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Greenery as a mitigation strategy to urban heat and air pollution: a comparative simulation-based study in a densely built environment.

Abstract

The urban heat island and the urban air pollution concentration are two major climate-change-related phenomena affecting the built environment worldwide. This paper aims to verify the potential effect of different mitigation measures through a simulation study. In detail the present study focuses on the analysis of the environmental impacts of urban vegetation, such as green facades, vertical greenery, and green pavements. After an extensive screening of the literature review, an investigation of the impact of the most common built environment design variables in a defined case study led to the definition of a typical urban canyon was tested. The results show that the presence of trees in a street canyon could reduce the air temperature peaks by 5-10 °C, while the high-level vegetation canopies can lead to a deterioration in air quality with a PM concentration increasing by 1.2-1.5%. Instead, using low-level green infrastructure improves the air quality conditions on the sidewalk, reducing the NOx in the range of 10-20%. The analyzed high-level greenery generated an air temperature reduction effect on a street level ranging from 8 to 12°C. The present work contributes to clarifying the potential mitigation effect of green infrastructure in a densely built environment, where the risk of increasing temperatures and air pollutants is foreseen to be more intense in the coming years.

Keywords: Urban Heat Island, Air Pollution, Mitigation Strategies, Built Environment, Resilience

1. Introduction

Greenhouse gas emissions are progressively less driven by industrial activities and instead mainly originate from energy services required for providing suitable indoor environments (e.g., heating and cooling, lighting, appliances) and mobility [1]. In addition, cities are becoming greyer: they are made of dense building materials, absorbing energy from the sun; fewer trees to provide shade and cooling effect; and fewer green areas to cool by evapotranspiration and absorb air pollutants. Thus, cities are becoming more frequently prone to suffer intense Urban Heat Island (UHI) and Air Pollution (AP), especially within dense Built Environments (BE).

In addition, cities and dense urban areas are now more densely populated. Therefore, more people would be exposed to UHI and related risks. In fact, the United Nations estimated that in 2018, 55% of the world's population lived in urban areas, and in the next two decades, it will reach 66% [2]. In particular, cities' common characteristics enhance UHI and AP related to Slow Onset Disaster (SLOD) risks; that is: low albedo materials, human gatherings, increased use of air conditioners, reduced green areas, urban canopy, blocked wind flow and pollutant emission [3]. In order to contrast such conditions, existing literature has reported that the presence of vegetation plays a key role in improving air quality and enhancing the microclimate of the open space [4].

Consequently, this research work aims to study natural-based solutions, testing and quantifying the potential impact that selected green mitigation strategies (MS) (i.e., hedges, trees, and green facades) can have at a large scale and their effectiveness in different contexts based on the comparison of PET (Physiological Equivalent temperature), NOx concentrations and PM concentrations as performance indicators. The large-scale impact is extrapolated from the results of different computer-aided simulation tools on the study case's simplified urban canyon archetype. These simulations were also employed to perform sensitivity analysis on influencing parameters to explore multiple configurations and effects. In addition, the presented work can be embraced as a protocol for designers to demonstrate the relevance of some design decisions toward a more salutogenic urban design. Finally, in contrast with some of the previous works on UHI, the analysis is focused on reducing the stress on pedestrians during daylit hours instead of studying nocturnal UHI.

1.1 Overview of UHI and AP mitigation strategies

Evidence on the UHI effect and AP have been documented in cities worldwide [5]. As mentioned before, cities are more likely to suffer these phenomena, and certain portions of the city are more prone to increase the intensity of UHI and AP [3].

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Although several studies have researched the causes of UHI and AP and the possibilities to reduce them, most have focused on the relevance of urban morphology and materials to environmental conditions [6][7]. The geometry of the canyon influences the urban energy balance in various ways. For example, it increases/decreases the surface exposed to the exchange processes (allows/blocks solar radiation influx), determines the level of interaction between the surfaces that compose the BE, limits/augments the ability to disperse the long-wave infrared radiation, and limits/enhances air turbulence. Regarding canyon morphology, the parameters proven most influential on temperature and radiation exchanges are canyon orientation, aspect ratio (H/W), and sky view factors [8]. For example, according to [9], the building disposition directly impacts temperature levels: in narrow street canyons, the air temperature increase by 2-4°C. In fact, long and narrow street canyons are characterized by poor ventilation (i.e., low wind velocity), which in addition contributes to the accumulation of air pollution. At street intersections, buildings should be receded, and open plazas or green spaces should be created to stimulate the diversion and distribution of wind flows to different directions; hence, avoiding the formation of vortex zones that hamper the dispersion of air pollutants. Nevertheless, these are not very likely to change in a privately owned area of a dense urban space.

