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Optimizing human thermal comfort and mitigating the urban heat island effect on public open spaces in Rome, Italy through sustainable design strategies

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The climate affects how a city's outdoor spaces are utilized. It is more likely that people will use and appreciate public areas designed for pedestrian use, such as parks, squares, streets, and foot-cycle pathways, when they provide a comfortable and healthy environment. A predicted increase in global temperature has made the climate uncomfortable, especially during the summer when heat stress is strengthened and anticipated. This phenomenon is more severe in urban areas, often affected by the Urban Heat Island (UHI) effect. Since the spatial characteristics of a city influence its climate, urban design can be deployed to mitigate the combined effects of climate change and UHI. This research is conducted to study the UHI effect on thermal comfort in an urban open space in Rome (Italy) and aims at identifying and implementing a methodology that urban designers can follow to reduce the impact of urban heat islands and increase thermal comfort in urban outdoor space. This study is based on an urban design concept adopting the Sustainable Development Goals as guidelines; it investigates how UHI's effect affects the use of public space and examines the influence of urban microclimatic conditions on the thermal perception of users through PET, PMV and PPD values, that were assessed through simulations with ENVI-MET software. The study thus proposes a redesign for the site in Rome, with a masterplan based on sustainable design principles, aimed at improving the microclimatic conditions in the site. The design solution was then validated through ex post simulations.

Urban heat challenges, SDGs and public spaces

How a city's outdoor spaces are used is determined by its climate. When public spaces designated for pedestrian usage have a comfortable and healthy environment, they will be used and enjoyed more frequently. To attract people, climate comfort must be a central consideration in the design as people will avoid using open city areas if they are too hot, cold, windy, or otherwise thermally uncomfortable. Therefore, factors like sunlight, shade, vegetation, and protection from elements must be incorporated throughout the planning and design[1].

Creating a comfortable microclimate should be a high priority, not an afterthought when developing welcoming public spaces. Climate considerations must be embedded in all aspects of urban planning and public realm design for city spaces to be utilized and enjoyed by users. The changes to land surfaces and building materials in urban areas impact how heat is absorbed, stored, and transferred. Constructed surfaces like concrete and asphalt have thermal and optical properties that allow them to absorb a large fraction of incoming solar radiation. As a

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result, urban surfaces like roads and rooftops can reach temperatures ranging from 27 to 50 °C hotter than the surrounding air[2], leading to the development of Urban Heat Islands (UHI).

Urban heat challenges

Metropolitan areas globally are confronting escalating challenges stemming from urban heat, a phenomenon amplified by the UHI effect and the increasing frequency of heatwaves[3]. These urban heat challenges pose a threat to the prosperity, livability, and sustainability of cities. Developing a comprehensive understanding of the multifaceted nature of urban heat is crucial for devising effective strategies to mitigate its detrimental impacts.

Table 1 provides a detailed overview of the key aspects of urban heat challenges. It highlights how urban overheating can disrupt essential urban systems, such as air conditioning facilities, outdoor activity patterns, and shelter availability. The health-related impacts of heat exposure also emerge as a major concern, underscoring the need for improved knowledge and awareness among urban populations[4].

Sustainable development goals as urban challenges antidote

The link between climate change (CC), urban heat related challenges and the Sustainable Development Goals (SDGs)—defined in 2015 within the UN 2030 Agenda[12]—is multiple. In fact, the Agenda aims, by 2030 and beyond, to create a sustainable world that prioritizes the needs of people and the environment[13]. In order to support this ambitious goal, the research presented in this contribution examined the urban heat related challenges—including urban overheating, heat-related health impacts, inadequate monitoring and prediction systems, the need for effective adaptation and mitigation strategies, differential energy consumption patterns, reduced air quality, infrastructure deterioration, social vulnerability, and economic challenges[5–11]—, along with suggested solutions, and their linkages to relevant SDGs (Fig. 1).

By examining Fig. 1, it becomes apparent that the SDGs can play a crucial role in addressing these challenges. For instance, "Urban Over Heating" can be faced by implementing solutions such as green infrastructure, public awareness campaigns, and early warning systems, which are aligned with SDG 11 (Sustainable Cities and Communities) and 3 (Good Health and Well-being). Similarly, "Urban Heat Islands" can be addressed by adopting solutions such as green roofs, cool pavements, and urban planning strategies that prioritize public spaces, which are linked to SDG 11 and 7 (Affordable and Clean Energy). The third challenge, "Air Pollution", can be tackled by implementing solutions such as renewable energy sources, energy-efficient transportation, and waste management systems, which are associated with SDG 7, 9 (Industry, Innovation, and Infrastructure), and 11. By leveraging the SDGs, a comprehensive approach can be developed to address the complex challenges posed by urban heat and create sustainable, resilient, and healthy urban environments.

However, while SDGs potentially represent a powerful antidote to the intertwined urban challenges, CC affects progress on most of them, particularly those related to poverty, hunger, health, water, cities and climate action[14]. Impacts such as extreme weather and sea-level rise have the potential to prevent or reverse development gains. CC mitigation and adaptation measures, instead, can help to achieve many SDGs at the same time through actions like converting to renewable energy or improving climate-resilient infrastructure[14], but coordinated solutions—promoting climate resilience while supporting sustainable, equitable development—are needed, especially in urban environments.

Urban overheating	Urban areas experience extreme heat due to heatwaves and the urban heat island effect (UHI). These phenomena threaten urban prosperity and livability and call for immediate and effective solutions Air Conditioning Facilities Outdoor Activity Patterns Sheltering Area	5,6
Heat-related impacts on health	Studies explore the relationship between heat exposure and mortality/morbidity. Heat-induced health impacts are a major concern Knowledge and Awareness of Impact	5,7
Monitoring and prediction systems	Developing effective monitoring, prediction, and warning systems to inform citizens about extreme heat conditions Measures, Strategies and Services Monitoring, forecasting, and warning	5
Adaptation and mitigation strategies	Researchers seek strategies like urban greening and other techniques to mitigate urban heat Green Infrastructure Blue Infrastructure Cool and Permeable Materials Urban Planning and Design	5,6
Energy consumption and temperature	The heat island effect affects energy consumption differently in commercial and residential sectors. Measures to mitigate this effect can lead to energy savings	6
Reduced air quality	The combination of higher temperatures and increased energy consumption in urban areas can lead to worsened air quality, as higher temperatures can exacerbate the formation of ground-level ozone and other pollutants	7
Infrastructure challenges	The increased temperatures can lead to the deterioration of infrastructure, such as roads, bridges, and buildings, as well as the increased risk of power outages and water supply disruptions	8
Social vulnerability	UHI effects disproportionately affect disadvantaged neighborhoods. Identifying priority areas for intervention is crucial to mitigate climate change's impact with an equity perspective	9,10
Economic challenges	These include increased energy costs due to higher air conditioning usage, the need for infrastructure maintenance and repair caused by extreme heat, reduced labor productivity due to heat-related illnesses, and potential property value decline in intensely hot areas. Addressing these challenges requires strategic planning, investment in green infrastructure, and effective policies to mitigate the economic impact of urban heat	10,11

Table 1. Urban heat challenges (Authors' elaboration).

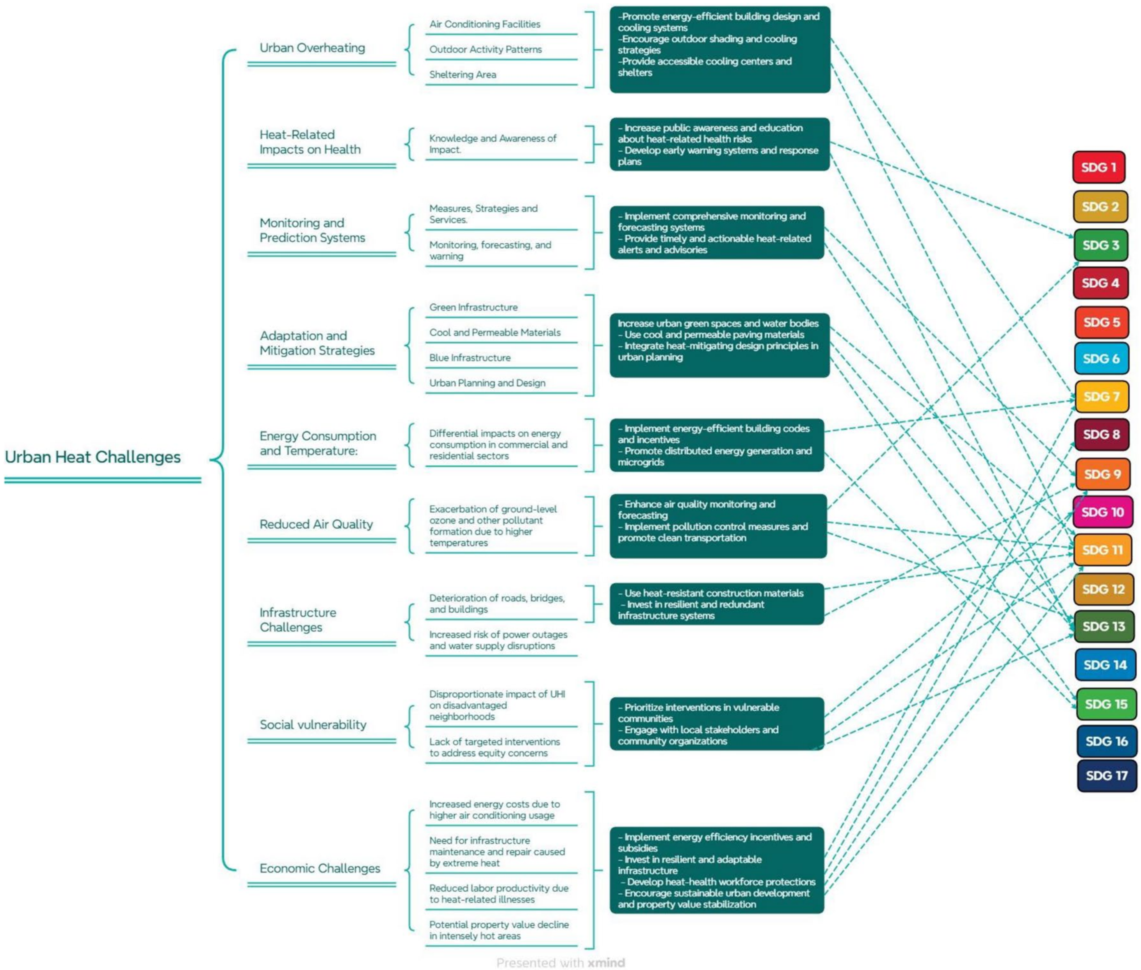

Figure 1. Relation between Sdgs and Urban Heat Challenges (Authors' elaboration).

