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Climate Mitigation and Adaptation Strategies for Roofs and Pavements: A Case Study at Sapienza University Campus

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Abstract: The progressively emerging concept of urban resilience to climate change highlights the importance of mitigation and adaptation measures, and the need to integrate urban climatology in the design process, in order to better understand the multiple effects of combined green and cool technologies for the transition to climate responsive and thermally comfortable urban open spaces. This study focuses the attention on selected mitigation and adaptation technologies; two renovation scenarios were designed and modeled according to the minimal intervention criterion. The study pays attention to the effect on surface temperature and physiological equivalent temperature (PET) of vegetation and high albedo materials characterizing the horizontal boundaries of the site. The Sapienza University campus, a historical site in Rome, is taken as a case study. These results highlight the importance of treed open spaces and the combination of permeable green pavements associated with cool roofs as the most effective strategy for the mitigation of summer heatwaves and the improvement of outdoor thermal comfort.

Keywords: permeable pavements; cool roofs; cool pavements; green roofs; urban heat island (UHI) mitigation; PET

1. Introduction and Research Background

1.1. Climate Change and the Built Environment

Cities constitute the arena where the most relevant social and environmental challenges are concentrated. Two factors have placed cities at the center of public attention in general and of the academic interest in particular: the ever-increasing population density on one hand and climate change on the other [1]. Urban areas cover less than 3% of the earth's surface, however, they are responsible for an estimated 71% of global energy-related carbon emissions [1]. In particular, climate change, which it is at the same time a global and local issue, is expected to increase the frequency and intensity of extreme temperature and precipitation events, towards which urban areas play a crucial role. The increased average temperatures and the related climate change phenomenon proved to have different negative effects on the urban environment; in fact, the thermal balance of cities is highly affected by the increased absorption of solar radiation and the corresponding increase of sensible heat released by urban structures, higher anthropogenic heat, higher emissions of infrared radiation, and other specific sources [2–4]. In this regard, urban heat island (UHI), that is to say the higher ambient temperatures registered in the city compared to the countryside, is the most documented and complex phenomenon of urban climate [5] and climate change [6,7]. As underlined by Georgiakis and Santamouris [8], urban structure material characteristics and energy consumption patterns influence the thermal balance of cities and the intensity of the UHI. As stated by Akbari and Kolokotsa [3], despite its long history of discovery, dated and documented over a century ago, the effect of the UHI on urban climate and the built environment during the summer have only been the focus of research over the last three decades; more specifically, the recent research can be divided into two major groups: first, research that focuses the attention on the evaluation of the summertime effects of UHI on energy use, air pollution, outdoor ambient temperature, and citizen health; second, studies that focus the attention on the development and evaluation of materials and technologies to counter the effects of summertime UHI. In order to understand the relationship between climate change and architecture, the concept of 'scale' is fundamental [9]: the urban built environment is a complex of urban structures, greenery, and natural and artificial energy fluxes, each interacting in different ways and time with each other. The different material characteristics bring a diverse energy balance and budget of each surface that ultimately generate contrasts in surface characteristics, leading to mutual interactions by radiative exchange and small-scale advection [9]. Similarly, if we consider thermal comfort in the outdoor environment, with the added complexity of the wide spatial and temporal variability of environmental conditions, the interactions between the physical environment, as well as physiological and psychological mechanisms, become even more challenging [10]. In fact, regarding the human energy balance, human perception of heat is governed mainly by the local environment and thermo-physiological processes [11], therefore, it represents a complex theme of research and discussion, and from the climatic perspective it cannot be described only by air temperature (Ta) variations, as it is also influenced by other meteorological variables such as the mean radiant temperature (Tmrt), wind speed (v), and water vapor pressure (VP), as clearly underlined by Lee et al. [12]. In this regard, climate change and the related UHI phenomenon, by deteriorating the outdoor comfort conditions have highlighted the role of urban open spaces in providing environmental, ecological, social, and economic benefits to cities which are indispensable for healthy urban living [13,14]. Since the main focus of the paper is to improve outdoor thermal comfort conditions in urban open spaces and to discuss useful advice and observations regarding the thermal environment for urban design, the scale of the present study corresponds to the urban canopy layer (UCL) which describes the part of the atmosphere between the surface and the tops of buildings and trees, where the local climate is dominated by the materials and the geometry of the urban environment. The scale of analysis is fundamental not only for the demarcation of the problem but also in order to better understand the interrelation among architecture–urban climate–outdoor comfort, thus, the importance of microclimatology to inform urban designers and ultimately the relevance of a transdisciplinary approach in this field. Overall, it is important to recognize that cities are part of the solution to climate change, and thus they offer many opportunities to develop mitigation and adaptation strategies to deal with climate change, especially through urban planning and design.

1.2. Mitigation and Adaptation Strategies toward Urban Resilience

In recent years, parallel to the sustainable development and climate change debate, there has been an increasing interest in the concept of 'climate resilience' and more generally 'urban resilience' [15]. The term 'resilience' comprises different levels of interest and provides insights into complex socio-ecological systems and their sustainable management. Urban resilience refers to the ability of an urban system and all its constituent socio-ecological and socio-technical networks, across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity [16]. As underlined by the OECD (Organisation for Economic Co-operation and Development), a resilient city has the ability to absorb, recover, and prepare for future shocks, may it be economic, environmental, social, and institutional [17]. The concept of a city resilient to climate change comprises two main aspects or actions: mitigation and adaptation strategies. While mitigation tries to reduce the impact that can lead to higher energy consumption and emissions [18], adaptation aims to decrease the other harmful effects of climate change and to prepare the built environment for climate emergency [19]. Several strategies may belong to both categories since they represent a complementary set of actions to counteract climate change. In order to simplify the consistent and transdisciplinary body of research, it is possible to divide the current prevalent studies in three fields of analysis, studies focused on: (i) smart materials, such as high reflective materials (e.g., *cool materials*, *cool colored materials*), (ii) green infrastructures, such as parks, *green roofs*, *green walls*, *garden systems*, *pervious pavements*, and trees in general, and (iii) blue infrastructures, in particular *water mist cooling systems*. Among these three fields of study effective mitigation strategies are: the increase of vegetated surfaces (such as grass, green roofs, and green walls) and green spaces and the elevation of the urban materials' albedo (that is the ratio of global radiation reflected to the global radiation received by a surface) [20]; nevertheless, the increase of green spaces may be included, together with the *rain garden systems*, to the *adaptation measures*.

1.3. Overview on the Mitigation Potential of Cooling Materials and Green Infrastructures

The present study concentrates on two specific mitigation measures: 'cool materials' and green infrastructures (GI), identified to be the most efficient solutions for the environmental mitigation of urban open space in terms of reduction of built surfaces overheating and ambient outdoor temperatures, CO_2 emissions in the atmosphere, and on cooling energy demand [3,18]. In particular, highly reflective materials also referred to as 'cool materials' for their capacity to present low surface temperatures, are a large class of materials ranging from natural to artificial, as underlined by Pisello in her comprehensive and systematic review [21]. Regarding the cool pavement technology, a field study conducted in Athens [22] showed that reflective pavements could reduce surface temperature in an urban park by up to 7.6 °C under non-shaded condition. However, it is fundamental to evaluate how much of the reflected radiation is absorbed by the surrounding surfaces of the built environment, such as walls or by pedestrians themselves [23–26]. In fact, Erell et al. [24] underlined that use of cool colored materials may increase albedo substantially without altering visual appearance; however, because the human body is non-selective in its absorption of solar energy, the effect of albedo modification on thermal sensation could be negative. On the other hand, a combination of cool materials and trees showed positive effects both on outdoor temperatures and on thermal comfort as well, as demonstrated in a study by Shahidan et al. [27] and Laureti et al. [28]. Therefore, the use of cool coatings for the ground level (i.e., cool pavements) display different mitigation performances and require attention on the material characteristics of the surrounding area and on the morphology of the site. Regarding the application of cool materials on the roof level, different experimental and theoretical studies on cool roofs [29] have proved how they show a relevant impact on the indoor microclimate and on outdoor ambient temperature, but compared to cool pavements, they have a small direct influence on outdoor thermal comfort at pedestrian level because of the long distance [30]. Nevertheless, if applied to low-rise buildings and in combination with other strategies, they show higher influence on ambient temperature and thermal comfort [31]. In this regard, the interest towards the combination of cool and green technologies in order to maximize their mitigation potential represents the principal framework of the present study. Regarding the second set of mitigation measures, 'green infrastructures' (GI) are considered the most effective for urban cooling—primarily through shading and the reduction of ground surface temperatures, and in some cases through evapotranspiration as well [20]. As underlined by Kumar [21], GI can positively contribute to reducing the impacts of climate change by, for example, reducing heat stress, improving air quality, and decreasing flood risks. Recent studies conducted by Ketterer and Matzarakis [32] and Lee et al. all [12] showed that green surfaces proved to highly influence outdoor thermal comfort, and among all GI, trees proved to be a feasible form for the mitigation of heatwaves. Trees display a higher performance on thermal comfort and heat mitigation than grass because of their geometry and their related higher shading effect, the evapotranspiration processes, and thanks to their capacity due to their foliage density, to modify and interact with natural ventilation [33]. Regarding green roofs, when applied on a city scale they reduce the average ambient temperature of the city by a value between 0.3 and 3 °C [34]. In reference to their effect on outdoor thermal comfort at pedestrian level, Peng et al. [35] evaluated the effects of extensive and intensive green roofs compared to existing bare roofs on pedestrian thermal comfort on different sites in China; the results show a mitigation in terms of physiological equivalent temperature (PET) from the two green technologies, with a small decrease of the temperatures perceived at pedestrian level since here the outdoor PET, dominantly determined by radiation, can hardly be modified by greenery situated on rooftops. Nevertheless, green roofs are a relevant microclimate measure if we consider a larger scale of application for their effects on ambient temperatures, the natural based services they provide, along with their retention capacity. Finally, another interesting strategy belonging to GI and referred to also as Sustainable Drainage Systems (SuDs) are permeable pavements (e.g., interlocking concrete pavers) and porous pavements (e.g., porous concrete). These are a hybrid strategy because of their multiple effects on soil, atmosphere, and indirectly on human comfort. In a recent study conducted by Fini et al. in Italy (i.e., Como) [36], four different types of pavements have been tested and the authors have observed that a reduction of evaporative cooling from soil paved with permeable and impermeable pavements contributed to significant soil warming. Enhancing evaporation from the paved soil by the use of porous pavements may contribute to mitigating urban heat islands [37]. Therefore, in this work, cool materials, green roofs, and permeable pavements are investigated as passive solutions for urban open spaces and urban canyons of the historical city, especially for the horizontal surfaces.

2. Purpose of the Work

The outlined state of the art highlights the most relevant mitigation measures among material technology and green strategies; in defining the main research areas implemented so far and the principal findings, the present paper aims to go beyond the objectives of the main studies and to focus the attention on the effects of UHI mitigation technologies on outdoor thermal comfort, in order to better understand their behavior and then their performance towards the urban microclimate, especially in a historical Mediterranean context. In that regard, even though the present research follows a consolidated methodology of urban climate assessment, it belongs to a recent line of studies that evaluate the application of innovative materials for the amelioration of the microclimate conditions in Mediterranean historical tissues, especially in Italy [38,39]. Based on the existing knowledge, several questions concerning mitigation and adaptation strategies for counteracting UHI and climate change risks have been raised from the urban design perspective. In particular, in light of the concept of energy redevelopment and the Italian scenario of the consolidated and historical tissues, the historical heritage view both as a single building and as a district network, seems to be an intriguing field of experimentation [40]. Building upon previous studies, the present paper concerns the evaluation of specific mitigation measures on local microclimate conditions and on pedestrian thermal comfort in historical urban open spaces in the city of Rome, in central Italy.