Instead, it is more likely to profit from the properties of cool surface materials/typologies within urban areas to greatly contribute to tackling the UHI. For instance, the extensive use of high-albedo or highly reflective materials has been advocated to mitigate the urban heat island, especially in warm-climate cities [10]. These properties determine how the sun's energy is reflected, emitted, and absorbed [1]. By increasing the reflectivity of the building materials, there is a reduction of daytime surface temperature, mainly during the summer season. In fact, it has been proven that under the same peak solar conditions, the surface temperature for a black material is about 50°C higher than the air temperature. In comparison, for a white material, the surface temperature is only 10°C higher [15]. Specific building surface types, such as cool roofs, reduce, in the long-term, the temperature of the urban environment; they are characterized by materials with high albedo coefficient and/or evapotranspiration (e.g., water pond), allowing materials to stay up to 28–33°C cooler than conventional rooftops during peak summer [15]. Also, the high reflectivity of building walls tends to decrease the canopy air temperature [15].

However, some constraints should be considered for the strategies: restricting the maximum pavement albedo to avoid potential glare effects on drivers and pedestrians and increased reflected solar radiation directly towards pedestrians resulting in higher thermal stress (thus, lower outdoor thermal comfort).

On the other hand, it is possible to act on the building envelope by using photocatalytic materials to manage AP. These types of interventions allow air purification by contrasting the concentration of particles through the degradation of nitrogen oxides. But these materials must be constantly maintained to avoid diminishing their air purification capacity due to saturation.

In contrast, green strategies have been documented to contribute significantly to both phenomena, without intrusive interventions on the built fabric and with rather a positive impact on the building performance and pedestrians' comfort [15].

1.2 Strategies targeting UHI and AP with the presence of high and low-level greenery

The use of high and low-level vegetation (e.g., trees and hedges) is also widely recognized, in general, as a promising strategy for mitigating UHI and AP [14]. It can regulate and lower surface and air temperatures through the evapotranspiration process and by providing shading, which directly reduces the building's consumption during the summer season, a higher outdoor thermal sensation, and a lower heat stroke risk [15]. Moreover, the most suitable tree and plant can be chosen according to their size (i.e., canopy dimensions), seasonality (evergreen/seasonal), and pollutant absorption characteristics [17].

It is widely agreed that green areas integrated into the BE can improve air quality conditions by acting as natural filters of air pollutants [18]. Still, within street canyons, high-level vegetation canopies (trees) have led to a deterioration in air quality, while low-level green infrastructure (hedges) improved air quality conditions. The use of shrubs or hedges with heights lower than 2 m should be encouraged to improve roadside air quality, and large, dense trees should be avoided around roads with heavy traffic [9]. The greenery position is also important; roadside trees and hedges reduce the heat perception in highly polluted areas [19].

Also, it has been demonstrated that leaves can deposit and capture particulates on their surface [20], and plants' presence increases the turbulence of the air flows, which favors the dispersion of the pollutants particles [21]. Therefore, green areas are highly recommended near highly trafficked zones or those likely exposed to sensitive demographic groups (e.g., schools and hospitals) [22].

Regarding the materials used in the BE, high albedo, high thermal emissivity, and low heat capacity play a key role in UHI mitigation [11]. For instance, vegetative facades can also reduce up to 7.7°C the surface temperature peaks of the

building facades through evapotranspiration and shading in summer [24] and increase the thermal insulation in winter. The use of green roofs with limited vegetation (e.g., extensive green roofs with sedum herbs) can moderate the effect of the urban heat island, especially during the day, reducing surface temperature up to 5°C [12] and on top city-wide ambient temperature up to 10°C [15]. However, the extent of these MS depends on climate, plants' density foliage, and land coverage intensity.