Climate change and UHI: criticalities and mitigation strategies

The latest IPCC report shows clear evidence that global warming is continuing and intensifying: with every additional 0.5 °C of global temperature rise, there are discernible increases in hot temperature extremes, including more frequent and intense heat waves[15]. Morevoer, IPCC states that continued greenhouse gases (GHG) emissions at current or higher rates will cause further warming and associated changes[16]. These findings underscore the urgent need to limit global warming by reducing GHG emissions, while underlining the need for climate adaptation measures against extreme heat, especially in cities.

Figure 2 shows the projected extent of CC in major cities of the world by 2050. CC has, in fact, a greater impact on cities where—due to the heat-absorbing surfaces such as concrete and asphalt—increased temperatures and heat islands are predicted to rise as CC accelerates[17].

Different studies have evaluated the intensity of UHIs and expect significant future warming in cities: during heat waves, London was found to be nearly 5 °C warmer than adjacent rural areas[19]; modeling of climate impacts on cities such as New York predicts 1–3 °C rises in UHIs by the 2050s[20] in fact, extreme heat events connected to CC increase in metropolitan areas by the UHI effect, impacting public health disproportionately[21]. Figure 3 shows more in general the effect of UHIs in raising temperature in the urban center compared to that of the surrounding suburbs. Temperatures vary between − 3.3 °C (rural areas outside) and + 4.3 °C (densely populated areas) for the diurnal UHI intensity indicator throughout the summer season, whereas temperatures vary between + 0.7 °C and + 4.1 °C for July[22].

In order to reduce GHG emissions while simultaneously lowering local urban temperatures, better urban planning and design are needed, including strategies like green infrastructures and reflecting materials, important for adapting cities to higher temperatures[20,21].

In fact, UHIs can be mitigated by increasing vegetation cover, adding green infrastructure, using cool roofs, pavements and coatings, improving building energy efficiency and implementing smart growth principles. Adding green spaces and trees provides evapotranspiration cooling while reflective roofs and pavements reduce solar absorption[24]. Compact, mixed-use development limits sprawling heat-retaining surfaces[25]. Cool pavements, shade structures, and water features also help lower temperatures through evaporation and convection[17]. These strategies, which largely refer to urban public spaces, can work together to reduce UHIs and create cooler, more livable cities.

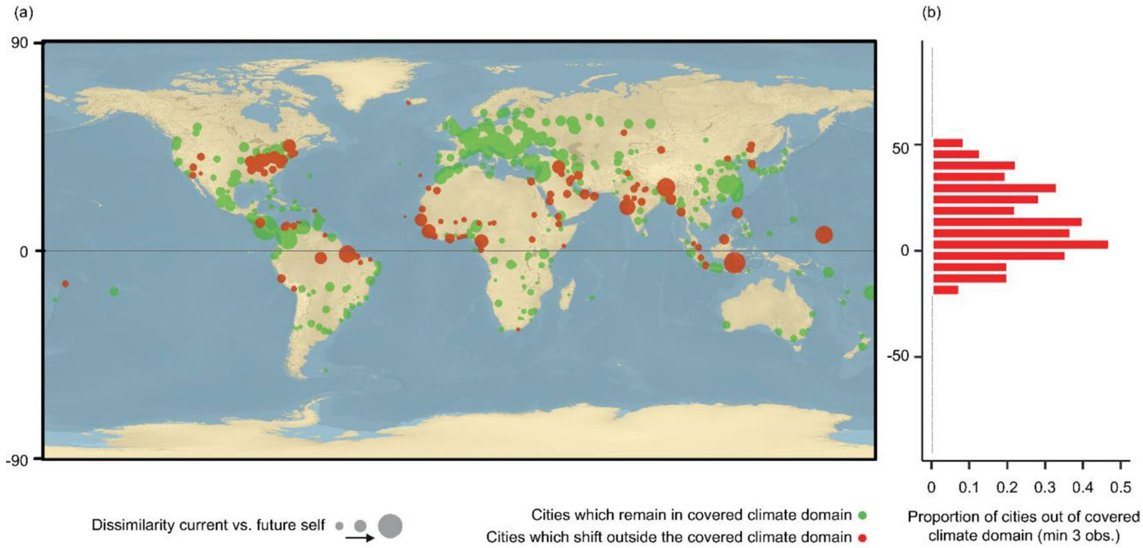

Figure 2. The figure shows the extent of CC in major cities of the world by 2050. (**a**, **b**) the extent of change in climate conditions. Cities predicted to have climates that no major city has experienced before are colored in red (mostly within the tropics). Cities for which future climate conditions reflect current conditions in other major cities of the world are shown in green. The size of the dots represents the magnitude of change between current and future climate conditions. The background of the maps are a combination rasters available in the public domain, i.e. of USGS shaded relief only and hydro cached. https://doi.org/10.1371/journal.pone.0217592.g002[18].

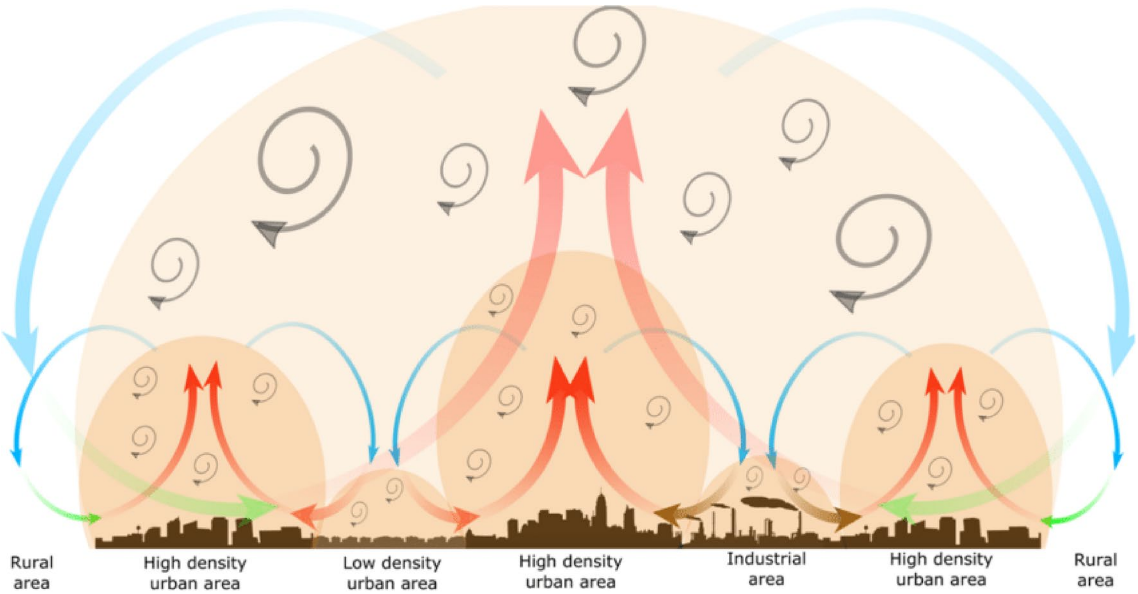

Figure 3. A schematic figure showing a complex structure of UHI in the gigacity, where within one large UHI, multiple individual UHI circulation patterns are formed between the lower and higher-density urban areas with the lack of rural areas. Within the gigacity, the UHI circulation is not bringing cooler and cleaner air from rural areas but draws in already hot air[23].

He et al.[4] examined the research landscape on urban heat mitigation and adaptation strategies, finding significant growth driven by CC and urbanization impacts like UHIs and heat waves, but also critical gaps including: a lack of interdisciplinary integration across different fields; an overemphasis on technical solutions rather than policy/governance aspects; a limited consideration of environmental justice issues surrounding the disproportionate heat vulnerability faced by marginalized populations. His study[26] emphasizes the need for equitable implementation of urban design interventions to mitigate UHI in disadvantaged communities facing disproportionate heat exposure due to factors like excessive impervious surfaces and lack of green spaces. Recommended strategies include increasing green infrastructure for shading/cooling, using cool pavements/roofs, improving ventilation corridors, and potentially modifying urban geometry. These measures focused on reducing heat sources and providing cooling should be prioritized in heat-vulnerable, low-income areas as part of just heat action planning to address cause-related environmental injustice.

State of the art: investigating UHI effect mitigation strategies in urban open spaces

In the preliminary phase of this research, an in-depth analysis of 25 research papers investigating the UHI effect was conducted and mapped as shown in Fig. 4[22,27–49]. These studies employed various analytical frameworks, examined case studies across diverse climatic zones, and proposed a range of mitigation and design strategies to address the UHI phenomenon. Envi-met simulation tool was the most used method, employed in 38% of the studies. ArcGIS, a geographic information system software, was utilized in 8% of the cases. Other simulation tools, such as InVEST, MODIS EVI, and PSU/NCAR, accounted for 27% of the studies. Lastly, 27% of the studies relied on numerical analysis tools for their analysis framework as shown in Fig. 5.

After analyzing the mitigation and design strategies proposed across the 25 studies, a diverse range of approaches emerged. The most prevalent strategy, adopted by 46% of the studies, involved the implementation of greenery and vegetation, such as parks, urban forests, green roofs, and other vegetated areas. This nature-based approach is widely recognized for its multifaceted benefits, including mitigating urban heat island effects, improving air quality, promoting biodiversity, and enhancing overall livability.

Roof treatments, including green roofs and cool roofs, were proposed in 22% of the studies, highlighting the importance of addressing the built environment's impact on urban microclimate and energy efficiency. Additionally, 8% of the studies recommended incorporating water spaces and blue bodies, recognizing their potential for cooling and enhancing the overall urban landscape. Material characteristics, such as insulation and albedo, were investigated in 14% of the studies, indicating a focus on optimizing building materials and their thermal properties. Furthermore, 5% of the studies explored the influence of different geometries, such as building heights and proportions, on urban microclimate and environmental performance.