In this research, the additional need to consider the constraints of preserved historical urban areas, which usually are subject to restrictive regulations towards urban transformation, is considered. Therefore, in line with growing relevance of mitigation and adaptation measures for counteracting UHI and to cope with climate hazards, the present study aims to investigate among the numerous strategies, those climate mitigation solutions that follow two criteria: minimal intervention, in order to address the architectural constraints of historical urban areas, and the combination of green and smart material technologies, in order to make urban open spaces more resilient to climate change and UHI and increase thermal outdoor comfort for the creation of mixed and vibrant public spaces [41]. Thus, the analysis of the influence of innovative cool materials and green surfaces on the urban canyon horizontally surrounding built surfaces is carried out. The following is a synthesis of the main questions and objectives underlying the present study.

Principal questions:

1. What are the different impacts and the magnitude of cool materials on outdoor thermal comfort?
2. What are the different impacts and magnitude of green systems on outdoor thermal comfort?
3. In which way do architectural morphological factors, such as height and width ratio (H/W) etc., influence the mitigation potential of the selected technologies?
4. What are the most efficient technological combinations in terms of mitigation of outdoor ambient temperatures as well as thermal comfort improvement?

Principal objectives:

1. To understand the behavior of cool materials and green technologies under different exposures and applications (i.e., open unshaded areas, narrow unshaded areas, natural shaded areas, artificial shaded areas; roofs and pavements), in terms of microclimate and thermal comfort modification.
2. To understand the combined effect of natural elements and smart technologies on outdoor thermal comfort.
3. To evaluate the most efficient design combination for a climate design approach in the renovation process of urban open spaces in the historical context.

3. Methodology

In order to evaluate (i) pedestrian comfort levels and (ii) the effectiveness of selected mitigation techniques, the study has been carried out based on the following steps:

- Data collection of the main local microclimate parameters from a consolidated national Test Reference Year (TRY) dataset [42];
- Selection of the most relevant mitigation measures for the microclimate renovation of the site;
- Selection of the most representative day for the summer period by cross-referencing the hottest days and the mean attendance rate of the site;
- Microclimate simulation of the case study urban area and comparative analysis of microclimate mitigation scenarios;
- Results analysis and comparison by means of selected microclimate parameters, surface temperature (T_s), and physiological equivalent temperature (PET) [43], in order to understand the multiple and varied effect of cool materials and greenery on outdoor thermal comfort.

This section presents the urban open space object of study and the methodology followed to assess the outdoor microclimate benefits resulting from the mitigation scenario proposed for the renovation of the university communal open spaces. Underlying this study is the premise to represent a streamlined and synthetic methodology for the comparison and evaluation of the microclimate behavior of specific design scenarios for climate adaptation and mitigation. A synthetic representation of the methodology is represented in Figure 1.

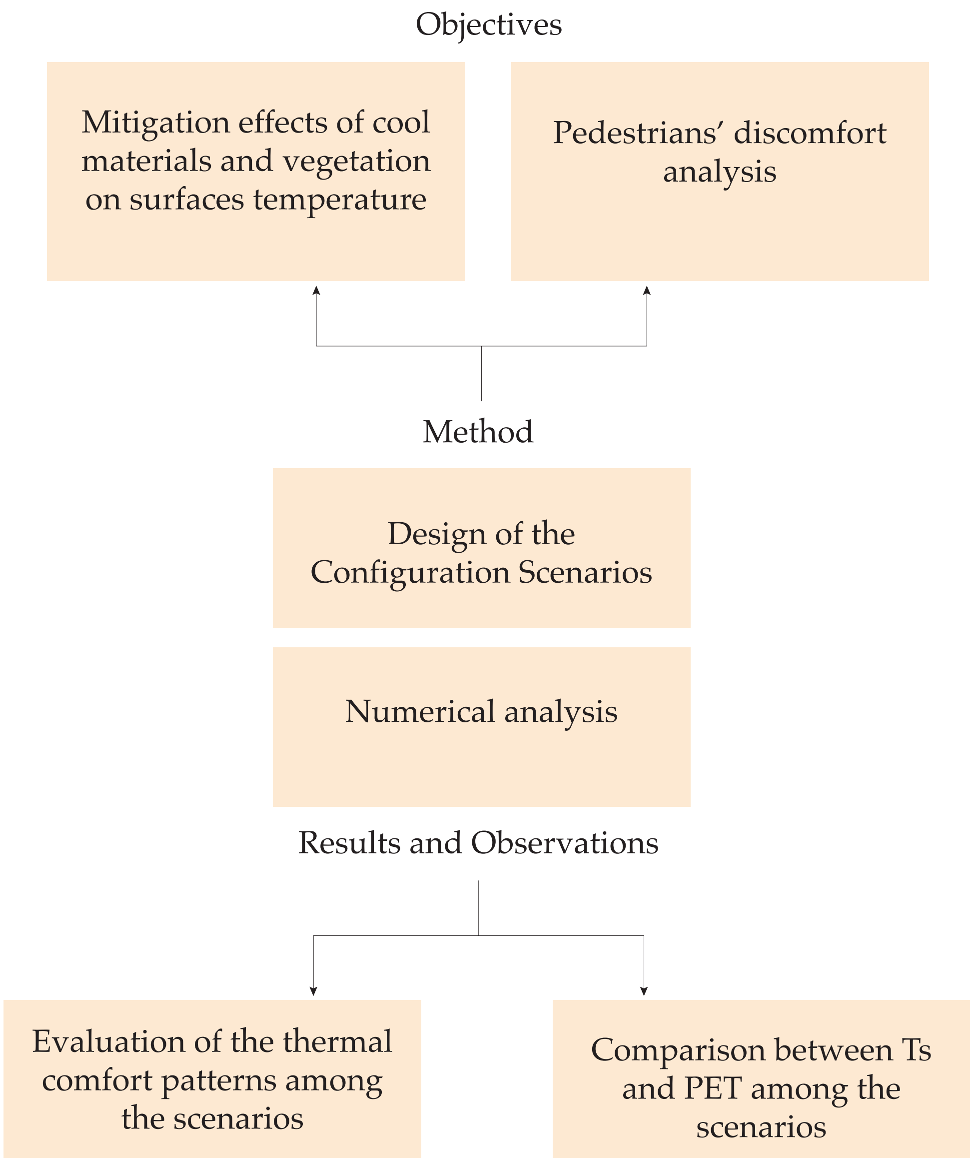


Figure 1. Scheme of the applied methodology. T_s: surface temperature; PET: physiological equivalent temperature.

3.1. Case Study: Site Location and Microclimatic Characteristics

The study was carried out at Sapienza University campus, known as University City (coordinates 41°54′10.32″ N, 12°30′51.72″ E, 45 m elevation) and here referred to as University Campus, located in the 2nd Municipality in the city of Rome. The city of Rome is characterized by a typical Mediterranean climate, and according to Köppen–Geigen classifications, it belongs to the dry-subtropic Csa [44]. The intermediate seasons, spring and fall, are characterized by mild and warm temperatures, with the majority of rainfall occurring in the month of November and April; the winter season is mild and wet with isolated phenomena of low temperatures and snowfall, whereas the summer season is usually hot, humid, and characterized by low precipitation. The University Campus (about 44 ha or 110 acres), was selected for its cultural, historical, social, and architectural relevance. It was selected firstly, for its cultural significance (or dimension) since it is one of the principal centers of advanced education and research in Italy [45]. Secondly, for its position: it is part of the 2nd Municipality, in the proximity of the historic center of the city and Tiburtina railway station—an important transport hub. The campus, which is part of the University district, shares its borders with other historical districts, such as San Lorenzo, a second public transport hub (Verano Square), and the Verano Monumental Cemetery, which with its 83 ha (205 acres) represents a consistent green area for the district's microclimate. Third, it represents a pole of attraction of the city's cultural life for its public spaces and social events and ultimately for its architecture; the campus is in fact characterized by a consolidated tissue of architectural value belonging to the Italian Modernist Architecture heritage and presents a relevant distribution of green areas, which amount to 20% of the campus' open spaces, whereas the built area amounts to 30% of the entire campus area. The study concentrates on a specific area of the University Campus, in order to focus the attention on the material characteristics of the built environment and to analyze the effect that selected materials and combinations of vegetation can have on the microclimatic conditions, as well as on the outdoor thermal comfort of pedestrians, with the ultimate goal to inform urban designers on specific best practices for the energetic and environmental renovation processes to be applied within the Campus, as well as in similar urban districts in the city of Rome. In particular, the site object of study is a quadrangular area of 84,000 m^2, and it comprises two main areas: the central street boulevard in the southeastern sector of the Campus, called Viale Piero Gobetti, that connects the monumental eastern entrance from Piazzale Aldo Moro to the second area represented by the center of the Campus, Piazzale della Minerva, as shown in Figure 2. Overall, the built areas measure 44% of the entire site of analysis, whereas the open spaces measure 56% of the remaining space, with green areas covering about 19%.

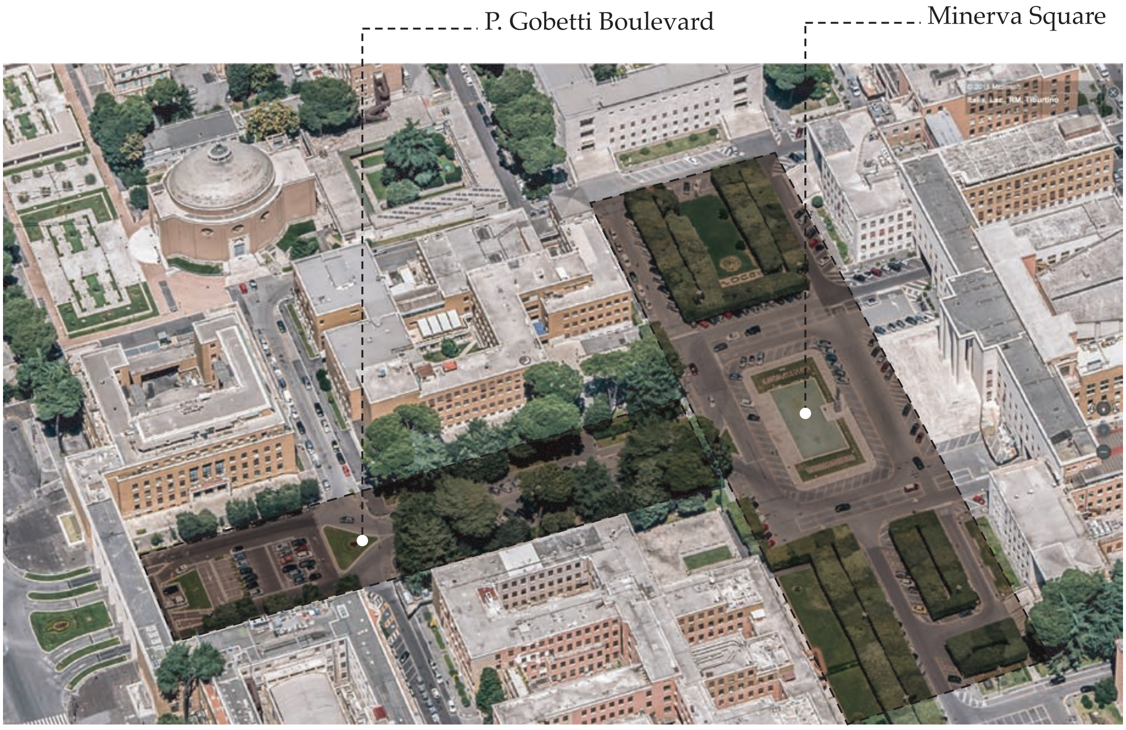


Figure 2. Site location of Gobetti Road and Minerva Square in Sapienza University campus. Source: Bing Maps 2018 [46].