Nevertheless, UHI should also be tackled at ground level to directly improve the quality of the surroundings for pedestrians. Increasing green areas (intended as heat sinks) can lower air and surface temperatures at the street level during the day. Vegetative facades can be another solution, improving building energy performance while absorbing pollutants. Moreover, when integrated with the built environment, large areas of greenery (e.g., urban forest) help suppress dust particles, improving air quality around buildings and busy highways; and reducing inhabitants' respiratory illness. Green roofs can also be used as effective air pollution abatement measures [25]. However, their ability to remove pollutants is normally lower compared to trees, vegetation barriers, and green walls, given their low surface roughness and distance away from pollutant sources [26]. Nevertheless, green roof technologies require less walkable space than trees and green belts and can be adapted to arrange part of building surfaces and structures such as bridges, flyovers, retaining walls, and noise barriers.

Although direct reductions of traffic emissions have been enforced, passive pollutant control measures are considered suitable for remedy. Areas with limited natural ventilation in the street canyons enhance the accumulation of air pollutants at the footpath level, augmenting exposure for pedestrians. In this context, solid and porous vegetative structures immersed in urban street canyons (e.g., low boundary walls, shrubs, hedges), which affect less wind flow and pollutants dispersion, should be preferred.

Most of the screened literature and previous works on greenery MS have concentrated on analyzing large portions of the urban built environment or open areas, thus, reducing the possibility of extrapolating the analysis to the rest of the urban space or other contexts. Moreover, most strategies have been tested singularly by tackling one aspect only (UHI or AP), without combining different greenery MS, specifically trees combined with green facades. Therefore, this work has concentrated on studying in parallel the UHI and AP effect of singular and combined greenery MS on a basic typological urban unit.

2. Methods

In order to measure the effect of selected MS, different tools have been integrated into a structured workflow because of their capabilities, the required computing time, and the large number of variables to consider. The simulation process has been divided into two steps, and the whole procedure has been summarized in Figure 1. As described in §2.1, the first part comprised a set of parametric simulations with Rhino and Ladybug Tools to construct and analyze different urban unit archetypes considering the surface materials' dimension, orientation, and albedo. This preliminary study led to finding and establishing the most critical and representative archetype configuration, heat-wise, characterized by higher solar exposure and mean radiant temperature; as the tested parameters do not modify the air pollutant distribution, and no wind direction was set at this stage. The second part encompassed a set of simulations for evaluating the effectiveness of the green MS on the defined canyon archetype, all modeled with ENVI-met.