The case studies cover a diverse range of climates, including tropical, arid/semi-arid, Mediterranean, subtropical, humid continental, and temperate zones. Tropical regions with high temperatures and precipitation were well-represented, as were hot and cold desert climates with low rainfall. A significant number focused on Mediterranean and subtropical areas with mild, wet winters and hot, dry summers. Humid continental climates with

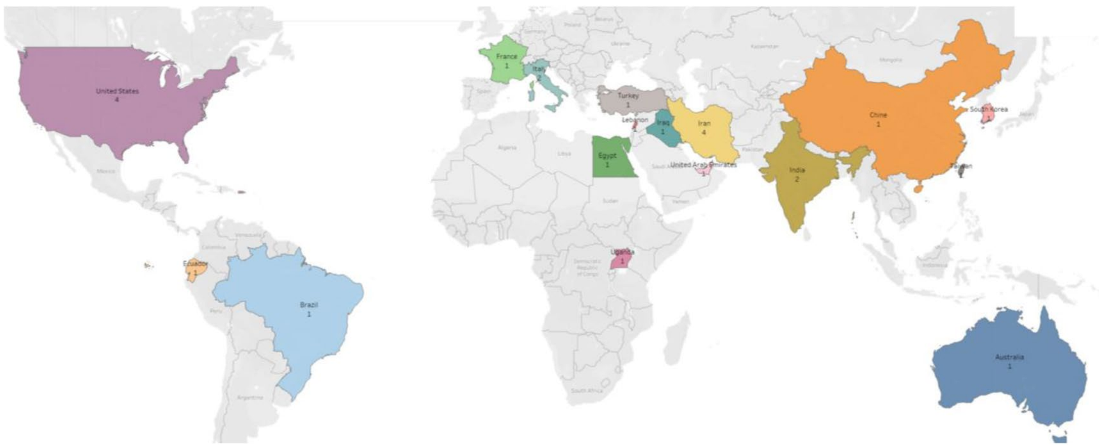

Figure 4. Map that provide a global overview of different studies of urban heat mitigation strategies adopted across countries and cities. (Authors' elaboration).

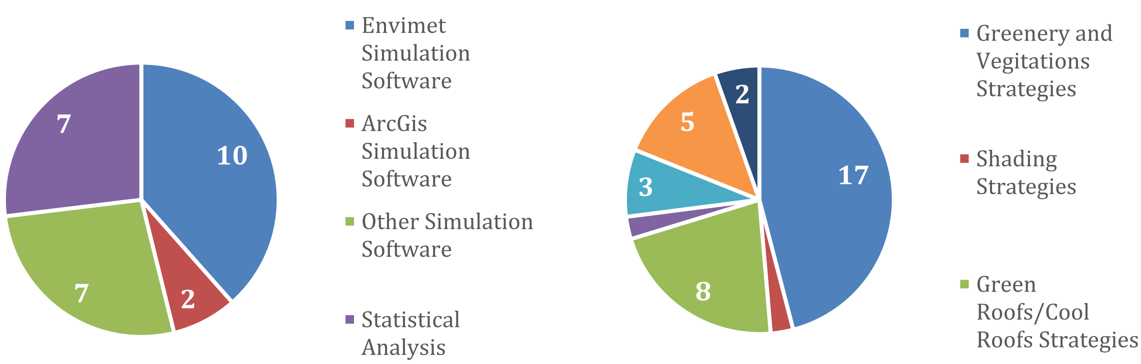

Figure 5. This chart provides an overview of the prevalent computational techniques and modeling tools adopted in researches on sustainable urban planning and climate adaptation measures to address urban heat island effects. (Authors' elaboration).

distinct seasons and temperate regions were also examined. This climatic diversity allows for a comprehensive understanding of urban mitigation strategies tailored to different environmental contexts.

Sustainable design for urban open public spaces

Most urban heat adaptation strategies are to be implemented in urban open public spaces. In this sense, sustainable design can at the same time improve environmental comfort and ensure a safe and attractive public space. Effective spatial enclosure and strategic placement of seating, lighting, and vegetation foster lively public life[50]. Since the 1970s, many concepts have focused on the relationship between human behavior and the environment, use, and shaping of public space. By connecting the city's urban context, public space developed legibility. They define the city's identity by bringing the locals together for different types of activities by adopting objectives including quality, diversity, adaptability[51].

As shown in Table 2, the SDGs, specifically SDG 11 on sustainable cities and communities, strongly connect with seminal urban design principles including Kevin Lynch's legible city form[52], Allan Jacobs' lively streetscapes[53], Donald Appleyard's livable streets[54], and the people-centered approach of UK bodies like DETR and CABE[55]. Recent research continues to show how these foundational ideas on walkability, human-scale design, social vibrancy, and community identity help drive progress on inclusive, safe, resilient, and sustainable cities in line with the SDGs[12].

Implementing the SDGs, particularly number 11, is crucial for creating thermally comfortable outdoor spaces in urban areas. As stated in the UN's "2018 Revision of World Urbanization Prospects" report, by 2050, half of the population is projected to live in urban areas[56]. This underscores the urgency of addressing UHI effects and lack of thermal comfort, which disproportionately impact vulnerable populations. Implementing SDG target 11.7 on providing universal access to safe, inclusive, and accessible green and public spaces can help mitigate urban heat through strategic greening and shading[12].

Starting from a literature review on existing frameworks for UHI effect assessment and mitigation, the objective of this research is to develop a comprehensive criteria and strategic framework to evaluate and guide the design of sustainable urban open spaces based on the integration of SDGs and established urban design principles to reach human comfort and mitigate the UHI effect. In particular, this research develops SDG-linked evaluation criteria and metrics for sustainable urban open spaces by identifying synergies between SDGs and urban design best practices. The proposed criteria are validated through application to case studies of urban public spaces using Envi-met modeling. Guidance and strategic recommendations are provided to align future open spaces developments with sustainability, well-being, and resilience goals. The research demonstrates the value of integrating SDGs into decision-making processes to enable sustainable performance improvements for urban open space projects.

Methodology

The research shows that successful urban open spaces put human needs first, utilizing design principles that create inclusive spaces for connection, creativity, and an enhanced quality of life. Elements like small blocks, pedestrian accessibility, greening, and flexible community uses can transform open spaces into welcoming places that reflect local identity. A human-centered approach also applies safety principles to foster positive interactions and reduce crime. By synthesizing diverse urban design theories, our proposed Open Community Spaces framework aims to create socially sustainable public realms that promote health, equity, and livability for all, aligning with Sustainable Development Goals such as Sustainable Cities and Communities, Climate Action, and Peace and Justice. This research highlights the need for urban open spaces to nurture social capital and respond to human-scale needs if they are to truly serve their communities while advancing the SDGs' vision for inclusive, safe, resilient, and sustainable cities.

The methodology displayed in Fig. 6 shows the process linking SDGs with established urban design principles from sources like Kevin Lynch, Allan Jacobs, Donald Appleyard, and DETRE/CABE guidelines. These principles are mapped to desired urban characteristics like human-scale design, connectivity, greening, inclusive access, distinctive sense of place, flexible community uses, and human-centered safety.

Specific design actions (coded elements a-g) are then proposed to achieve these characteristics. An initial proposal incorporating these actions undergoes environmental impact validation, at this stage, a design checklist was proposed based on the provided design actions to evaluate different design alternatives.

A case study project focusing on an urban space at Viale Carlo Felice Gardens was undertaken to examine the provided evaluation criteria. The base case was analyzed, and a renovation case was proposed by applying specific design actions extracted at the previous stage.

Subsequently, an environmental simulation using the Envi-met software was conducted to evaluate both the existing base case and the renovated case, enabling an understanding of how the proposed design actions influenced the environmental performance of the urban space.

Finally, the Results from the environmental impact validation simulations was used to provide valuable insights into the performance and behavior of the renovated design under various conditions to evaluate the renovated case based on the criteria outlined in the provided checklist.

To summarize, the methodology provides an iterative, analytical process that translates high-level sustainability goals into concrete urban design actions, validates their environmental impact through simulations, learns from case studies, and verifies the final proposal against established criteria.

Our framework integrates urban design best practices with the SDGs to create public spaces that benefit both people and the planet.

			No poverty (SDG 1)	Good health and well-being (SDG 3)	Clean water and sanitation (SDG 6)	Affordable and clean energy (SDG 7)	Decent work and economic growth (SDG 8)	Industry, innovation, and infrastructure (SDG 9)	Reduced inequalities (SDG 10)	Sustainable cities and communities (SDG 11)	Responsible consumption and production (SDG 12)	Climate action (SDG 13)	Life on land (SDG 15)	Peace, justice, and strong institutions (SDG 16)	Partnerships for the goals (SDG 17)
Kevin Lynch	A1	Vitality	×	●	×	×	●	×	●	×	×	×	×	×	×
	A2	Sense	×	×	×	×	×	×	×	●	×	×	×	●	●
	A3	Fit	×	×	×	×	×	×	×	●	×	×	×	×	×
	A4	Access	●	×	×	×	×	×	●	●	×	×	×	×	×
	A5	Control	×	×	×	×	×	×	×	×	×	×	×	●	●
Allan Jacobs and Donald Appleyard	B1	Livability	×	●	×	×	×	×	×	●	×	×	×	×	×
	B2	Identity and control	●	×	×	×	×	×	×	●	×	×	×	●	×
	B3	Access to opportunities, imagination, and joy	×	×	×	×	●	●	●	×	×	×	×	×	×
	B4	Authenticity and meaning	×	×	×	×	×	×	×	●	●	×	×	×	×
	B5	Community and public life	×	●	×	×	×	×	×	●	×	×	×	●	×
	B6	Urban self-reliance	×	×	×	●	×	●	×	●	●	●	×	×	×
	B7	An environment for all	×	●	●	×	×	×	×	●	×	●	●	×	×
DETRE/CABE	C1	Character	×	×	×	×	×	×	×	●	×	×	×	×	×
	C2	Ease of movement	×	×	×	×	×	●	×	●	×	×	×	×	×
	C3	Diversity	×	×	×	×	×	×	●	×	×	×	×	●	×
	C4	Continuity and enclosure	×	×	×	×	×	×	×	●	×	●	×	×	×
	C5	Legibility	×	×	×	×	×	×	×	●	×	×	×	●	×
	C6	Adaptability	×	×	×	×	×	×	×	●	×	●	×	×	×
	C7	Quality of public realm	×	●	×	×	×	×	×	●	×	×	×	×	×

Table 2. This table shows the relation between SDGs and urban design principles (Authors' elaboration).