Figure 3 shows an overview of Gobetti Road and of Minerva Square, it is possible to observe the main materials used for the ground level and the façades. The main street, Viale Piero Gobetti, is a rectangular area, in particular a large street canyon with a northeast-southwest orientation, measuring approximately 174 × 62 m^2; the pedestrian sidewalks measure in width about 14 m in the first sector and 20 m in the second sector, whereas the driveway area measures in width about 34 m, including a central parking area in the first sector, and 18 m in the second sector of the street. The surrounding buildings alongside Viale Piero Gobetti, representing the urban interface of the street and its main interacting surfaces, are about four floors high, with an average elevation of 17–20 m and a height/width ratio (H/W) equal to 0.32. Thus, the street is exposed to solar radiation but the presence of the tree rows (principally: *Quercus ilex*, *Pinus pinea*, and *Cedrus atlantica*) offer a shaded environment other than the building shade. The ground floor is characterized by different types of pavements: granite single stones (α = 0.40) and asphalt (α = 0.20) for the road, travertine (α = 0.80), asphalt (α = 0.20), and grass (α = 0.22) for the pedestrian sidewalks. The building façades are finished in lime plaster characterized by pastel shades (α = 0.45), bricks (α = 0.40), and travertine slabs at the base of the building (α = 0.80). It must be underlined that the identification of the materials was made during the site survey phase, whereas the corresponding albedo coefficients were taken from the ENVI-met software database. The central square, called Minerva Square for the presence of the monumental statue of the Greek divinity of wisdom (i.e., Minerva), is a large rectangular mixed-use area, with an east-west orientation, measuring approximately 78 × 256 m, symmetrically divided in two by a central pedestrian area of 24 × 48 m with grass and a rectangular fountain in it. The square is characterized by several green areas of different sizes and trees located on the outer perimeter, and several parking areas. The surrounding buildings are about four to five floors high, with an average elevation of 17–25 m and a height/width ratio (H/W) equal to 0.30. The ground floor of the square is characterized, similarly to the street area, by granite single stones (α = 0.40), asphalt (α = 0.20), travertine (α = 0.80), and grass (α = 0.22), with a larger presence of green spaces. The façades are characterized by bricks (α = 0.40), orange-colored lime plaster (α = 0.45), and travertine slabs (α = 0.80). Table 1 summarizes the principal materials characterizing the two areas of analysis.

(a) (b)

Figure 3. A picture of Gobetti Road (**a**) and Minerva Square (**b**), taken on 15 July 2016.

Table 1. Material characteristics of the initial condition scenario (S0).

Initial Condition Scenario (S0)	Section 1—Gobetti Boulevard (Entrance)	Section 2—Gobetti Boulevard (Middle)	Section 3—Minerva Square
H/W ratio *	0.32	0.32	0.30
Pavements	Granite single stones (α = 0.40) Asphalt (α = 0.20) Travertine slabs (α = 0.80) Grass (α = 0.22)	Granite single stones (α = 0.40) Asphalt (α = 0.20) Travertine slabs (α = 0.80) Grass (α = 0.22)	Granite single stones (α = 0.40) Asphalt (α = 0.20) Travertine slabs (α = 0.80) Grass (α = 0.22)
Façades	Bricks (α = 0.40) Orange-colored lime plaster (α = 0.45) Travertine slabs (α = 0.80)	Bricks (α = 0.40) Orange-colored lime plaster (α = 0.45) Travertine slabs (α = 0.80)	Bricks (α = 0.40) Orange-colored lime plaster (α = 0.45) Travertine slabs ((α = 0.80)
Roofs	Concrete tiles (α = 0.30)	Concrete tiles (α = 0.30)	Concrete tiles (α = 0.30)
Vegetation	– – *Quercus ilex* (deciduous) (α = 0.20) *Citrus x aurantium* (deciduous) (α = 0.40)	*Cedrus atlantica* (evergreen) (α = 0.18) *Pinus pinea* (evergreen) (α = 0.18) *Quercus ilex* (deciduous) (α = 0.20) –	*Cedrus atlantica* (evergreen) (α = 0.18) *Pinus pinea* (evergreen) (α = 0.18) *Quercus ilex* (deciduous) (α = 0.20) *Citrus x aurantium (deciduous)* (α = 0.40)

* H/W ratio is an aspect ratio used to define the geometry of an urban open space, in particular of a street canyon, and it is defined as the ratio between the height to the width of the canyon.

3.2. The ENVI-Met Software

Since the main focus is to study the impact of combination modification in terms of greenery (i.e., grass and trees) and albedo of urban materials at ground and roof level on outdoor microclimate and thermal comfort; plant, surface, and air interaction modeling is essential. Therefore, the numerical simulations were performed through the use of ENVI-met V4.3.1, a three-dimensional validated microclimate modeling system [47]. ENVI-met V4 is a non-hydrostatic prognostic model of thermal interactions based on the fundamental laws of fluid dynamics and heat transfer; it represents a CFD (Computational Fluid Dynamic) modeling used in many studies to evaluate, in terms of biometeorological conditions, the urban layout, which is modeled through four systems: soil, vegetation, atmosphere, and buildings. ENVI-met has been extensively validated in recent years and it has been coupled with building energy models such as Energy Plus for the estimation of indoor microclimate and energy savings issues [48] and more recently with Grasshopper and TRNSYS [49,50] for increasing the accuracy in the simulation of urban outdoor comfort. Starting from version 4.0 solar radiation analyses, vegetation modeling, advanced plant simulation, detailed building physics, and air pollution are included. The tool's accuracy in calculating the urban canopy microclimate simulations derived from the use of the orthogonal Arakawa C-grid numerical discretization scheme, is illustrated by the researchers' team [51]. Regarding the radiative fluxes, the software allows the modeling of both short and longwave radiation, and the determination of the outdoor air temperature and relative humidity based on the calculated 3D wind field and the different sources and sinks of sensible heat and vapor located in the model domain. Regarding the vegetation model, ENVI-met supports different kinds of green surfaces and elements from simple plants (i.e., grass and vertical plants) to more complex 3D vegetation geometry (i.e., large trees). ENVI-met considers plants as species with an integrated water balance control and heat and water stress reaction concept [52]. Regarding the buildings, each surface, roof, or wall, is represented by its own thermodynamic model, and the Materials Database allows the definition of the material stratigraphy of roofs, walls, and pavements. For the present study ENVI-met v.4.3.1 has been used and Scenario 0 (i.e., S0), the initial condition of the University Campus, represents the baseline for the microclimatic analysis and the comparison with the proposed design scenarios. Urban morphology, in particular the sky-view factor (SVF)—that is the proportion of the sky dome that is 'seen' by a surface, either from a particular point on that surface or integrated over its entire area [5] and it varies from 0 to 1, which refer, respectively, to a completely obstructed and completely free sky [53]—affects deeply the local microclimate parameters, especially in terms of wind speed and direction and radiation fluxes. Thus, in the second phase of the 3D model in SPACE, all the most relevant buildings were considered in order to represent a detailed resolution of the area for the pedestrian level and a realistic spatial configuration of the major 3D elements influencing the local microclimate.

3.3. Study Time and Initial Meteorological Conditions

The study was conducted during the summer season, considered for the specific climate of the city of Rome a critical period of the year for the exasperation of the outdoor comfort conditions, and in particular, the month of July was selected because of its high ambient temperature values [54] and thus, it was considered an appropriate period to observe the effects of cool materials and vegetation on the outdoor microclimate and thermal comfort conditions. The study is based on a 24-h simulation conducted on 15 July 2016. The specific day was selected after comparison of several meteorological databases (e.g., Enea-Climate Archive, Roma Urbe Meteorological Station, Weather Underground, ItMeteo TRY) for two criteria: first, for a climatic factor, since it presents high ambient temperatures, and second, for a social factor, since it represents one of the most populated days of the University Campus, corresponding with the summer exam sessions. The meteorological data were collected from the ItMeteo TRY—Test Reference Year (environmental) database [42]. Table 2 shows the temporal and microclimate parameters for the simulation computing, whereas Table 3 shows the "simple forcing" of the air temperature and humidity values in 24 h.

Table 2. Initial settings for the microclimate simulation: time, date, and meteorological parameters, summarized from the ConfigWizard tool.

Parameter	Value
Start date	15 July 2016
Duration time	06:00:00
Total simulation time	24 h
Wind speed (v)	3.6 m/s
Wind direction	230°
Roughness length (z_0)	0.01
Initial air temperature (T_{air})	20.00 °C
Specific humidity at model top	10.6 g/Kg
Relative humidity in 2 m (RH)	68%
Cloud cover (cc)	0

Table 3. Simple forcing of air temperature and humidity values in ENVI-met v.4.

Var/Ti	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**
T_{air} (°C)	24.64	23.87	23.09	22.32	21.55	20.77	20.00	21.29	22.58	23.87	25.16	26.44
UR (%)	57.60	59.33	61.07	62.80	64.53	66.27	68.00	65.11	62.22	59.33	56.44	53.56
Var/Ti	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
T_{air} (°C)	27.73	29.02	30.31	31.60	30.83	30.05	29.28	28.51	27.53	26.96	26.19	25.41
UR (%)	50.67	47.78	44.89	42.00	43.73	45.47	47.20	48.93	50.67	52.40	54.13	55.87

The ENVI-met simulations were carried out from 8:00 to 20:00 on 15 July 2016, plus a stabilizing period. The input data used in ENVI-met derived, as aforementioned, from the ItTYR database, and specifically they include: air temperature (T_{air}), relative humidity (RH), air velocity (v) and direction (dir), and cloud cover (cc). For the analysis, the evaluation resulted in three points at street level (points A, B, and C), with different H/W ratio and morphological characteristics, as shown in Figure 6 in paragraph Section 3.4. The evaluation of the outdoor thermal comfort was carried out by means of the PET index (physiological equivalent temperature) [55,56], defined as the air temperature in a standardized indoor setting at which the heat balance of the human body is balanced at the same core and skin temperature as under the outdoor conditions being assessed. The basis for the calculation of the PET index is the Munich Energy-balance Model for Individuals (MEMI). PET has been selected among other thermal indexes, because of its extensive application to analyze thermal comfort in different climates [57,58]. In addition to the consolidated and wide use of the index, the accuracy of the calculations, the inclusion of both meteorological parameters and biological parameters (such as age, sex, metabolism, clothing insulation), one of the main advantages in the use of the PET index lies in the widely known measuring unit (degrees Celsius), which, as stated by Matzarakis et al. [59], makes the results more comprehensible to regional or urban planners; whereas PET shows limitations in the calculation of the variations in air humidity and clothing insulation, which show weak influence [60]. Nevertheless, even though PET requires some adjustments for the different climates [56], its practicability and applicability plays the most important role as stated by Epstein and Moran [61]. In order to calculate PET, we used the ENVI-met package's PET index calculator, BioMet. As for the thermo-physiological parameter of the human body, we assumed a "typical European male" (35 years old, 1.75 m tall, weight 75 kg), with a clothing index of 0.6 clo (corresponding to a summer business suit) and an activity (metabolic) rate of 80 W [43], considered typical for a standard person in the outdoors.

3.4. Mitigation Scenarios Definition

For the model simulations, the University Campus object of study from Viale Gobetti to Piazzale della Minerva, has been transformed into a model grid with the dimension 154 × 154 × 30 cells with a resolution of 2 × 2 × 2 m, corresponding to a real area of 308 × 308 × 60 m, equal to about 95,000 m^2, as shown in Figure 4. Note that the model area is rotated 71° out of grid north, and in order to improve the stability of the mathematical models used by the microclimate simulation tool, 6 nesting grids were added on each side of the model area, as shown in Figure 5.