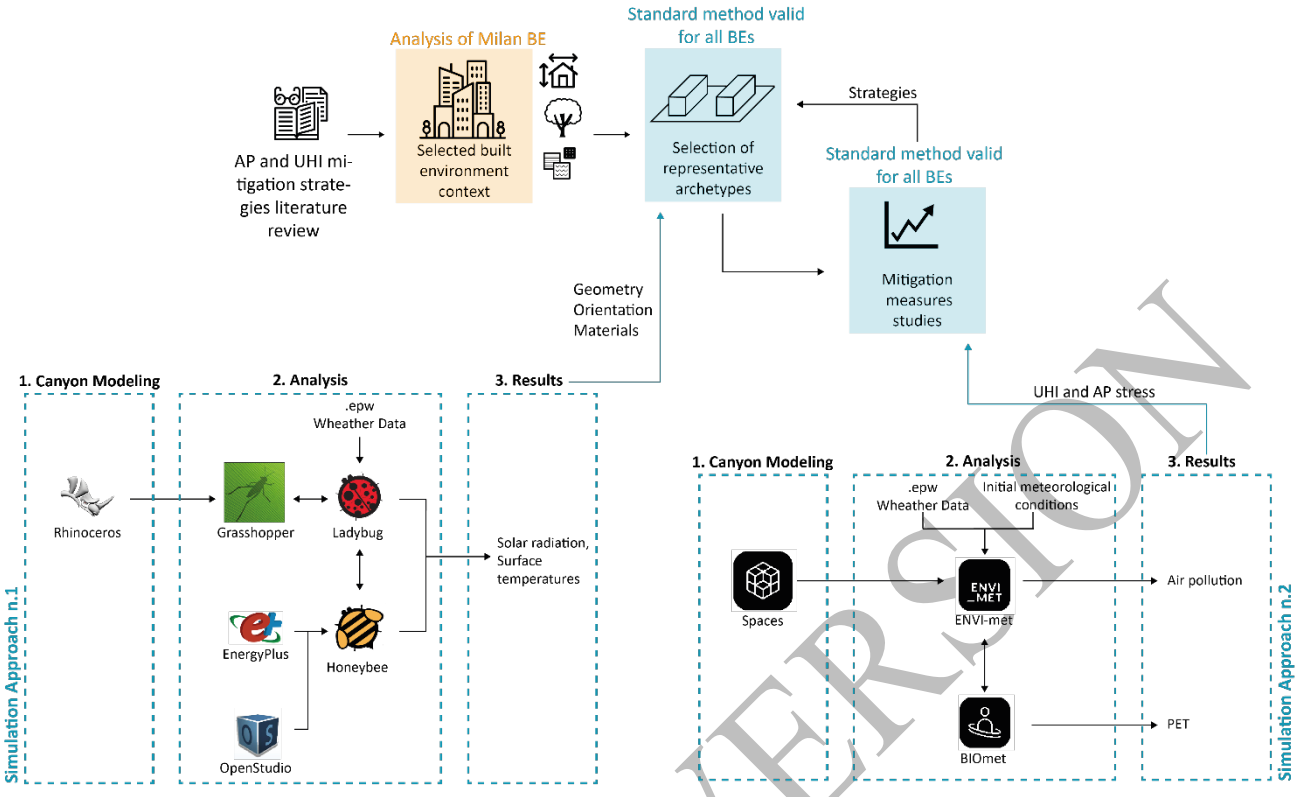

Figure 1. General description of the methodology proposed for detailed UHI and AP analysis within the BE.

2.1 Canyon archetype and site-specific mitigation tests

This step is focused on narrowing the typical geometrical characteristics (i.e., H/W and orientation) and materials (albedo). In this respect, Rhinoceros and Grasshopper have been chosen to test different canyon configurations parametrically. Initially, the 3-dimensional geometry is constructed using Rhinoceros. Then, Grasshopper and Ladybug Tools are exploited to parametrically set the environmental conditions and compute the behavior of solar radiation and surface temperatures. Specifically, Ladybug has been used to perform and visualize detailed climate data analysis for supporting environmentally informed design. It has also been used to import standard EnergyPlus Weather files (.epw) into the Grasshopper environment. Instead, Honeybee (coupled with OpenStudio and EnergyPlus) was used to run and visualize solar radiation distribution simulations, to study surface temperatures of building facades and ground.

All the simulations have been carried out on canyons with buildings with heights equal to 25 m and different road widths (H/W < 0.80). The geometry has been selected as a representative representation of a typical suburban Italian city area characterized by buildings with floors ranging from 5 to 12. In order to avoid having a significant impact on the edge effect, a reduced analysis grid surface has been placed in the center of a 100 m-long canyon to speed up the simulation process and enable the study of all involved variables. The analysis grid is 10 m wide and has a sensor spacing of 2 m, which covers both sides of the canyon's building facades and the road width.

The simulations on the canyons were tested under the Milanese climate context on June 21st, selected as a representative summer day characterized by high solar radiation and elevated air temperatures. Different combinations of H/W ratios, albedo coefficients, and orientations have been tested, providing information on the incoming solar radiation and surface temperatures, useful to determine the most critical canyon configuration to try the MSs later. The relevant radiative properties of surface materials have been selected from the approximate values and ranges presented in BS 8206-2 [27] and by Salleh et al. (2014) [28]. The simulation settings for this preliminary study have been summarized in Table 1. A total of 13 simulations have been conducted and compared. The configuration that can guarantee lower solar exposure and lower surface temperature distribution has been selected for each simulation.

The tests have been planned to select a relevant canyon width before testing the canyon orientation and finishing radiative properties. The selection of the H/W ratio to study in depth is based on the criticality of the conditions found and their representativity. Likewise, the effect of the canyon orientation/azimuth has been evaluated by rotating the canyon 0°, 45°, 60°, 90°, 135° and 150° from the north, and a relevant orientation has been selected to further consolidate a canyon archetype. Finally, different façade finishing surface colors (i.e., white, grey, and black) have been allocated and compared to see their variance and select the most appropriate for the canyon archetype.