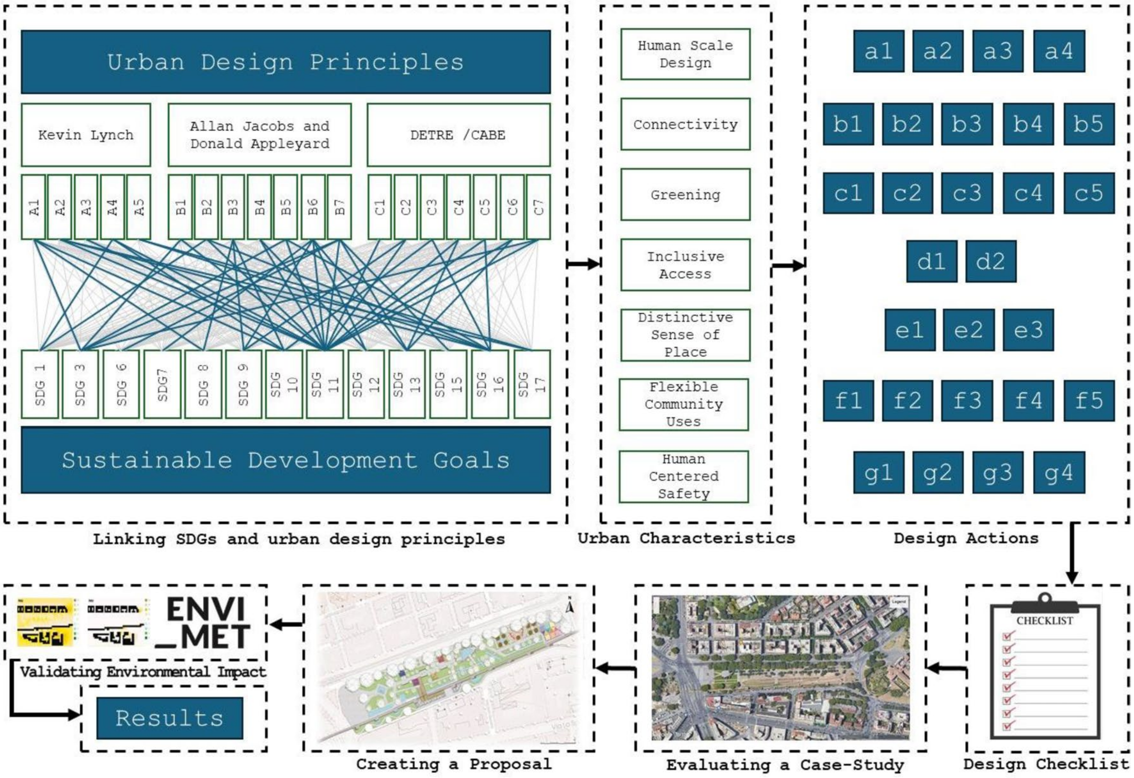

Figure 6. Graph that represents the conceptual framkework of the research, linking urban design principles with SDGs through an evaluation process to create a design proposal (Authors' elaboration).

This research adapts the previous concept, which focuses on designing open spaces that promote social connection, walkability, accessibility, sustainability, and a sense of place, according to the literature studies, the main principles of the concept are:

- Human-Scale Design: focuses on Spaces designed for pedestrians first, this principle relates to SDG 11 (Sustainable Cities and Communities) by creating walkable, livable urban environments.
- Connectivity: There are multiple route options to move through the space, with high connectivity to surrounding areas, Pathways promote walking and there are amenities to activate the space. this principle is related to SDG 11 by promoting safe, affordable, and sustainable transport options in urban areas.
- Greening: Landscaping, trees, planters, and greenspaces are integrated throughout to provide greenery, shade, biodiversity, and sustainability benefits this principle relates to SDG 13 (Climate Action) and SDG 15 (Life on Land) by integrating nature and biodiversity into city landscapes and increasing green cover.
- Inclusive Access: The space is accessible to all ages and abilities, with amenities like seating areas, kids' areas, different services, and shades to serve different needs. Accessible routes connect destinations. this principle relates to SDG 10 (Reduced Inequalities) by providing accessible public spaces for people of all ages, genders, and abilities and SDG 11 (Sustainable Cities and Communities).
- Distinctive Sense of Place: Local culture, history, and environmental features are shown through public art, programming, and place-making strategies. The space tells the story of the community. this principle relates to SDG 11 by providing access to safe, inclusive green and public spaces for all.
- Flexible Community Uses: The space adapts to support different community uses like markets, performances, art festivals, and more. By using seating and interactive elements that allow flexibility. this principle relates to SDG 11 by providing universal access to safe, inclusive, and accessible green and public spaces.
- Human-Centered Safety: Design promotes natural surveillance and positive social interactions, using principles of Crime Prevention Through Environmental Design (CPTED). Lighting, visibility, and arrangements prioritize pedestrian comfort. this principle relates to SDG 16 (Peace, Justice, and Strong Institutions) by reducing violence and crime through environmental design.

All these principles are connected to urban sustainability which requires holistically addressing environmental, economic, and social needs in an integrated way through urban planning, policy, and community action. So according to the adopted concept, the methodology of this research has translated the main design principles into design actions that reflect the social, environmental, and economic aspects through Figure 7.

The methodology of this research is structured through the following steps displayed in the schematic diagram of Figure 6 to achieve the main objective of the study. The strategy adopted is to show how urban heat islands (UHI) influence thermal comfort in an urban open space in Rome, Italy, and how urban design can be used to

Figure 7. This diagram represents how the key design concepts were transformed into design actions that reflected the social, environmental, and economic aspects (Authors' elaboration).

mitigate these effects. For this reason, a redesign of the urban open space is proposed which incorporates the principles of bioclimatic design to mitigate the effects of UHI to improve thermal comfort to achieve a good level of thermal comfort in the area being tested (Case study of Viale Carlo Felice gardens in Rome). The selected site represents a typical public open green space in an urban environment. It was selected based on its importance, historical context, as it incorporates important heritage architecture, and effect on the urban form of the city, as well as for some criticalities like the fact that it is currently prone to pluvial flooding in case of heavy rains. The project will extend irrigation across the green area, reinforce eroding slopes, replace part of the drainage system, and consider adding an underground water recycling tank and fountain to prevent flooding while improving irrigation and planning for future additions according to the request of the local community[57].

The methodological framework set out in this contribution is based on the most recent scientific literature[58,59] and on international documents and reports on input modeling-simulation-output simulation design simulation systems, constituting a reference framework for the identification of the environmental technological systems being analyzed scientific (input modelling), the definition of possible intervention scenarios with the selection of the most suitable alternative solutions based on the simulation results obtained (simulation), finally the definition of an intervention model adaptable to different contexts (output modelling).

The research, was developed through:

- The collection of climate data and the analysis of the main environmental factors;
- The identification of focal points in the context, representative of bioclimatic behavior;
- The definition of the environmental profiles of the context (surface materials, vegetation and heights of the urban context) using direct observation in site visits and the tools of Google Earth and Google Street View;
- The modeling of the microclimate of the study areas ex ante, through the ENVI-met software (version 5.1.5) to evaluate how different development models, including variable quantities of pavement and vegetation, influence localized temperatures;
- The development of parameters that highlight the individual's psychophysical well-being condition in relation to the environment in which he finds himself, such as the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD);
- The processing of environmental parameters such as Physiological Equivalent Temperature (PET) (°C);
- The design of the park, as a listed historical park, the redevelopment was carefully designed to avoid major changes that could compromise the heritage value and historical features of the site.

– The evaluation and discussion of the outcomes of the parameters examined with the dynamic simulations and bioclimatic-environmental evaluation of the pre- and post-operation state in summer conditions at 9.00 and 15.00.

It is necessary to specify how the input environmental data within the predictive environmental simulation software ENVI-met 5.1.5 were analyzed by consulting thermal and energy simulation programs such as, among others, Energy Plus and the data study climate data in the historical series of the last 25 years granted by the Department of Italian Civil Protection and the Meteorological Service of the Italian Air Force (Figure 8). The model created has a real size of 150 × 90 m (50 × 30 m in the model created, with grid cell dimensions 3 × 3 × 3 m) and a rotation, with respect to the North, of 335°. The same was achieved by placing the area subject to intervention as the center of gravity and the consolidated residential context as the margin. The model was equipped with a nesting area of 10 cells, equal to 30 m, to improve the quality of the simulation. The objective of the simulation, in summer conditions, is to demonstrate the effectiveness of technological-environmental solutions within the project area, capable of reducing overall, compared to the actual state, the environmental comfort indices perceived by users such as be the PMV, the PPD and the PET.

Case-study of Viale Carlo Felice gardens

This study utilizes ENVI-met software to simulate different urban design interventions in a case study neighborhood and evaluate their potential to mitigate UHI effects. ENVI-met allows the modeling of microclimate dynamics in urban areas with a high spatial and temporal resolution.

The Research area is in Rome, Municipio I, Esquilino, its street park called Viale Carlo Felice Gardens (41.8867° N, 12.5107° E), is a significant site located between the Lateran Basilica and the Basilica of S. Croce, within the Aurelian Walls' ring. This area has been open since the Middle Ages.

On the other side of the Aurelian Walls, the southern portion of Viale Castrense runs parallel just outside the Aurelian Walls, which delineate Rome's historic city center. Viale Castrense is a long, straight urban arterial road located southeast of Rome's city center. It stretches approximately 2 km from the Aurelian Walls to the intersection of Via Tuscolana, the buildings lining Viale Castrense are simpler and smaller in scale here compared to the taller residential blocks further north. Their modest 3–4 story heights are sympathetic to the adjacent historic walls.

The Aurelian Walls are ancient fortification walls built in the third century AD to defend the city of Rome, the Aurelian Walls have had a significant impact on Rome's microclimate and UHI effect. Their imposing brick and concrete materials absorb heat during the daytime and slowly release it at night, helping regulate temperatures. The walls also act as a windbreak and reduce the air flow.

As shown in Fig. 9, the Esquilino Area is 3.09 km^2 with a population Density of 10 685,11 ab./km^2, The population density decreases as the distance from the center increases, indicating the metropolitan system's primarily monocentric character. Except for the eastern quadrant, which has generally been the most urbanized, the outer urban regions are usually characterized by very low-density indices.

The high population density in urban areas can strengthen infrastructure, boost economic productivity, and enable social connections, but density also presents challenges like providing thermally comfortable public spaces; improving microclimate conditions could encourage more outdoor time, benefiting health, well-being, and social life, so cities must balance density's benefits while enhancing public space microclimates to maximize quality of life.