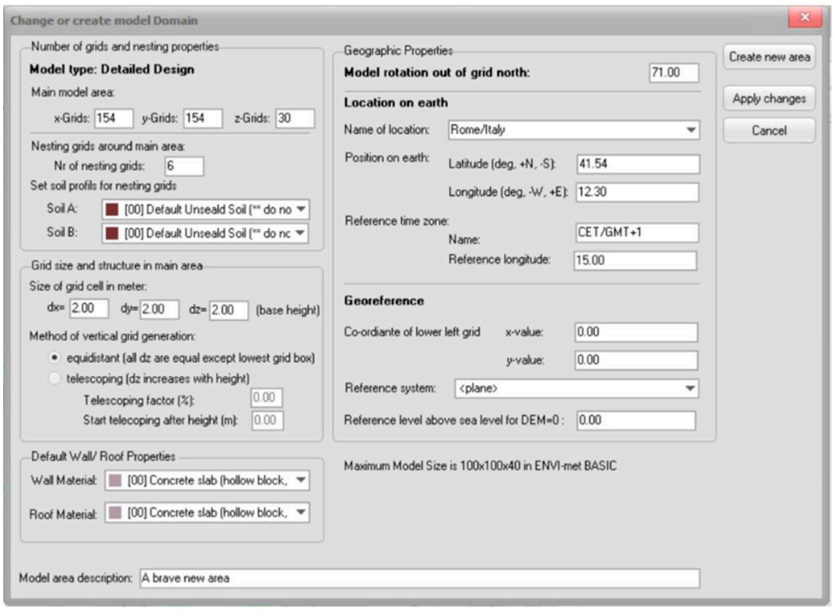


Figure 4. ENVI-met model of the case study area, initial condition scenario (S0).

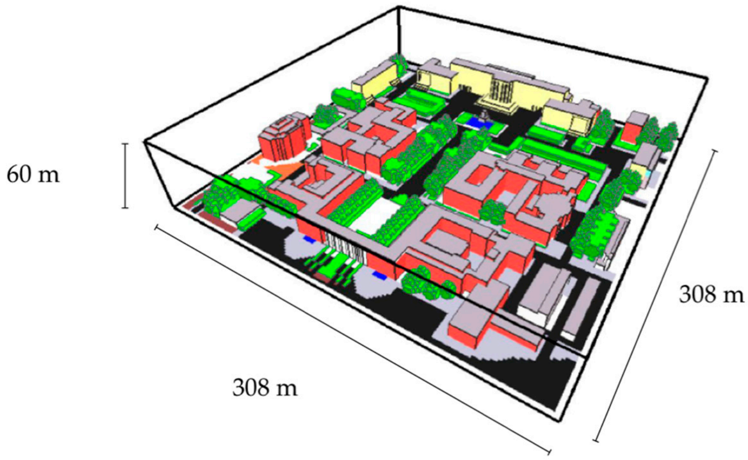


Figure 5. Initial setting of the SPACE model.

The model of the case study in its current configuration, Scenario 0 (S0), the literature review of recent environmental and climate adaptive design scenarios, whether constructed, experimental, or theoretical [62,63], and the latest European recommendations concerning climate adaptive design guidelines for the renovation of urban districts [19], were taken into account for the proposal of mitigation strategies for the local microclimate. Two mitigation scenarios were proposed, each comprising the combination of vegetative surfaces and cool surfaces on the urban environment: particularly on the lower level of the urban canopy layer, the pedestrian levels (i.e., ground), and on the upper level (i.e., roofs). Urban walls and façades have been excluded from the transformation proposal for two reasons: first, in order to focus the attention on the ground surfaces and to investigate on the influence of change in the roof albedo on pedestrian thermal comfort, and secondly, because of the strict national system of architectural preservation constraints regarding in this case the façades appearance.

The following strategies were considered:

- Increase of urban pavement permeability ≥50%,
- Change of existing cement roof into green roof ≥50%,
- Change of ≥50% urban pavements into cool colored pavements (albedo ≥ 0.40),
- Change of the total area of roofs into cool roofs (albedo ≥ 0.65).

Therefore, the two mitigation scenarios were developed as follows:

- Scenario 1 (S1): modification of urban pavements in mixed pervious surfaces, in particular permeable pavements made of cement tiles and grass, and conversion of the total area of the roof level into cool roofs (albedo ≥ 0.65);
- Scenario 2 (S2): modification of urban pavements with cool colored materials pavements (0.89 ≤ a ≥ 0.45) and conversion of the roof surfaces into green roofs.

For the present study, the cool materials investigated were selected from two studies carried out by Santamouris et al. and Gobakis et al. [18,64] and simulated recently in another urban open space of the historical tissue in the city of Rome [28]. Table 4 summarizes the materials database used in the initial scenario, S0; in the first renovation scenario S1 (green pavements + cool roof), and in the second renovation scenario S2 (cool pavements + green roofs), whereas Table 5 summarizes the albedo and leaf area density (LAD) coefficients of the tree species present in the University Campus and modelled in ENVI-met. Finally, Figure 6 shows in plan the variations in materials among scenario S0, S1, and S2. Table 6 presents the material modification of the built environment's surfaces in percentage.

Table 4. Materials database of the analyzed scenarios: S0 initial condition, S1 first renovation scenario (green pavements + cool roofs), S2 (cool pavements + green roofs).

	S0		S1		S2	
Surface	**Name**	**Albedo (a)**	**Name**	**Albedo (a)**	**Name**	**Albedo (a)**
Roofs	concrete tiles	0.30	white Portland cement with dolomitic marble plaster * (WCP)	0.89	grass	0.20
Walls	brick wall	0.40	brick wall	0.40	brick wall	0.40
	brick wall + travertine fixtures	0.80	brick wall + travertine fixtures	0.80	brick wall + travertine fixtures	0.80
	brick wall + cement plaster	0.40	brick wall + cement plaster	0.40	brick wall + cement plaster	0.40
	concrete wall + travertine fixture	0.80	concrete wall + travertine fixture	0.80	concrete wall + travertine fixture	0.80
	concrete wall + cement plaster	0.40	concrete wall + cement plaster	0.40	concrete wall + cement plaster	0.40
Pavements	asphalt	0.20	asphalt	0.20	cool colored thin layer asphalt	0.45
			grass	0.20		
	concrete used pavement	0.40	concrete used pavement	0.40	concrete used pavement	0.40
	granite single stones pavement	0.50	granite single stones	0.50	cool pigmented concrete tile	0.65
			grass	0.20		
	travertine slabs	0.80	travertine slabs	0.80	granite shining	0.80

* abbreviated classification as illustrated in the plan's legend.

Table 5. Greenery characteristics.

Name	Albedo (a)	Leaf Area Density (LAD) m^2/m^3
Cedrus atlantica (evergreen) (Cat)	0.18	0.70–0.80
Pinus pinea (evergreen) (Pp)	0.18	0.70–0.80
Quercus ilex (deciduous) (Qi)	0.20	0.80–0.90
Citrus x aurantium (deciduous) (Ca)	0.40	0.50–0.60

Table 6. Surface material characteristics.

	S0		S1		S2	
Surface	**Name**	**Percentage (%)**	**Name**	**Percentage (%)**	**Name**	**Percentage (%)**
Roofs	concrete tiles (α = 0.30)	100%	white Portland cement with dolomitic marbles plaster * (WCP) (α = 0.8)	100%	grass (α = 0.22) concrete tiles (α = 0.30)	72% 28%
Walls	brick wall (α = 0.40) +travertine fixtures (α = 0.80)	50%	brick wall +travertine fixtures (α = 0.80)	50%	brick wall +travertine fixtures (α = 0.80)	50%
	brick wall + lime plaster (α = 0.45)	15%	brick wall + cement plaster (α = 0.40)	15%	brick wall + cement plaster (α = 0.40)	15%
	concrete wall + travertine fixture (α = 0.80)	30%	concrete wall + travertine fixture (α = 0.30)	30%	concrete wall + travertine fixture (α = 0.30)	30%
	concrete wall + cement plaster (α = 0.40)	5%	concrete wall + cement plaster (α = 0.40)	5%	concrete wall + cement plaster (α = 0.40)	5%
Pavements	asphalt (α = 0.20)	50%	asphalt (α = 0.20) grass (α = 0.22)	25% 25%	cool colored thin layer asphalt (α = 0.45)	50%
	concrete used pavement (α = 0.40)	16%	concrete used pavement (α = 0.40)	16%	concrete used pavement (α = 0.40)	16%
	granite single stones pavement (α = 0.50)	4%	granite single stones (α = 0.50) grass (α = 0.22)	2% 2%	cool pigmented concrete tile (α = 0.65)	4%
	travertine slab (α = 0.80)	11%	travertine slab (α = 0.80)	11%	cool colored thin layer asphalt (α = 0.45)	11%
	grass (α = 0.22)	19%	grass (α = 0.22)	19%	Grass (α = 0.22)	19%

* abbreviated classification as illustrated in the plan's legend.

Figure 6. Initial condition scenario S0 (a), first renovation scenario S1 (b), second renovation scenario S2 (c). Point A, B, and C represent the selected location for the comparisons among the scenarios.

3.5. ENVI-Met Limitations and Definitions in the Modelling

The scenario solutions have been adjusted and approximated within the specific constraints of the ENVI-met software, therefore:

1. The grid cell dimension used for the ENVI-met models measures 2 × 2 m, in order to optimize the time needed for the calculation as well as to maintain a proper level of detail;
2. Walls and roofs were modelled in the Database Manager specifying their three characteristic layers, and for the characterization of the exterior layer of walls and roofs we chose to apply the prevalent material, that is cement and bitumen for the roofs and travertine and aerated brick block with lime plaster (pastel color) for the walls.
3. Pervious pavements, consisting of mixed cement pavers and grass, have been approximated by interspersed strips of grass and cement, since it is still not yet possible to model mixed materials within a singular cell.

4. Results

4.1. Spatial Analysis of Thermal Comfort Distribution for the Simulation Scenarios

The observations of the PET Thermal Maps are focused on the two areas of main interest. The first area, Gobetti Road, is divided in three sections: the first section corresponding to the southwest entrance (from Aldo Moro Square), the second section corresponding to the central crossroad, and the third section corresponding to the area near Minerva Square presenting an enlargement of the road section with two smaller entrance squares to the Chemical Faculty building (right side) and the Physics Faculty (left side) building. The second area of interest corresponds to the central main square (i.e., Minerva Square), and could be theoretically divided in three sections as well: the central section with the monumental fountain, the Minerva statue, and the benches and green lawn areas; the eastern section to the right; and the western section to the left, both characterized by rectangular gardens enclosed by a group of *Quercus ilex* (Qi) tree rows.