Grid properties				
Grid size dimensior	x-nodes	100		
	y-nodes	150		
	z-nodes	50		
Size of grid cell in meter	dx	2 m		
	dy	2 m		
	dz	2 m		
Canyon Geometry				
Canyon length	100 m			
Building width	15 m			
Building height	25 m			
Canyon width	15 m / 20 m / 25 m / 30 m			
Weather data				
Climate file [.epw]	Milan (Linate Airport)			
Analysis period				
Solar radiation analysis	21st June for 24 hours			
Surface temperatures analysis	21st June from h14.00 to h16.00			
Canyon azimuth				
North orientation	0° / 45° / 60° / 90° / 135° / 150°			
Common color associated radiative properties				
Percentage of absorbed solar radiation	White	25 %		
	Grey	50 %		
	Black	90 %		
Surface Material associated properties				
	Asphalt	Ground	Plaster	Walling
Roughness	Elevated	Elevated	Low	Medium
Thickness [m]	0.5	2	0.025	0.13
Conductivity [W/mK]	0.75	0.32 - 4	0.6918	0.89
Density [kg/m³]	2360	2050	1858	1920
Specific Heat [J/kgK	960	800 - 1480	836	790
Thermal absorption coefficient [%]	90	70	50	50

Table 1. Energy model and simulation settings of the selected representative canyon following the described Approach 1 in Figure 1.

2.2 BE mitigation strategies tests

After selecting the typical canyon, the second part of the simulations study was carried out through the ENVI-met environment to analyze the potential effect of different MSs on the chosen geometry.

This software is a validated three-dimensional computational fluid dynamics (CFD) model tailored for parallel simulating urban atmospheric processes, such as pollutant dispersion and microclimate effect. The flow solver of this program is based upon the Reynolds averaged Navier-Stokes (RANS) equations and uses the E-ε model for turbulence effects. This software has been exploited in this work to obtain results on perceived temperatures and air pollution concentration distribution (i.e., PM and NOx).

The geometrical model has been directly constructed on ENVI-met's GUI, and a grid of 100x150x50 cells, each of 2x2x5m, has been set for analysis. Within this area, the identified critical street canyon has been modeled. Buildings have been modeled following the most common construction characteristics of the Italian BE, selecting a moderately insulated wall and roof with a surface material with a medium albedo coefficient (albedo = 0.5). Then, only traffic has been added as a pollution source, which has been modeled as linear along the canyon, considering daily intensity variations. The heat stress is computed as Physiological Equivalent Temperature (PET) [29] for a representative pedestrian based on the representative building occupant described on ISO 8996 [30]. Different strategies are applied

and tested independently once the street canyon has been modeled with its materials and sources. For the MS based on vegetation, one type of tree, hedge, and green wall have been selected with the characteristics summarized in Table 2. Following the approach in §2.1, simulations were carried out on June 21st, but on only the warmest sunlit half of the day, to avoid extensive simulation times and ensure both critical temperatures and pollution are present. The time window has been selected for including the highest solar radiation intensity and the most polluted hours (during the evening). The results obtained from these simulations have been later used to evaluate and compare the effectiveness of strategies to provide guidelines for urban planners, aiming at mitigating the UHI and AP phenomena.

Grid properties			
Model dimensions	x-grids	100	
	y-grids	150	
	z-grids	50	
Size of grid cell in meter	dx	2 m	
	dy	2 m	
	dz	5 m	
Method of vertical grid generation		dz ol lowest gridbox is split into 5 subcells	
Nr. of nesting grids		5	
Geometry			
Canyonlength		100 m	
Building width		15 m	
Building heigh		25 m	
ENVI-met Weather data (initial conditions)			
Wind measured in 10 m height m/s		0.5	
Wind direction		NORTH	
Roughness length at measurement site		0.01	
Min and max temperature of atmosphere		14 – 30 °C	
Min and max relative humidity in 2m		50 - 75 %	
Buildings' materials			
Typology		Default wall – moderate insulation	
Thickness of layers		0.01 plaster - 0.12 insulation- 0.18 concrete	
Possible usage		Wall or roof	
Roughness length		0.02	
Albedo		0.5	
Traffic			
Default height		0.15 m	
Source geometry		Line	
Daily traffic value veh/24h		8000 (Medium/High intensity)	
Number of lanes in the street segment		2	
LDV (light duty vehicles		5%	
HDV (heavy duty vehicles)		2.5%	
MC (motocycles)		0.5%	
Urban bus (public transport)		3%	
Coaches		1%	
Cars		88%	
	Loamy soil	**Asphalt**	**Grey pavement**
z0 roughness length	0.015	0.01	0.01
Albedo	0	0.2	0.5
Emissivity	0.98	0.9	0.9
Background pollutants concentration			
NO		10 µg/m^3	
NO_2		90 µg/m^3	
Ozone		60 µg/m^3	
PM 10		40 µg/m^3	
PM 2.5		30 µg/m^3	