Climate & environmental analysis

Temperatures vary between − 3.3 °C (rural areas outside) and + 4.3 °C (densely populated areas) for the daily UHII intensity indicator throughout the summer season, whereas temperatures vary between + 0.7 °C and

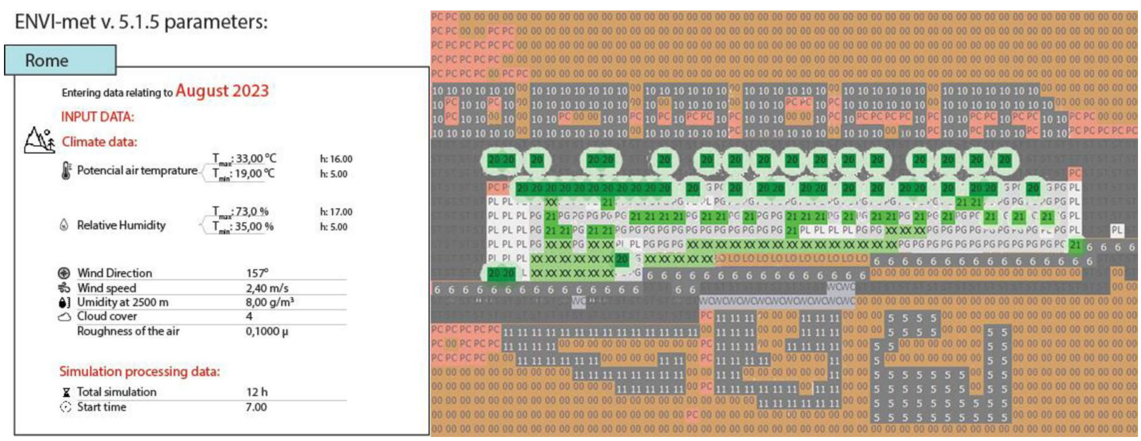

Figure 8. Input environmental data and digitized model set in predictive environmental simulation software ENVI-met v.5.1.5. (Authors' elaboration).

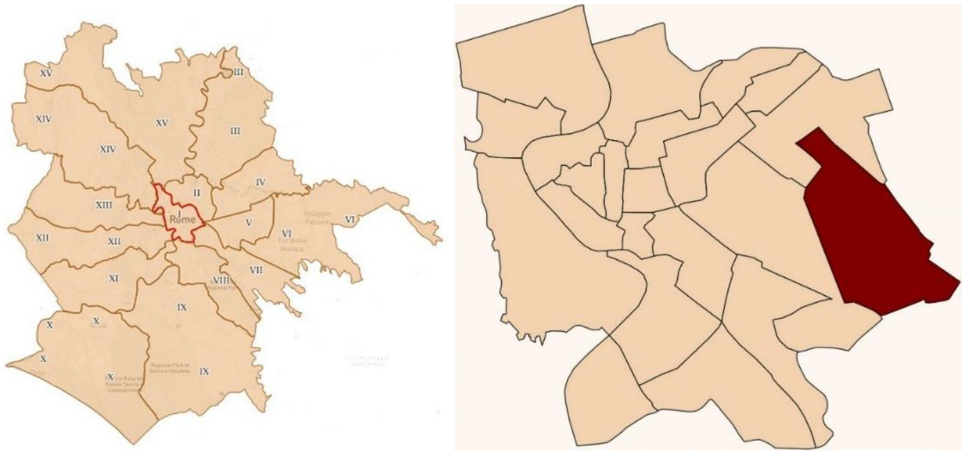

Figure 9. Map of Municipio I, Esquilino area, The background raster imagery used in this map was obtained from the following public source, "File:Roma Municipio I locator map.svg—Wikipedia." Accessed: Nov. 24, 2023. [Online]. Available: https://commons.wikimedia.org/wiki/File:Roma_Municipio_I_locator_map.svg (distributed under CC BY-SA 4.0 license; https://creativecommons.org/licenses/by-sa/4.0/)[60].

+4.1 °C for July. The phenomena of the UHI may be seen in both scenarios, but with varying intensities, in most of the municipalities I, II, IV, and V, and more limitedly in the XIII as shown in Fig. 10.

Urban structure

The site is well-served by many transportation options. There are strong bus and tram connections, Metro line A has two stations in the area. Active transportation options in the form of walking, and to a lesser degree cycling, exist in the project area, but the consistency of any strong bike network is fragmented.

The bus routes are concentrated along the major arterial roads. Having clear, safe, and well-lit sidewalk access from within the neighborhoods to the bus stops on the arterial roads is critical to making these facilities functional and attractive to residents, and well-used all year round, The local community destinations residents visit regularly—like parks, schools, community centers, libraries, museums, places of worship, clubs, shops, and transit—are located at a walkable distance as shown in Fig. 11; improving access to and experience at these neighborhood places can positively impact residents' feelings, enjoyment, sense of belonging and pride.

Existing and redesign

As shown in Fig. 12, the existing master plan of Carlo Felice Gardens and the Viale Castrense (41.88° N, 12.51° E), its linear urban park along an arterial road, the space is edged by the Aurelian walls, several trees line the perimeter providing partial shade. The garden, fenced off and open to the public during the day, is divided into a succession of planes and longitudinal paths, belvederes and fountains that punctuate the perspectives revealing historical suggestions and new livability. The central path is bordered by a double row of holm oaks divides the expansive open green areas, while the one along the sidewalk, bordered by a row of plane trees, has been reinstated with new specimens, restored, and equipped for resting[47]. The innermost part is organized on different heights, connected by several stairways. Overall, the space lacks diversity, with minimal amenities for recreation, social gathering, or relaxation as shown in Fig. 13.

As shown in Fig. 14, the master plan of the Viale Carlo Felice gardens after the redesign that aims to mitigate urban heat island intensity and enhance thermal comfort, the concept of the redesign was to integrate more vegetation, optimized tree placement, better connectivity between sub-spaces, replace paving materials, add water features, and expand shaded areas. Low-water native trees and shrubs have been placed along the main axe and throughout the spaces and gathering places to provide additional evapotranspiration cooling and shading. Trees surrounding pathways were cut and thinned to maintain visibility for safety and surveillance. The tree arrangement was changed to balance access to protection and shade with enough solar penetration to warm the public spaces in cool weather.

Pedestrian pathways were redesigned to link seating areas, play spaces, and food kiosk areas for better flow between activity zones. Fountains and splash pads were added to several plazas and nearby food vendors to provide localized evaporative cooling effects. The drainage was designed to recirculate water. Shade structures such as pergolas and canopies have been developed over gathering spaces and playgrounds. The shades were designed and sized to provide complete shade during the hot midday hours while allowing lower winter sunlight to penetrate.

The redesigned master plan aims to improve social connections, boost the local economy through more food and retail options, cut irrigation needs, and enhance thermal comfort through passive microclimate moderation techniques optimized for seasonal use patterns. By following the strategies shown in Table 3 that worked in synergy to reduce urban heat stress and create a vibrant community space after comparing it with the existing design.

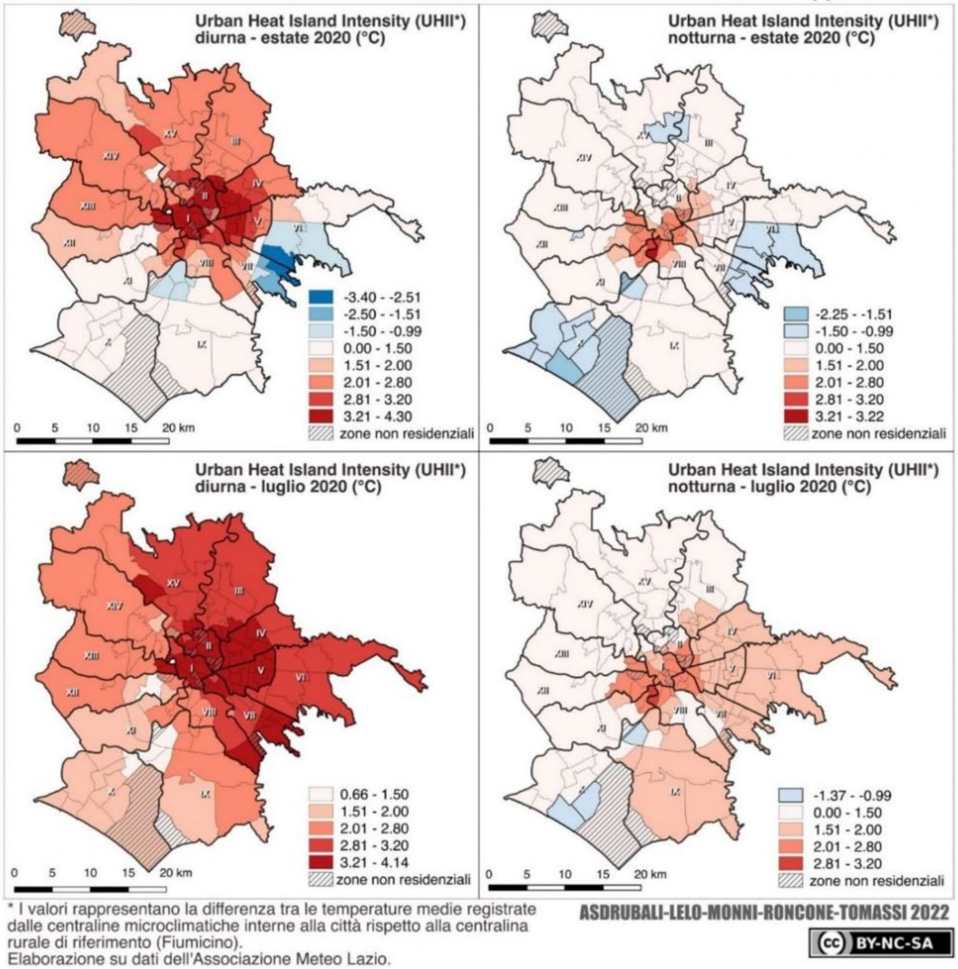

Figure 10. Maps that show the phenomena of urban heat island effect and intensity in Rome, Italy (distributed under CC BY-SA 4.0 license; https://creativecommons.org/licenses/by-sa/4.0/)[61].