In particular, in the first section of Gobetti Road, the PET values range between 20.00 and 22.50 °C under the *Quercus ilex* (Qi) (LAD 0.80–0.90 m^2/m^3), tree rows and in the nearby areas, whereas at the center of the granite pavement (α = 0.50), the PET values are between 32.50 and 35.00 °C. The second section of the road presents PET values between 20.00 and 22.50 °C, especially under the tree rows (*Pinus pinea* (Pp), *Quercus ilex* (Qi), *Cedrus atlantica* (Cat)) and PET values between 30.00 and 32.50 °C on the asphalt road (α = 0.20), whereas on the third section of Gobetti Road, near Minerva Square and in correspondence with the faculties' entrances on the east and west side, PET values increase gradually and consistently near the buildings' façades. In fact, nearby the building entrances there is an area corresponding to PET values above 42.50 °C, then the values decrease progressively with a radial spatial step of about 4 m^2 between 40.00 and 42.50 °C, 35.00 and 37.50 °C, and then near the central square the PET values reach a range between 32.50 and 35.00 °C. Regarding the thermal comfort in the second area of interest, Minerva Square, for scenario S0 the PET values are 32.50 and 35.00 °C in the central section of the square and cover about 45% of the total square, while lower values are registered under the rectangular gardens characterized by Qi tree rows, and much lower PET values below 22.50 °C are visible in correspondence with the western façades of the administration buildings on the northeast side of Minerva Square. For S1 (b) and S2 (c), PET maps show values similar for intensity and distribution in Gobetti Road and in Minerva Square, as well as to the initial condition scenario, S0. In fact, if we consider scenario S1 (b) at 8:00, the area in the first section of the Gobetti Road on the granite pavement (α = 0.40) presents PET values between 32.50 and 35.00 °C, and below 22.50 °C underneath the Qi tree rows, and in the second section the PET values under and near the mixed tree rows (i.e., Qi, Pp, Cat) range between 30.00 and 32.50 °C, as in scenario S0. Similarly, in the third section of Gobetti Road, as well as in the Minerva Square, the PET values present the same quantities and distribution of S0: higher values in the buildings façades facing east, where PET ranges between 37.50 and 42.50 °C, and in the middle of Minerva Square, where there is the fountain, the little green lawns, and in the nearby pedestrian area characterized by mixed pervious pavement, PET ranges between 32.50 and 35.00 °C, with an improvement in a small rectangular area near the statue where PET measures 32.50 to 35.00 °C. Finally, the lowest PET values, under 22.50 °C, as it happened in S0 are visible in correspondence with the area shaded by the administrative building in the northeast of the analyzed square. For S2, the PET values at 8:00 are the same for intensity and distribution observed in S0 and S1, that is to say: PET values between 32.50 and 35.00 °C on the granite pavement (α = 0.40) area not shaded by trees; 35.00 to 37.50 °C under the Qi and Ca trees; 30.00 to 32.50 °C on the asphalt road (α = 0.20) surrounded on the sides by consistent voluminous tree rows in the second section of Gobetti Road; below 22.50 °C under the tree rows; between 35.00 and 40.00 °C near the buildings' entrance façades; and ultimately between 32.50 and 35.00 °C in the 45% of Minerva Square. The lowest PET values in scenario S1 and S2 at 8:00 are registered in shaded areas: in particular, the building shading pattern provides the most efficient mitigation effect with PET values below 22.50 °C, for the shaded areas under tree rows, the PET values vary according to the tree's density; along Gobetti Road where there are voluminous trees characterized by high LAD values, the PET values are below 22.50 °C; whereas under the smaller tree rows on Minerva Square characterized by lower LAD, the PET ranges between 25.00 and 27.50 °C.

At 14:00, the PET values of S0 range between a minimum value of 38.10 °C and a maximum value of 58.80 °C, whereas S1 range between a minimum value of 37.80 °C and a maximum value of 57.80 °C, and S2 between a minimum value of 31.57 °C and a maximum value of 58.40 °C. At 14:00, S0 shows a consistent presence of high PET values between 42.50 and 45.00 °C, distributed in the unshaded areas of Gobetti Road and Minerva Square, whereas underneath the tree rows in the first section of Gobetti Road, the PET values range between 35.00 and 37.50 °C, and in the second section under the areas shaded by the mixed plant tree rows, the PET values range between 32.50 and 35.00 °C. Regarding Minerva Square, it presents 90% of the area with PET values between 42.50 and 45.00 °C, with the exception of the areas under the smaller tree rows in the twin gardens, where PET ranges between 37.50 and 40.00 °C. The courtyards present PET values between 40.00 and 42.50 °C. For S1 and S2, the PET distribution and range intensity at 14:00 is similar to S0 since the variations are smaller, and the relevant differences are visible in some selected areas. If we consider S1 in the second section of Gobetti Road, the areas shaded by the tree rows characterized by different plant species present a larger distribution of lower PET values than S0, between 32.50 and 35 °C, and similarly 80% of the courtyard presents lower PET values than S0, between 35.00 and 37.50 °C instead of 37.50 to 40.00 °C (S0). If we consider S2 at 14:00, PET values are similar in distribution and range intensity to S0, and in some areas they appear to be higher or the high values appear to be more widespread. For example, if we consider the third section of Gobetti Road, the shaded areas under the mixed plant tree rows near the chemistry buildings (on the right side); here the PET values corresponding to a range between 35.00 and 37.50 °C are more widespread than S0. This is an interesting result since it highlights an increase of PET values in the shaded tree areas near the cool pavement, likely due to the increased solar radiation coming from near the cool pavement ($\alpha = 0.89$).

At 18:00, the PET values of S0 range between a minimum value of 25.60 °C and a maximum value of 44.11 °C, whereas S1 presents PET values between a minimum value of 25.20 °C and a maximum value of 43.96 °C, and S2 range between a minimum value of 25.20 °C and a maximum value of 43.97 °C. S1 and S2 show also in this case PET values with similar range intensity to S0; the major differences visible in S1 and S2 compared to S0, are linked to the extension of the lowest PET values. In fact, if we take a closer look at Figure 6, the PET values ranging between 25.00 and 27.50 °C are more widespread than in S0, as shown in Figure 6, and this result strengthens the consideration of the positive effect in mitigating outdoor temperatures and thermal stress of cooling techniques for pavements and roofs.

Principal findings of the PET spatial distributions in S0, S1 (mixed pervious pavements + cool roofs), and S2 (cool pavements + green roofs):

1. Cool materials with high albedo ($\alpha > 0.70$) when exposed to direct solar radiation show very small improvements in terms of PET, as shown in Figure 7f and Table 7;
2. Mixed permeable pavements (combination of concrete tiles + grass) when exposed to direct solar radiation show consistent improvements (ca. −2.5 °C) in terms of magnitude of PET but contained influence in spatial distribution, as shown in Figure 7e;
3. Mixed permeable pavements (combination of concrete tiles + grass) when exposed to diffuse solar radiation, allocated in urban canyons with surrounding trees and combined with cool roofs, shows the highest performance (−2.5 °C) in terms of thermal comfort improvement, as shown in Figure 7e.

Table 7. Principal surface temperature values at point A, B, and C for scenarios S0 (initial condition), S1 (grass pervious pavement + cool roofs), and S2 (cool pavement + green roof) at 8:00, 13:00, 15:00, and 18:00, on 15 July 2016.

Time	T_s (A)			T_s (B)			T_s (C)		
	S0	S1	S2	S0	S1	S2	S0	S1	S2
8:00	28.9	22.5	26.6	28.4	22.1	26.5	25.7	22.4	26.6
13:00	44.8	37.6	39.5	42	38.2	37.8	38.3	39.4	39.6
15:00	44.8	41.4	40	34.8	32.8	33.3	39.3	40.5	40.3
18:00	31.8	28.4	30.6	30.7	28.6	30.1	32	29.2	31.5

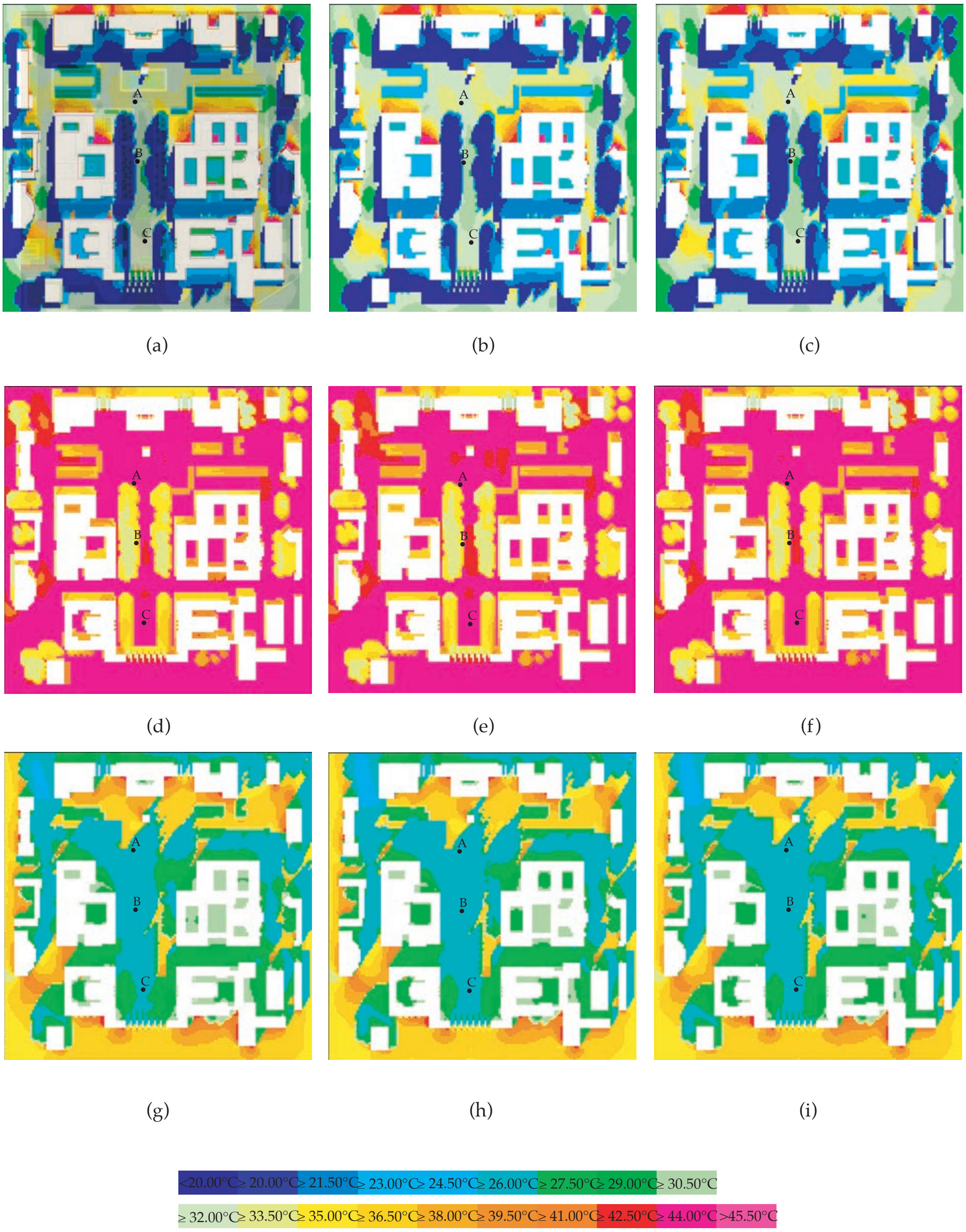


Figure 7. PET maps at 8:00, 13:00, and 17:00, on 15 July 2016, of S0 (initial condition), S1 (cool roofs + green pavements), and S2 (cool pavements + green roofs), in detail: S0 PET at 8:00 (**a**), S1 PET at 8:00 (**b**), S2 PET at 8:00 (**c**); S0 PET at 14:00 (**d**), S1 at 14:00 (**e**), S2 at 14:00 (**f**); S0 at 18:00 (**g**), S1 at 18:00 (**h**), S2 at 18:00 (**i**).

4.2. Comparison between Surface Temperature and Thermal Comfort of Different Points of Sapienza University Campus in the Simulation Scenarios

The percentage and distribution of greenery and cool materials on the ground and roof level vary for the different areas of the University Campus according to the design criteria described in

Section 3.4; the shading patterns vary as well, depending on the urban morphology of the area and on the tree arrangement, but remain the same among the scenarios since the main changes are related to the material characteristics of pavements and roofs. A direct comparison of the surface temperature and PET in three points of the urban open spaces throughout the day for scenario S0, S1, and S2 can highlight the coupled effects of these design parameters on urban microclimate and thermal comfort.

