategies in sensitive heritage environments to ameliorate thermal conditions. The workflow and findings presented in the research paper can be directly transferable to other high-density European urban contexts facing severe summer heatwaves. Furthermore, the results both prove the efficacy of the different mitigation measures proposed and validate the effectiveness of high albedo shielding systems as a cooling strategy. In conclusion, this study offers valuable insights into the possibility of adopting mitigation strategies also in UNESCO-protected spaces and proves the real possibility to ameliorate human comfort conditions in the outdoor environment. The study provides a reference baseline for UHI mitigation in historic centers, while acknowledging that real-world applications must address social and financial barriers as well as complex legislative requirements.

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