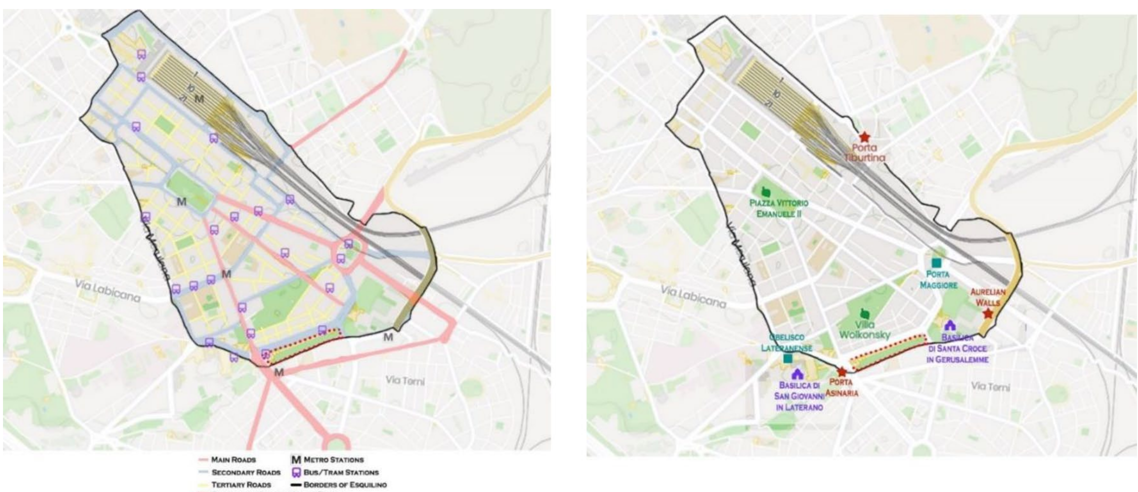

Figure 11. Roads maps and facilities around the study area, Background map from OpenStreetMap (2023), Retrieved from (https://www.openstreetmap.org) (Authors' elaboration).

Figure 12. Aerial view of Master plan map of the existing case of Viale Carlo Felice Gardens, From Google Maps," 41° 53′ 12.1″ N 12° 30′ 38.5″ E. Accessed: Nov. 24, 2023[62].

Figure 13. Pictures for the existing case of Carlo Felice Gardens and the Viale Castrense (Authors' elaboration).

Microclimatic simulations for the design verification

The new design will be validated using ENVI-met simulations to quantify anticipated improvements. Using ENVI-met to validate the redesign includes developing microclimate simulations that compare the existing layout to the proposed changes. For a peak summer day in July, key indicators such as air temperature, humidity, wind speed, Physiologically Equivalent Temperature (PET), Predicted Mean Vote (PMV), and Predicted Percentage Dissatisfied (PPD) are quantified across the site. The simulations show how additional vegetation, reflecting materials, water features, and optimized sun access and shading can lead to demonstrable gains.

Figure 14. Master Plan of Viale Carlo Felice Gardens after the redesign with the adopted concept (Authors' elaboration).

Aspect	Provided solutions	Existing	Renovation
Social	Active travel like walking and biking	◕	●
	Different amenities for physical activities like exercise stations, and kids' areas	◕	●
	Separate bike infrastructure like protected bike lanes	○	●
	Easy access to services and facilities safely and conveniently	●	●
	Child-friendly landscape elements	◕	●
	The space elements harmonious with the surrounding character	◕	●
	welcoming and playful components at ground level	○	●
	Direct sidewalks for pedestrian routes	○	
	Landscape elements proportionately to surrounding buildings' character in the place	◕	●
	Different functions and sources of light to provide security	○	●
Economic	Diversify public space uses like markets, events, and celebrations to maximize users	○	◕
	Diversity of amenities and activities to attract people to the space	◕	●
	Local public markets, and vendor spaces	○	●
	Distributed activities in public places and spaces	○	◕
	Arts, culture, and social activities for all ages	○	◕
Environmental	Plant trees and greenery to reduce pollution	◕	●
	Use trees to define the human scale	◕	●
	Plant diversity for ecological diversity	◕	●
	Shades and water features for a cool microclimate	○	●
	Energy-efficient lighting to reduce consumption	○	●
	Separate vehicle and pedestrian paths for safety	◕	●
	Bike lanes and walking paths to replace driving trips	○	●
	Determine the locations of street trees in a way that does not obstruct vision and communication between internal and external spaces	◕	●
	Safe-equipped sidewalks with protection against weather conditions	○	◕

Table 3. This table shows the solutions provided in the master plan, grouped in social, economic and environmental. (By Authors). ● Existing Solution. ◕ Partially Existing. ○ Missing Solution.

The metrics of PET, PPD, and PMV were selected due to their widespread acceptance and effectiveness in quantifying outdoor thermal comfort. PET directly translates the complex outdoor conditions into a relatable temperature scale, making it easier to interpret thermal perception. PMV provides a standardized model to predict the mean thermal sensation experienced by people in a given environment. Importantly, PPD allows for evaluating the percentage of occupants or pedestrians who would be dissatisfied with the thermal conditions, enabling the comparison of design alternatives and setting targets for thermal acceptability. Together, these three indices offer a comprehensive assessment of the microclimate's impact on human thermal comfort.

The simulation results are chosen at 9 AM and 3 PM, 9 AM was likely selected as the analysis time because it represents typical morning conditions in an urban open space as shown in Fig. 15: By 9 am the city has begun warming under the morning sun, but peak heat island intensity has not yet built up. This shows more moderate urban heating. It falls within the range of common morning usage by people commuting or accessing the space before the workday. 3 PM is commonly used for urban microclimate studies in the literature. Using this standard time allows comparison of results to other studies in Rome or similar cities. Performance benchmarking—3 PM represents a high-stress test of the open space's microclimate and thermal comfort. By mid-afternoon, the urban surfaces have had many hours to absorb solar radiation and re-emit this as thermal radiation, leading to peak air and surface temperatures. the simulation shows performance at a peak demand time of day, and it represents when urban heat island effects are most extreme, allowing the analysis to focus on mitigation strategies.

The research methodological approach interconnects urban design principles with SDGs through creating an evaluation criteria that is validated using modelling and simulation process. It's based on current literature and guidelines on urban design simulation frameworks. The existing case has analyzed the existing urban characteristics like connectivity, greening, accessibility, etc. (Existing case simulation). After analyzing the main weakness points in the existing case, different design actions and interventions that are related to the weakness points have been used and an optimized design proposal is generated as the output, adapted for the specific context (Renovated case) that was analyzed, simulated and evaluated against environmental metrics (the simulation phase). Based on the results This comprehensive framework facilitates integrating sustainability principles into urban design for creating environmentally conscious development proposals.

The research followed an integrated 'input modeling-simulation-output' approach drawing from urban design principles and SDGs. In the input modeling phase, climate data, environmental factors, urban context profiles (materials, vegetation, building heights) were collected through observations, mapping tools, and analyses from the site visits.

The simulation phase uses ENVI-met software to model microclimate conditions and assess how different urban development scenarios with varying pavement/vegetation quantities influence localized temperatures. Environmental parameters like physiological equivalent temperature, predicted mean vote (PMV), and predicted percentage of dissatisfied (PPD) were simulated. The results from the simulations of the existing and renovated case scenarios were evaluated.

The output modeling involved predicting variations in heating/cooling energy consumption due to microclimate mitigation interventions. An intervention scenario was defined by selecting the optimal solutions based on evaluating their environmental bioclimatic performance against the preset objectives.

In Figs. 16, 17, 18 and 19 the output of the ENVI-met model is shown as PET, PPD, and PMV index maps for the summer scenario at two different hours of the day: 9 AM, and 3 PM. Which was chosen as they represent

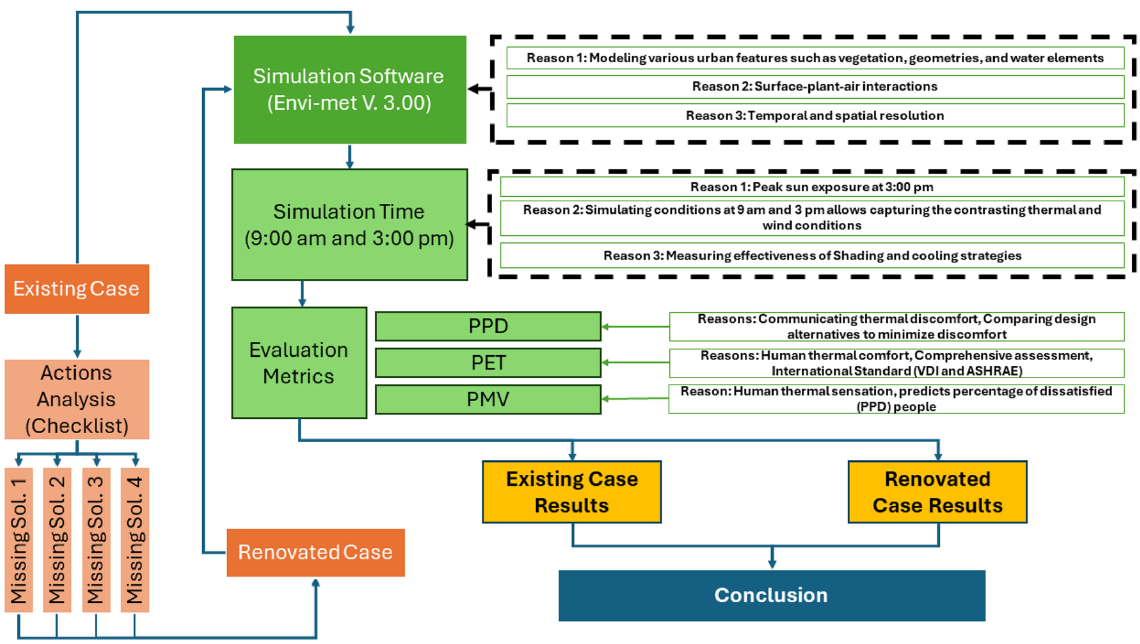

Figure 15. A graphical figure that shows the integration of microclimatic simulations in the design process (Author's elaboration).