The selected points depicted in Figure 5 are:

1. Point A: located in the north sector of the campus, in the middle of Minerva Square (east-west orientation) near the rectangular fountain, central and exposed most of the day to direct radiation in all the scenarios (S0, S1, S2) and partially to building shade, it displays the indirect effect of water near an asphalt road on S0, the direct effects of green pervious pavements in S1, and of cool pavements in S2;
2. Point B: located in the center of the north sector of Gobetti Road (northeast-southwest orientation), affected by trees in every scenario, shows the effect of different pavements (i.e., cement and grass for S1, and cool pavements for S2) on thermal comfort with the combined effect of trees;
3. Point C: located in the southwest sector of Gobetti Road, in the middle of the traffic road, mostly exposed to direct solar radiation, with the only shading effect of the surrounding buildings and with the indirect effect of trees, here more distant than at point B, depicts the interactions between building shading patterns, different types of pavements (traditional granite stones for S0, grass for S1, cool pavement for S1) and greenery (grass and trees).

Figure 8a shows the daily trend of surface temperature (T_s) among the scenarios at point A. If we consider the general tendency, T_s for S0 starts from a minimum value of 29.0 °C registered at 8:00, increasing up to the peak of 45.3 °C at 14:00 when the area is under direct solar radiation, slowly decreasing to 43.0 °C at 16:00, and then considerably till 20:00, with a value of 28.5 °C with the surrounding shadow patterns. At 8:00, T_s for S1 presents a value of 22.5 °C, increasing up to 40.5 °C at 14:00, and reaching the peak of 41.4 °C at 15:00, then starting to decrease to 25.4 °C at 20.00. S2 presents a trend similar to S1 but with higher values, with the exception of the interval between 14:00 and 15:00 when it shows lower values than S1. In fact, S2 starts with 26.6 °C at 8:00, increasing to 40.2 °C at 14:00, and then decreasing to 28.0 °C at 20.00. Focusing the attention on 8:00, 14:00, and 18:00, which presents high attendance rate, at 8:00 T_s for S0 is 29.0 °C, for S1 is 22.5 °C, and for S2 is 26.6 °C, with a variation from S0 of −6.5 °C and −2.4 °C, respectively. At 14:00, T_s for S0 is 45.3 °C, whereas is 40.5 °C for S1, and 40.2 °C for S2, with a significant decrease from S0 of −4.8 °C and of −5.1 °C. At 18:00, T_s for S0 is 31.8 °C, for S1 is 28.4 °C, and for S2 is 30.6 °C, with a variation from S0 of −3.4 °C and of −1.2 °C, respectively.

Figure 8b shows the daily trend of surface temperature (T_s) among the scenarios at point B. T_s for S0 presents an initial value of 28.4 °C at 8:00, rising to the peak of 42.0 °C at 14:00, with an average increase of 2.0 °C per hour, then decreases to 28.2 °C at 20:00. T_s for S2 shows a similar trend to S0 but with lower values, registering 26.5 °C at 8:00, then gradually increasing up to 38.0 °C at 14:00, and decreasing to 28.0 °C at 20:00. On the other hand, T_s for S1 presents a different trend with significantly lower values in the morning and a rapid growth registered at 13:00, in fact, T_s for S1 presents an initial value of 22.1 °C at 8:00, gradually raising up to 34.5 °C at 12:00, and then registering a peak at 14:00 with a value of 40.6 °C, then it rapidly decreases at 15:00 with a value of 32.8 °C, and constantly to 26.0 °C at 20:00. If we compare T_s at 8.00, 14:00, and 18:00 for the three scenarios, S0 presents T_s value of 28.4 °C at 8:00, while S1 of 22.1 °C, and S2 of 26.5 °C, with a variation of −6.3 °C and about −2.0 °C, respectively. At 14:00, S0 register a T_s of 42.0 °C, S1 presents a similar T_s value of 40.6 °C, whereas for S2 T_s is 38.0 °C, with a variation of −1.4 °C and −4.0 °C, respectively. At 18:00, T_s for S0 is 30.7 °C, for S1 is 28.6 °C, and for S2 is 30.1 °C, registering a variation of about −2 °C and −0.6 °C, respectively, compared to scenario S0.

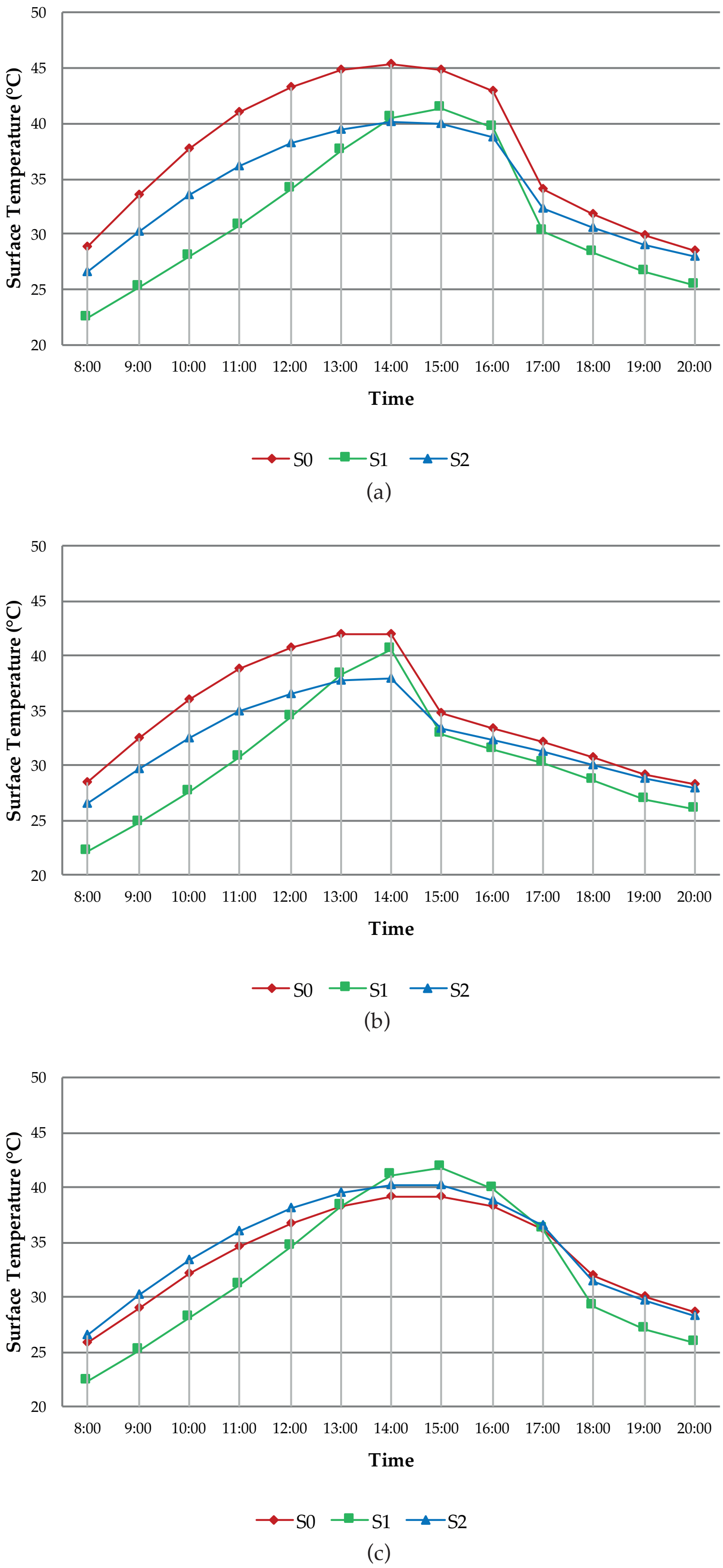
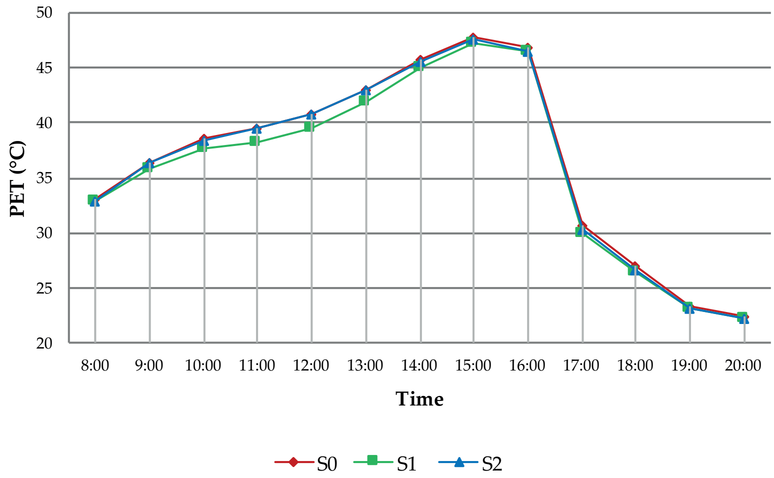


Figure 8. (**a**) Daily trend, on 15 July 2016, of surface temperature (Ts) at point A among the three scenarios: S0 (initial condition), S1 (green pavements + cool roofs), and S2 (cool pavements + green roofs); (**b**) daily trend of surface temperature (T_s) at point B in S0, S1, S2; (**c**) daily trend of surface temperature (T_s) at point C in S0, S1, S2.

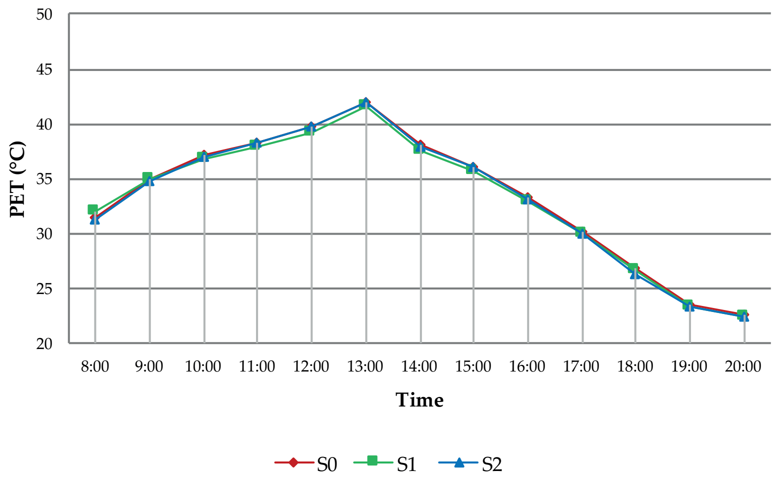
Figure 8c shows the daily trend of surface temperature (T_s) among the scenarios at point C. T_s for S0 presents an initial value of 25.75 °C at 8:00, rising to 39.1 °C at 14:00, and reaching the peak of 39.2 °C at 15:00, then gradually decreasing in the afternoon until 28.6 °C at 20:00. T_s for S2 shows a similar trend to S0 but with higher values, this is because in S2 the interest was to verify if a cool asphalt road could improve a road made of traditional granite stones, but since in this specific case the cool asphalt road presents a slightly higher albedo (α = 0.45) than the traditional stone pavement (α = 0.50), the surface temperature trend and values are slightly higher. Thus, S2 presents an initial T_s value of 26.6 °C at 8:00, then gradually increases up to 40.2 °C at 14:00, and decreases until 28.4 °C at 20:00. On the other hand, S1 presents lower values in the early morning, from 8:00 to 12:00, then it gets warmer than S0 in the peak hours and it gradually decreases in the afternoon. In fact, T_s for S1 presents an initial value of 22.4 °C at 8:00, then it increases reaching the peak of about 41.5 °C between 14:00 and 15:00, and after 17:00 it decreases until 25.8 °C at 20:00. If we compare T_s at 8.00, 14:00, and 18:00 for the three scenarios, S0 presents T_s value of 25.7 °C at 8:00, while S1 of 22.4 °C, and S2 of 26.6 °C, with a variation of −3.3°C and about +0.9 °C, respectively. At 14:00, S0 register a T_s of 39.1 °C, S1 presents a similar T_s value of 41.1 °C, whereas for S2 T_s is 40.2 °C, with a variation of +2.0 °C and +1.1 °C, respectively. At 18:00, T_s for S0 is 32.0 °C, for S1 is 29.2 °C, and for S2 is 31.5 °C, registering a variation of about −2.7 °C and −0.4 °C, respectively, compared to scenario S0.