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Trees characteristics	
Typology	Platanus x Acerifolia
Height	15 m
CO_2 fixation type	C3 - Plant
Leaf type	Deciduou Leafs
Foliage shortwave albedo	0.18
Foliage shortwave transmittance	0.3
Leaf weight [g/m^2]	100
Isoprene capacity	12
Green Wall characteristics	
Typology	Green facade + mixed substrate
Wall height	5 m
Plant thickness	0.15 m
Albedo	0.2
Substrate thickness	0.15 m
LAI [m^2/m^2]	1.5
Leaf angle distribution	0.5
Emissivity of substrate	0.95
Water coefficient of substrate for plant	0.5
Air gap between substrate and wall	0.1
Hedge characteristics	
CO_2 fixation type	C3
Leaf type	Deciduous
Albedo	0.2
Transmittance factor of leaf for shortwave radiation	0.3
Plant height	1.5 – 3 m
Root zone Depth	0.5
Lead Area (LAD) Profile	2.5
Root Area (RAD) Profile	0.1
Season Profile	1
Average male human parameters	
Age of person	35
Gender	male
Weight	75 kg
Height	1.75 m
Surface area	1.91 m^2
Static Clothing Insulation (clo	0.9
Total metabolic rate	86.21 W/m^2

Table 2. ENVI-met model and simulation settings, considering materials, geometry, traffic, vegetation, and specific simulation inputs.

Different greenery MS have been foreseen and grouped into 7 types (G1-G7) (Figure 2) which have been applied individually or combined. The results have been compared based on the absolute arithmetic difference of PET, NOx, and PM concentrations between the current state and the cases with greening MS.

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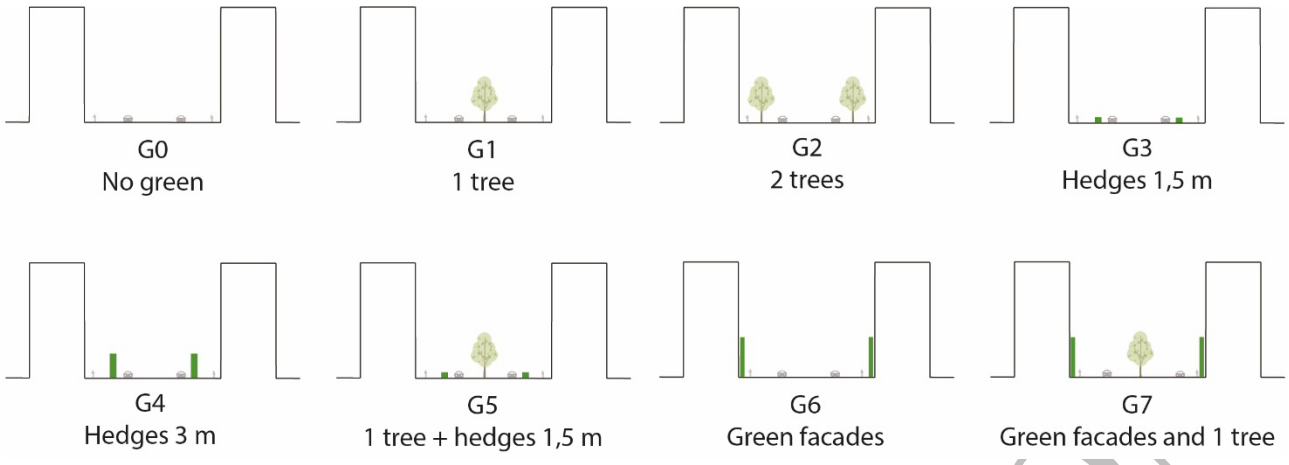


Figure 2 Representation of the seven tested greenery solutions for UHI and AP mitigation strategies.

As discussed in §1, vegetation can improve the UHI and air quality. The selected natural-based MS (Figure 2) comprises the use of single or multiple-row trees, hedges with different heights (1.5 m or 3 m) on the sidewalk, and green facades (5 m height).

3. Results

3.1 Selection and study of representative archetype: simulation results analysis

This section presents the results of simulation approach 1 (Figure 1) for selecting the typical BE archetype. Different H/W, orientations, and albedo coefficients were combined and tested (Table 1); regarding the width of the canyon, different dimensions were considered (while orientation and albedo remain fixed) given the assumption that in dense BE, it is common to have both large avenues and small secondary roads.