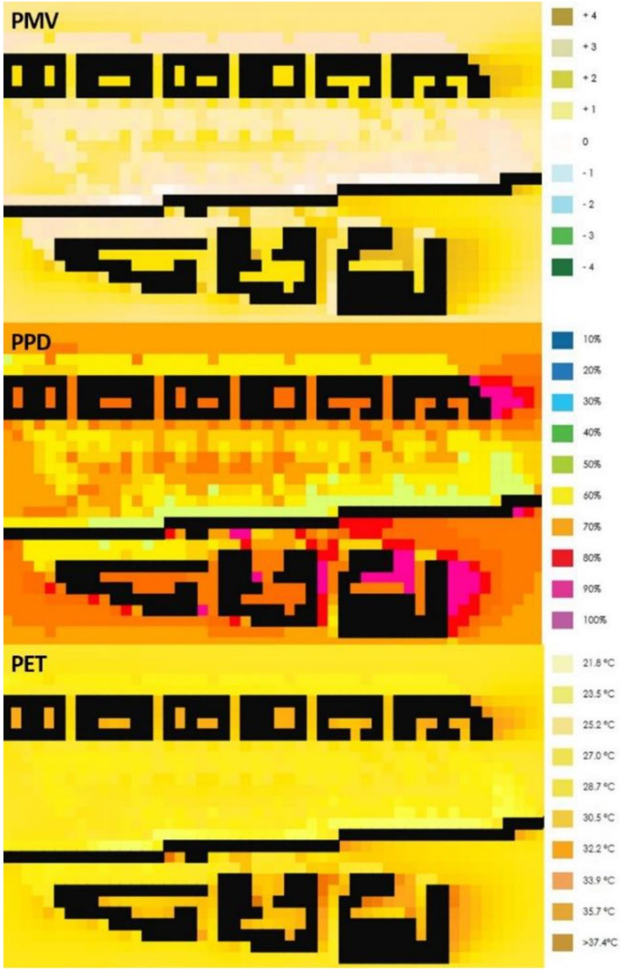

Figure 16. Simulated PMV, PPD, and PET, existing results at 9 AM in summer. (By Researcher). Figure 15: Simulated PMV, PPD, and PET, renovated results at 9 AM in summer. (By Researcher).

contrasting conditions within a typical diurnal cycle. At 9 AM, solar radiation is increasing from low morning levels, capturing the transition into warmer daytime temperatures. Conversely, 3 PM represents a period when solar radiation is near its peak, leading to maximum heating of urban surfaces and potential thermal discomfort. Maps serve as examples to demonstrate the variations of comfort index across the models' area at different hours, and findings will be explained in the following sections.

Microclimatic simulation at 09:00 AM

Existing case at summer 09:00 AM

The ENVI-met output maps at 09:00 as shown in Fig. 16 reveal substantial spatial variability in thermal comfort indices across the park area. PET values ranged from 21.80 °C to 37.40 °C, PPD from 55.65% to 73.71%, and PMV from 1.15 to 1.93, indicating thermal perceptions spanning comfortable to severe heat stress conditions. Although a few localized spots exhibited comfort levels, the highest values (PET > 35 °C, PPD > 70%, PMV ~ + 2) signify considerable morning heat accumulation requiring mitigation strategies. These simulation results highlight opportunities to modify the open space design and enhance microclimate conditions during critical morning visitor periods when thermal discomfort may discourage park utilization.

Renovation at summer 09:00 AM

The post-redesign ENVI-met simulations at 9:00 AM shown in Fig. 17 demonstrate the significant impact of the proposed mitigation strategies and design elements on thermal comfort indices. PET values ranged from 18.60 °C to 32.40 °C, PPD from 9 to 55%, and PMV from 0.00 to 1.00, reflecting improved microclimatic conditions with expanded zones of sub – 20 °C PET and PPD < 10%. Compared to pre-redesign conditions, the notable reductions in thermal indices, particularly morning PET, PPD, and PMV values, validate the enhancements achieved through added vegetation, rearranged structures, and material changes. While not eliminating discomfort entirely, the redesigned urban open space successfully lowered morning thermal perceptions, promoting more thermally comfortable access and use for visitors.

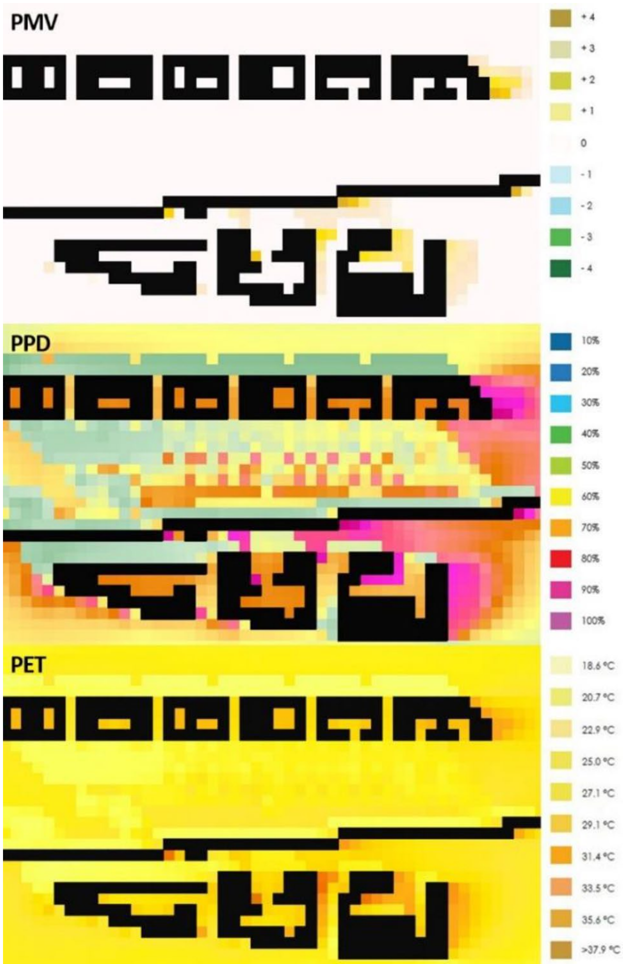

Figure 17. Simulated PMV, PPD, and PET, existing results at 9 AM in summer. (By Researcher). Figure 15: Simulated PMV, PPD, and PET, renovated results at 9 AM in summer. (By Researcher).

Microclimatic simulation at 03:00 PM

Existing at summer 03:00 PM

The 03:00 PM ENVI-met output maps shown in Fig. 18 reveal extreme heat stress conditions across the entire park area, with PET values ranging from 35.39 to 51.54 °C, PPD reaching up to 98.32%, and PMV between 1.83 and 3.97. These high thermal indices, quantifying "hot" to "very hot" thermal perceptions without any refuge zones, highlight the park's poor daytime thermal performance and the urgent need for heat mitigation strategies. Unlike the morning simulations, the results indicate a lack of spatial variations, with significant mid-afternoon overheating restricting occupancy and necessitating serious interventions to reduce thermal mass and improve microclimate conditions for public use..

Renovation at summer 03:00 PM

The post-redesign ENVI-met simulations at 9:00 AM shown in Fig. 19 demonstrate the significant impact of mitigation strategies on thermal comfort indices. PET values ranged from 30.34 to 47 °C, PPD reached 54.3–65%, and PMV varied between + 0.70 and + 1.5. Compared to pre-redesign conditions, the introduction of shading trees, increased vegetation, redirected walkways facilitating breezes, reflective pavers, misting features, and sheltered structures collectively lowered PET by up to 4 °C, reduced PPD by over 30 percentage points, and decreased PMV by over 2 points. These improvements verify the shift from uncomfortable to acceptable heat stress perceptions, providing accessible public space through passive yet effective techniques, despite some remaining hotspots requiring further intervention.

Figures 20, 21 and 22 illustrate the difference between the existing case and the redesign at 09:00 AM and 03:00 PM in PET, PPD, and PMV values, it is noticed that there is a significant variation in values after the redesign of the park.

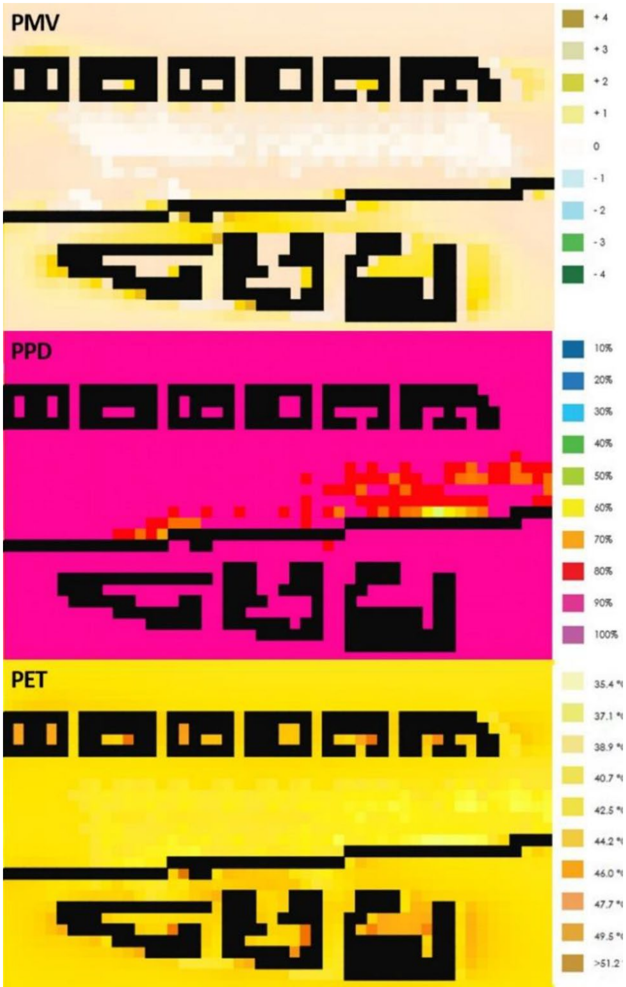

Figure 18. Simulated PMV, PPD, and PET, existing results at 3 PM in summer. (By Researcher). Figure 17: Simulated PMV, PPD, and PET, renovated results at 3 PM in summer. (By Researcher).

Discussion

This study emphasizes the role of sustainable design for cooling urban public spaces affected by UHI effect, while stressing—more in general—the importance of such spaces in developing social assets and meeting human-scale needs while promoting the SDGs' vision of inclusive, safe, resilient, and sustainable cities. The implementation of sustainable design principles, in fact, helps in prioritizing human needs and providing efficient, inclusive urban open spaces, enabling interaction, creativity, and an improved quality of life.

The proposed framework aims to create socially sustainable public realms that promote health, equity, and livability for all, aligning with SDGs such as Sustainable Cities and Communities, Climate Action, and Peace and Justice. By synthesizing diverse urban design theories, the methodology combines innovative techniques in sustainable urban design with the SDGs to create open spaces that benefit both people and the environment.

The adopted strategy is to illustrate how UHIs affect thermal comfort in an urban open space in Rome, Italy, and how sustainable design can be used to mitigate these effects, by suggesing the redesign of an urban open space based on UHI mitigation principles to improve thermal comfort and achieve a decent level of thermal comfort. The chosen site, the Viale Carlo Felice gardens—a typical public open space in an urban context—was chosen based on its significance, historical background, and effect on the city's urban form. To validate the variation between the original case and the upgraded design, the study area was modeled as a three-dimensional model using ENVI-met simulation software to simulate the impact of UHIs on the thermal comfort of the park. Then, the research compared the simulated results of the existing scenario, which uses actual data from the site visit, with the upgraded design.

The study involved creating a redesign plan that included incorporating more vegetation, refining tree placement, improving the connection between sub-spaces, replacing paving materials, integrating water features, expanding shaded areas, and simulating microclimate models to evaluate the used strategies' influence on physiologically equivalent temperature (PET), predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD).