If we consider PET values among the scenarios, the variations present small intensity amplitude as visible in Figure 9a, which represents the daily trends of PET values for point A. In particular, S0 displays a PET value of 33.05 °C at 8:00, it increases until a peak of 47.75 °C at 15:00, and then starts to decrease showing an abrupt reduction between 16:00 and 17:00, with a value of 34.1 °C, probably due to the shading pattern of the surrounding trees, until the evening at 20:00, when it reaches 22.4 °C. PET trends for S1 and S2 are similar and appear to have slightly lower values corresponding to S0 throughout the day. S1 registers a PET value of 32.9 °C at 8:00, it increases gradually until 13:00, and then considerably, reaching the peak of 47.2 °C at 15:00, and then showing a drastic decreasing trend at 17:00 when PET measures 30.0 °C, until 20:00 when it measures 22.2 °C. PET for S2 presents a value of 32 °C at 8:00, then it increases gradually until 14:00 when it measures 45.60 °C, increasing up to 47.5 °C at 15:00, and then gradually decreasing until 22.2 °C at 20:00. In general, PET for S1 is lower than for S2. In fact, if we consider PET values among the scenarios at 8:00, 14:00, and 18:00, S0 presents a PET of 29.9 °C, whereas S1 of 32.9 °C, and S2 of 33 °C with a variation compared to S0 of about −0.5 °C, respectively. At 14:00, PET for S0 is 45.8 °C, for S1 is 45.0 °C, and for S2 is 45.6 °C, with a variation of −0.8 °C and −0.2 °C, respectively. At 18:00, S0 shows a PET of 27.0 °C, whereas the PET value for S1 is of 26.4 °C, and for S2 is 26.6 °C, registering a variation compared to S0 of −0.6 °C and −0.4 °C, respectively.

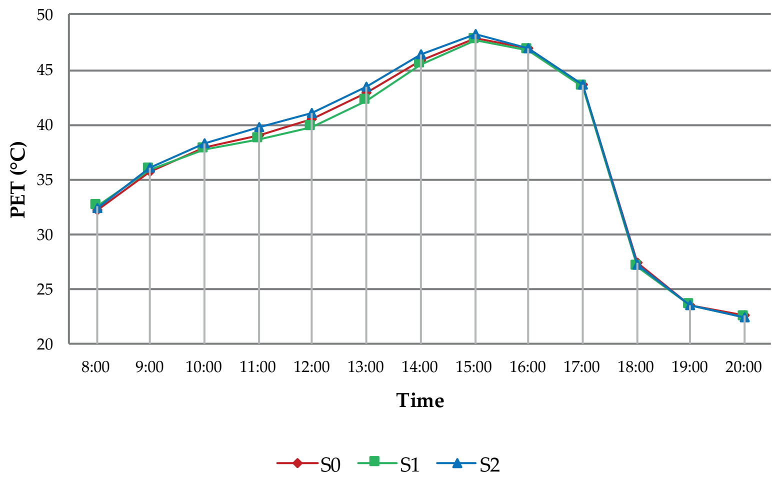
Figure 9b represents the daily trends of PET values for point B. S0 presents a PET value of 31.4 °C at 8:00, increasing gradually until 13:00 when it registers a drastic increase of 41.9 °C, then gradually decreasing until 20:00 with a PET value of 22.6 °C. S1 and S2 show a similar trend to S0 as at point A, with slightly lower values to S0, except S1 in the early morning. In fact, in S1, characterized by the combination of grass surfaces at pedestrian level and surrounding trees, presents a PET value of 32.0 °C at 8:00, then it increases gradually reaching the peak at 13:00 with 41.6 °C, slowly decreasing at 14:00 with a PET value of 37.6 °C, and constantly until 20:00 with a PET value of 22.4 °C. S2 presents a similar trend but with values more similar to S0, in fact, it shows a PET value of 31.3 °C at 8:00, increasing gradually until 3:00 when it registers a PET value of 41.9 °C, and then decreasing until 22.4 °C at 20:00. If we consider PET values at 8:00, 14:00 and 18:00, though small it appears the variation and behavior of the mitigation technologies applied. In fact, at 8:00, S0 presents a PET value of 31.4 °C, whereas S1 registers 32.0 °C, and S2 31.3 °C, with a variation of +0.6 °C and of −0.1 °C, respectively. At 14:00, S0 registers a PET value of 38.1 °C, S1 of 37.6 °C, and S2 of 38 °C, registering a variation from S0 of −0.5 °C and −0.1 °C, respectively. At 18:00, S0 registers a PET value of 26.8 °C, whereas S1 presents a PET value of 26.6 °C, and S2 of 26.4 °C, showing a variation of −0.2 °C and −0.4 °C, respectively.



(a)



(b)



(c)

Figure 9. (**a**) Daily trend, on 15 July 2016, of PET values at point A among the three scenarios: S0 (initial condition), S1 (green pavements + cool roofs), and S2 (cool pavements + green roofs); (**b**) daily trend of PET values at point B in S0, S1, S2; (**c**) daily trend of PET values at point C in S0, S1, S2.

Figure 9c represents the daily trends of PET values for point C. S0 presents a PET value of 32.3 °C at 8:00, increasing consistently until the peak of 47.8 °C registered at 15:00, then decreasing until 22.6 °C at 20:00. In general, S1 and S2 present similar trends to S0 but with a significant difference: S1 shows slightly lower values compared to S0, whereas S2, on the other hand, presents slightly higher values due to the material characteristics of the cool asphalt compared to the granite stones present in S0. In particular, S1 presents a PET value of 32.7 °C at 8:00, increasing consistently with an increment rate of about 2 °C until the peak of 47.6 °C at 15:00, it starts to decrease at 17:00, registering a PET value of 43.5 °C, and then rapidly from 18:00 when due to the shading pattern of the surrounding buildings, the PET value on the green pervious pavements is about 27 °C, until 20:00 when it measures a PET value of 22.4 °C. S2 presents a PET value of 32.4 °C at 8:00, it increases rapidly reaching the peak of 48.2 °C at 15:00, then it starts to decrease registering a rapid change, as for S0 and S1, between 17:00 and 18:00 when it shows a PET value of 27.2 °C, and lowering until a value of 22.4 °C at 20:00. If we consider PET values among the scenarios at 8:00, 14:00, and 18:00, S0 presents a PET of 32.3 °C at 8:00, S1 of 32.7 °C, and S2 of 32.4 °C, with a variation of +0.4 °C and +0.1 °C compared to S0. At 14:00, S0 presents a PET value of 45.8 °C, whereas S1 shows slightly lower value of 45.3 °C, and S2 slightly higher equal to 46.3 °C. At 18:00, S0 presents a PET value of 27.4 °C, S1 of 27 °C, and S2 of 27.2 °C, registering a variation of −0.4 °C and −0.2 °C compared to S0, respectively.

The following tables, Tables 7 and 8, offer a synthetic overview of the surfaces' temperature and PET values' trends throughout the day in the investigated scenarios, in order to underline the minimum and maximum values as well as the general trends of each scenarios.

Table 8. Principal PET values at point A, B, and C for scenarios S0 (initial condition), S1 (grass pervious pavement + cool roof), and S2 (cool pavement + green roof) at 8:00, 13:00, 15:00, and 18:00, on 15 July 2016.

Time	PET (A)			PET (B)			PET (C)		
	S0	**S1**	**S2**	**S0**	**S1**	**S2**	**S0**	**S1**	**S2**
8:00	33	32.9	33	31.4	32	31.3	32.3	32.7	32.4
13:00	43	41.9	42.9	41.9	41.6	41.9	42.8	42.2	43.4
15:00	47.8	47.1	47.5	36.1	35.8	36	47.8	47.6	48.2
18:00	27.0	26.4	26.6	26.8	26.6	26.4	27.4	27	27.2

5. Discussion

The present study proposes and analyses specific cooling technologies for the mitigation and adaptation to climate change of the urban open spaces within a university campus, belonging to the historical-consolidated tissue of Rome (i.e., Sapienza University campus, Italy), on a typical summer day (15 July). The primary hypothesis of this study was that during the summer the use of permeable pavements (pervious), made of cement pavers and grass, and cool pavements at the pedestrian level, and the use of cool roofs and green roofs at the building level, can create a general cooling effect on ambient temperatures, with a resultant positive effect on human thermal comfort.

Most of the studies, starting from three decades ago [3,65] investigating the climatic effect of cool materials (i.e., cool pavements and roofs) and green technologies (i.e., permeable mixed pavements and green roofs) on the urban micro-environment, have focused the attention primarily on the ambient temperature variations and on the climatic aspects of the design solutions proposed [65], whereas only a few studies have considered the integration and experimentation of cool materials and urban green infrastructures in historical contexts [38,66]. With the proceedings of the research in these two fields (i.e., cooling materials and green infrastructures) of cooling technologies, it is currently possible and necessary to focus the attention on their effects not only on ambient temperatures but on thermal comfort as well, and by doing so to underline the possibility of some specific design combinations among these technologies to comprise and preserve the 'image of the tissue' and therefore to be included in the renovation practices for the historical context. Based on these premises, the study proposes a simulation analysis of two renovation scenarios, based on the 'minimal intervention' criteria, in order to propose climate adaptation and mitigation solutions that are heritage-centered and attentive to architectural heritage sites, taking into account the effects and 'behavior' of cool materials and green infrastructures on outdoor thermal comfort.

It is important to underline, before proceeding further in the discussion of the findings and results of the present study, that the two renovation scenarios, S1 (permeable pavements + cool roofs) and S2 (cool pavements + green roofs), present a combination of green and cool technologies applied to different levels of the urban open spaces and built environment (i.e., ground and roof level); thus, although it is possible to understand or quantify the direct effect that technologies applied on the ground level have on pedestrians, on the other hand, it is not possible to accurately quantify the effect that roof modifications have on the pedestrian level, since the renovation scenarios are a combination of both technologies. Nevertheless, based on previous research and studies on the influence of roofs on outdoor thermal comfort, it is possible to state some inferences on their combined behaviors [66,67]. Secondly, the urban open spaces analyzed present a favorable initial condition: in fact, Gobetti Road presents an accurate system of tree rows of different plant species along its sidewalks, and Minerva Square presents three gardens distributed on the short sides and a central rectangular fountain, therefore the variations between the renovation scenarios (S1, S2) from one side and the initial condition (S0) on the other presents restricted intensity variations but nevertheless representative of the mitigation performance and efficiency of the cool and green technologies analyzed. In this regard, if we consider the effects that 'cool' and 'green' technologies have on surface temperatures (T_s) and on outdoor thermal comfort (PET), it is interesting firstly to underline how large variations in T_s correspond to small variations in terms of PET among the two renovation scenarios. This fact highlights the importance in the assessment of cool technologies to go beyond the traditional way of cool material studies and compare ambient temperatures with thermal comfort as well. In addition, this fact is most likely related to the initial condition scenario design which, as aforementioned, is characterized by gardens, green lawns, and tree rows on the sidewalks of the urban canyon (i.e., Gobetti Road), and therefore it represents a good initial condition and thus, the variations are of small intensity.