Simulations were conducted by analyzing the solar radiation intensity on different canyon configurations at 0º azimuth during the summer solstice's hottest hours (14:00 to 16:00) (June 21st). Figure 3 shows the estimated solar radiation distribution on outdoor surfaces for the different composed canyon geometries. The canyons with aspect ratios H/W = 1 and 0.83 resulted in the highest intensity of solar radiation during the investigated hours (solar horizontal distribution level approximately equal to 3 kWh/m^2). As reported in the following sections, the authors selected the case study with an aspect ratio H/W equal to 1 for the in-deep simulation study. The solar radiation on the vertical surface of the canyon is comparable with the widest configuration showing a similar mirrored shadow trend produced by the building facades. Thus, a geometry with two sidewalks, two carriageways for each direction, and additional space for trees in the center and/or on the sides has been chosen, considering that it is representative of most of the BE.

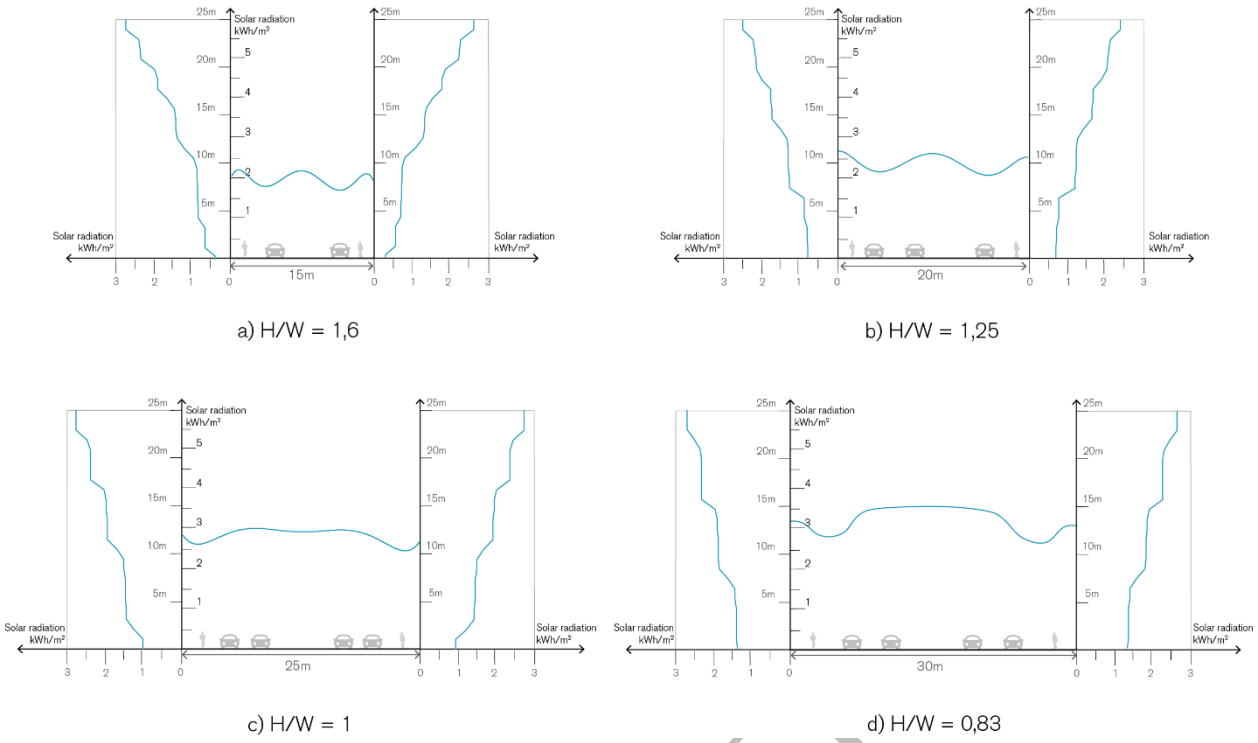


Figure 3. Solar radiation analysis on June 21st for different H/W urban canyons oriented at 0°.

Different canyon orientations have also been analyzed since the city's streets do not always follow a defined and regular orthogonal grid. From north, 0°, 45°, 60°, 90°, 135° and 150° have been tested as relevant street directions.