The cooling design strategies adopted in the case study are therefore an integrated set of solutions that combine and balance all the various options identified in the studies, selected and assessed in the literature review,

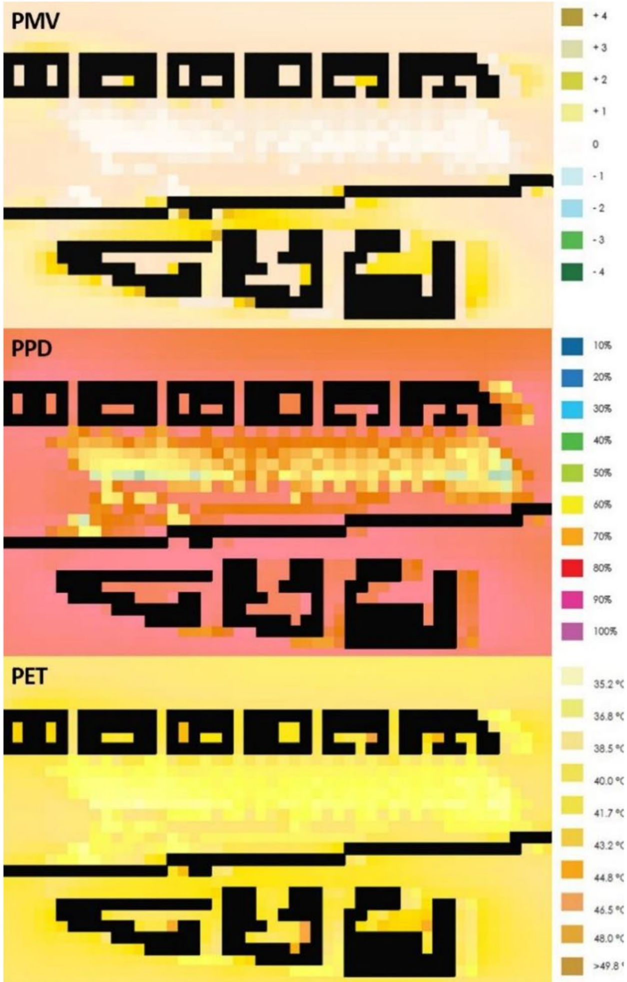

Figure 19. Simulated PMV, PPD, and PET, existing results at 3 PM in summer. (By Researcher). Figure 17: Simulated PMV, PPD, and PET, renovated results at 3 PM in summer. (By Researcher).

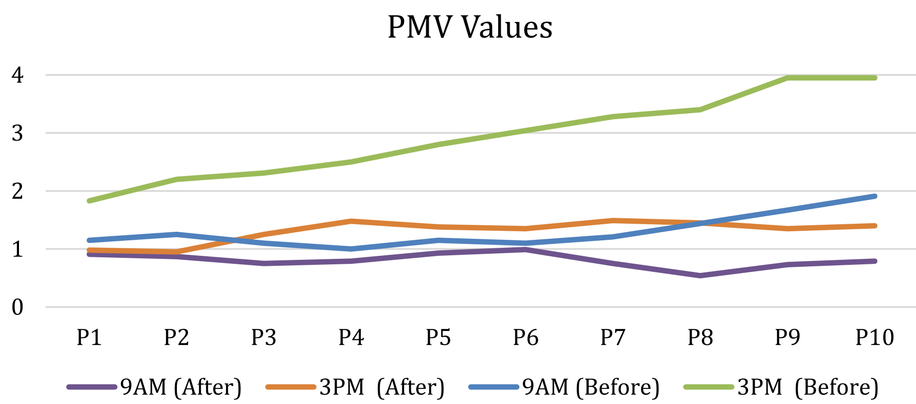

Figure 20. Comparison of PMV values after and before the redesign at 9 AM and 3 PM.

assumed as a base for the present research. The effectiveness of this balanced mix is proved through the adoption of PET, PMV and PPD parameters.

The adoption of specific environmental parameters listed above falls within the so-called "subjective" variables, actions that an individual carries out within an environment in response to the present microclimatic conditions. In particular, the use of thermohygrometric wellbeing indices such as the Predicted Mean Vote (PMV), the Physiological Equivalent Temperature (PET) and the Predicted Percentage of Dissatisfied (PPD)

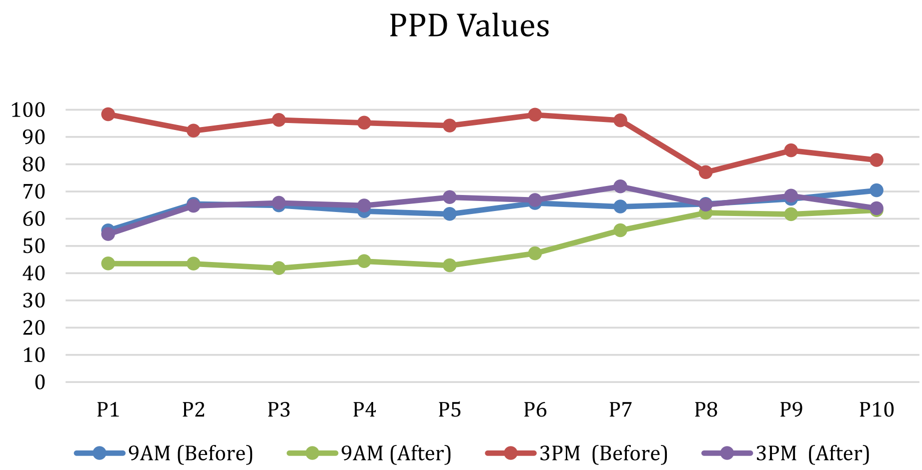

Figure 21. Comparison of PPD values after and before the redesign at 9 AM and 3 PM.

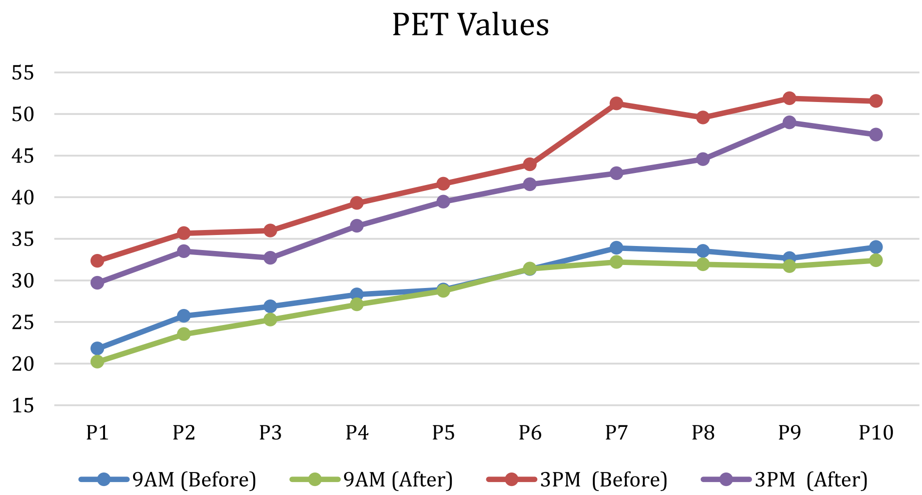

Figure 22. Comparison of PET values after and before the redesign at 9 AM and 3 PM.

allow us to understand the benefits of a thermal environment as a function of technological solutions adopted as well as variable parameters such as CC and increasingly extreme meteorological events.

The research revealed that the redesign concept has a significant cooling effect on PET, PMV, and PPD index during the summer day scenario. The simulation of the existing case at 9 am showed moderate heat stress, with PET up to 37.4 °C, PPD reaching 73.7% and PMV hitting 1.93; the redesign lowered morning PET by up to 19 °C, reduced PPD by 20%, and reduced the PMV by 1 point on average, providing quantitative validation of more comfortable conditions. Also, at 3 pm, extreme oppressive heat prevailed everywhere, with alarming PET of 51.2 °C, near total dissatisfaction of 97.39% PPD, and PMV up to 3.97; here the redesign had an even greater impact, reducing PET by up to 4 °C, lowering the PPD by more than 30 percentage points and decreasing the PMV by more than 2 points.

The Research offers a comprehensive framework by synthesizing diverse urban design theories with the SDGs, ensuring projects align with global sustainability goals which can help designers and decision-makers to utilize the evaluation checklist provided by this research to obtain a basic indication of how their design proposals perform against the SDGs in social, environmental, and economic terms. This tool aids in enhancing design proposals, allowing for a comparative analysis of different options to foster sustainable, resilient, and inclusive urban spaces. Additionally, the detailed redesign strategies, including the incorporation of vegetation, refined tree placement, improved connectivity, and integrated water features, serve as a practical guide for creating urban spaces that prioritize human comfort and environmental performance.

Therefore, the novelty of the developed framework is the emphasis on the subjective variables and the importance given to the outdoor comfort that is a crucial factor in ensuring that public open spaces can be really attractive and livable for all citizens. Limits of the developed research can be found in the difficulty of relying on average climate data when CC is currently so dramatically altering the trends and, therefore, in the need to rely on climate forecasts and projections in order to climate-proof any public space for the future years.

Conclusions

The goal of this study was to demonstrate the value of integrating sustainable development goals into the decision-making process for urban open space projects through the validation of SDG-linked evaluation criteria and metrics, providing key guidance and recommendations to enable sustainable performance improvements and make urban open spaces more comfortable for people to use by mitigating harmful heat levels. As a result, even amid high heat caused by CC, public areas could remain welcoming during the summer heat waves. At the same time, this research evaluates approaches for improving thermal comfort in a park in Rome. These focus on the integration of native low-water needing vegetation and on the optimization of trees, on the materials used for urban surface, on water features and the extensive use of shading systems, with the aim to change perceptions of deadly heat. By assessing the UHI impact and simulating solutions with appropriate modelling tools, finally, the research proves that—through sustainable cooling design strategies—outdoor spaces can be used despite rising temperatures, contributing to sustainability goals, and thus improving the city's quality of life. Therefore, it clarifies the important role of simulations in supporting a focused, holistic design approach, relying on a mix of strategies and techniques carefully integrated in the context to provide a fully effective mitigation of the UHI effect.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions
All authors contributed to the study conception and design. Material preparation, data collection, analysis, and design were performed by N.A. and P.A.; N.A., and M.G. designed, developed and extracted the simulation results; N.A., F.H., and A.F. wrote the original draft of the manuscript. All authors reviewed and commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing interests
The authors declare no competing interests.

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