5.1. Comparison of the Two Renovation Scenarios in Terms of PET

In fact, if we consider PET variations displayed by the two renovation scenarios, S2 displays little contribution to the mitigation of the outdoor thermal stress and in some cases an exacerbation: in Figure 9c (point C) the cool colored asphalt (α = 0.45) of scenario S2, despite having a lower albedo compared to the pavement of S0 made of granite stones (α = 0.50), displays slightly higher PET values due to the thermal inertia and thermal conductivity of the material (asphalt) which together with the albedo coefficient effects significantly the energy balance of the material itself, its release of sensible heat to the environment and thus its influence on outdoor thermal comfort, as underlined by Qin and Hiller [68]. On the other hand, S1 proves to be the most efficient solution for lowering surface temperatures and improving outdoor thermal comfort both in natural shaded areas (i.e., point B) and in unshaded areas with high H/W ratio (i.e., point A), as shown in Figure 9a (point A) where the permeable pavement exposed to direct solar radiation and located near the fountain registers a PET variation of −1 °C compared to S0, and Figure 9b (point B) where the permeable pavement located under the tree shadow registers a PET variation of −0.4 °C compared to S0.

5.2. The Influence of Permeable Pavements on Outdoor Thermal Comfort

Regarding the effect of permeable pavements made of grass and cement pavers, and in this analysis simplified and modeled as a lawn surfaces spaced out with cement tiles, the present study highlights different effects of the green technology on outdoor microclimate, especially its variations when used singularly or combined with other elements; for example, when coupled with trees or building shade. Permeable green pavements display a mitigation effect both on T_s and on outdoor thermal comfort in shaded and unshaded areas, with incremental differences. From the point of view of spatial distribution, as visible in Figure 7e at 14:00, permeable pavement technology (S1) shows a larger distribution of PET values between 30.5 and 32 °C underneath the tree rows in the central boulevard (Gobetti Road) combined with increased vegetated surfaces (grass lawn, related to the permeable pavements), and PET values between 42.5 and 44.0 °C in the center of the principal square (Minerva Square), with an average variation of −1.5 °C compared to S0, as shown in Figure 7d. Nevertheless, if we consider the improvement in terms of variation from the initial condition scenario S0, permeable pavements display small variations in terms of PET under trees and more under unshaded areas, as is visible in Figure 9a,b. In fact, permeable pavement at point A (unshaded area) shows a PET variation from S0 at 14:00 of about −0.80 °C, whereas at point B (shaded area) it shows a PET variation compared to S0 of −0.4 °C; this is due to the fact that at point B the initial microclimate conditions are more favorable than at point A, as visible from Tables 4 and 5.

5.3. The Influence of Lawn Surfaces on Outdoor Thermal Comfort

Regarding lawn surfaces and grass in general, it is important to underline that grass is a three-dimensional complex surface: the latent and sensible heat exchange that occurs during the evapotranspiration process might in some part of the day increase its surface temperature, as is visible in Table 4 and in Figure 8c (point C). In fact, at an unshaded point (point C), far from trees or water source, the daily climatic behavior of the lawn of the permeable pavement shows low surface temperature values during the morning and the late afternoon, and a relevant increase trend during the peak sun hours (from 12:00 to 16:00); moreover, during this period, when it is exposed to direct solar radiation, it shows slightly higher values compared to a sealed surface like in S0 (granite stone) as visible in Figure 9c (point C), when for example at 14:00 at point C, S1 shows a Ts of 41 °C compared to 39 °C of S0.

5.4. The Influence of Trees on Outdoor Thermal Comfort

Regarding trees, it is interesting to observe, as shown in Figure 7d–f, how at 14:00 PET values under the trees located in the small garden areas in Minerva Square are higher (between 38 and 39 °C) than under the trees in Gobetti Road (between 33.5 and 35 °C) because of the higher density of their crowns (related to a maintenance procedure); thus, the wind speed is slower than in Gobetti Road, where although the SVF is lower than in Minerva Square, the different types and varied distribution of plants guarantee more air movements, thus explaining the difference in PET values. This result is aligned with other previous studies conducted in parks and in surrounding sealed surfaces [32]. In general, during the daytime, the spatial variations of the two analyzed parameters, T_s and PET, within the whole simulation domain are less significant for grasslands (i.e., gardens, lawns, and permeable pavements) than those for trees. The cooling effect of vegetation is attributed to a variety of reasons, including its shading ability, its higher albedo compared with many urban surfaces, and its evapotranspiration capacity.

5.5. The Influence of Cool Materials on Outdoor Thermal Comfort

Regarding cool materials, previous studies have displayed the impacts of high albedo materials both on the indoor and outdoor environment, but if most of these studies have assessed the application of cool coatings on roofs, only recently the attention has shifted towards their application on pavements and their effects on pedestrian thermal comfort. The study highlights the high mitigation potential that cool pavements (with albedo between 0.89, 0.65, 0.45) have on surface temperatures and thus, in lowering outdoor air temperatures, as is visible in Figure 9a,b, except at point C which is visible in Figure 9c in which the cool asphalt applied (S2) presents lower albedo than the initial condition stone (S0) and therefore does not contribute much to the mitigation of T_s. If we consider the effect that cool pavements have on thermal comfort, the results of the microclimate simulations show limited but constant improvement throughout the day, with a mean variation of −0.2 °C in terms of PET during the peak hours (from 12:00 to 16:00).

5.6. The Influence of Roof Modification on Outdoor Thermal Comfort

Regarding the effect that cool roofs and green roofs might display on outdoor thermal comfort, their direct influence is small as underlined in a recent study conducted in Rome [28] and as also stated by Taleghani et al. [67] in a study conducted in Los Angeles, "cool and green roofs led to small changes in surface air temperature, mean radiant temperature, and consequently thermal comfort, due to the fact that these strategies modify the energy balance at roof level, well above the height of pedestrians". Regarding the shadow factor, it is necessary to underline that when considering the PET variations and its spatial and temporal distribution, visible in Figure 8d–f, the most effective strategy in improving outdoor thermal comfort is displayed by building shading, which is better when combined with permeable pavements, followed by tree shading, and thirdly, by artificial device shading (i.e., umbrella) as assessed and clearly stated in previous studies by Lee et al. [69] and Cheung and Jim [70].

6. Conclusions

This paper studies the potential of 'cool' and 'green' technologies to mitigate human heat stress at a historic university campus in Rome (Italy) during a typical hot summer day (15 July). The study is based on a human-biometeorological approach in order to investigate and evaluate the spatial and temporal change in T_s and PET among different urban scenarios. In particular, three urban scenarios were tested to examine the direct cooling effect of trees, grasslands, permeable pavements, cool pavements, and the indirect cooling effect of green and cool roofs at the pedestrian level. The results showed that trees are the most effective in mitigating human heat stress, followed by the combined use of trees and permeable pavements, and ultimately by cool pavements, especially when applied in space with low H/W ratio (i.e., courtyards) and near trees and green spaces. It must be underlined that this study presents some limitations in the methodology and in the amplitude of the thematic field of investigation, which nevertheless represents the logical premises of the work itself. The main limits of the present study are related to:

1. The case-study area. In fact, the study represents a specific analysis on outdoor thermal comfort in the urban open spaces of a university campus characterized by a consolidated and historical Mediterranean tissue. Nevertheless, the urban open spaces of the University Campus are considered typical of the Modernist architectural style, diffused in other parts of the city of Rome; they are evidence of the consolidated tissue of the city and are comparable for their geometry, morphological features, green spaces, and H/W of ca. 0.4 to several street canyons in the historical districts of Rome, and in that regard, though site-specific, the design scenarios present a high rate of replicability.
2. The meteorological conditions. The results are applied under a limited set of meteorological conditions, in fact, the study is focused on a specific season (summer) considered the most relevant for the exacerbation of outdoor thermal comfort and on a specific day (15 July), selected because it is representative of the hottest days in a meteorological Test Year Reference and the most frequented by users as well.
3. The methodology followed the climatic calculations, based on the CFD simulations, without in situ measurements. This methodology was selected for its simplicity and speed, in order to raise awareness among the university administration on the possibilities related to a microclimate and human-based approach for the renovation process intended for the University Campus and, by means of a virtual simulation model (ENVI-met), to prove the simplified process in integrating the microclimate knowledge in the design phases and to provide some observations for setting the basis for future design guidelines.

4. Finally, the design scenarios, in terms of technologies and materials. If we consider the scenarios proposed, only two type of design combinations have been selected and only a few set of 'green' and 'cool' technologies among them have been investigated. In particular, regarding the 'cool materials', the cool coatings selected represent only a small percentage of the extensive and expanding advanced materials database for cooling the built environment, therefore more investigations are required in terms of materials and combinations.

In general, the results of the present study highlight some observations and notions:

1. In terms of mitigation of human heat stress in the daytime, tree canopies display much more effectiveness than grasslands. In fact, if we consider the initial condition (S0), it is already visible that the tree rows along the central boulevard present PET values considerably lower (33.5 °C $\leq$ PET $\geq$ 35.00 °C) than those areas covered by grassland (44.0 °C $\leq$ PET $\geq$ 45.50 °C). Nevertheless, areas covered by grass and surrounded by trees, as in the central section of Gobetti Road, display better performance in terms of outdoor thermal comfort improvement (42.5 °C $\leq$ PET $\geq$ 44.00 °C) than isolated ones (44.00 °C $\leq$ PET $\geq$ 45.50 °C).
2. Shading strategy appears to be a relevant measure in improving outdoor thermal comfort and in terms of performance, the most effective is building shading followed by tree shading. In fact, building shading presents lower PET values than natural shading provided by trees; about −4 °C (as visible in the early morning) and −2 °C (at noon), except for dense tree canopies that display similar mitigation potential as building shades, during all the diurnal cycle.
3. Cool pavements show a mitigation of heat stress in unshaded areas as well as in natural shaded areas compared to traditional sealed surfaces (i.e., asphalt), although they are more effective when combined with trees. Nevertheless, if the traditional sealed surfaces are combined with dense tree canopies, the difference with cool sealed surfaces is of minor relevance (about −0.5 °C). The relevant difference of a combination of cool materials and trees is visible in the spatial extension of lower PET values compared to traditional sealed surfaces and trees.

These results highlight the importance of treed open spaces and the combination of permeable green pavements associated with cool roofs as the most effective strategy for the mitigation of summer heatwaves and the improvement of outdoor thermal comfort. For what concerns the application of the results provided by this study, they can be useful to inform architects, urban designers, and urban planners in the comprehension of the effects that 'green' and 'cool' pavements display in a typical Mediterranean urban open space on outdoor temperatures and thermal comfort, and to focus the attention on some effective design combinations. In addition, it helps to define and underline the microclimatic effects related to other design strategies and devices, such as the relevance and influence of shading devices in improving outdoor thermal comfort. In that regard, these findings suggest different directions for proceeding with other research and studies in the field of climate adaptation and mitigation strategies. Firstly, regarding the study itself, it could be interesting to extend the microclimate analysis to the night period in order to compare the diurnal and nocturnal trend of temperatures and to evaluate the effect of green and cool materials on the nocturnal UHI, and to include in the analysis the study of the sensible and latent heat fluxes of green surfaces in order better understand their thermal balance within the urban environment throughout the day. Following this path, it could be interesting to assess the effects of 'green' and 'cool' technologies during other times of the year in different seasons, such as winter and spring. Concerning other technologies and strategies, it could be useful and interesting to evaluate other 'green' and 'blue' technologies and urban design scenarios, such as evaporative cooling strategies (i.e., water misting systems), pervious pavements, and use of retroreflective coatings for pavements and building façades. In the view of advanced software workflow (i.e., grasshopper, BIM) it could be interesting to study what shading devices could be ephemeral, mixed with greenery and flexible, called Ephemeral Thermal Comfort Solution (ETCS), in order to provide short-term climate-adaptive strategies for pedestrian use during annual periods of higher thermal stimuli.

Author Contributions: The study was designed by A.B., A.B. and F.L. conceived the renovation scenarios. G.V. designed and performed the microclimate simulations, F.L. supervised and controlled the ENVI-met modelling phase. The results were then analyzed by F.L., M.Z. supervised the discussion, A.B. is the associate Professor of the research group, she wrote and reviewed the paper.

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