As shown in Figure 4, the incident solar radiation changes significantly for a canyon with the same geometry and different orientations. In a canyon-oriented north/south (Figure 4 a), the curves are symmetrical, indicating that, during the sun hours, both sides of the canyon are exposed equally. Rotating the geometry, as expected, one side of the canyon is more directly exposed to the sun with respect to the opposite side. Moving to East/West, the solar radiation becomes irregular, with the exposed side having 45% more solar radiation and the other side 66% less than the North/South orientation. The canyon rotated by 45° to the east (Figure 4 b) has been selected as a relevant archetype because it shows a good compromise among the different configurations with a reduced solar exposure mismatch (25%) between the different canyon sides.

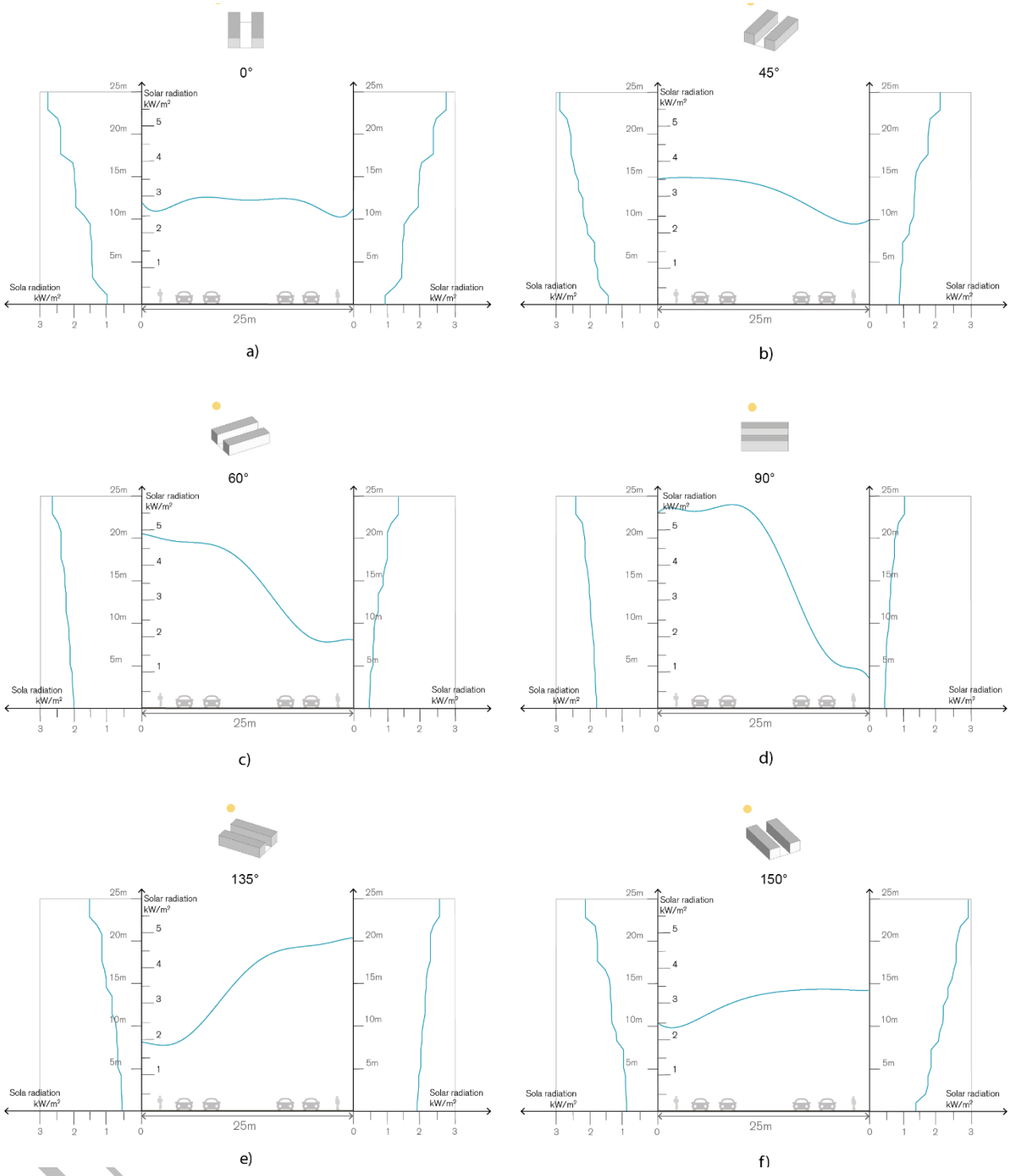
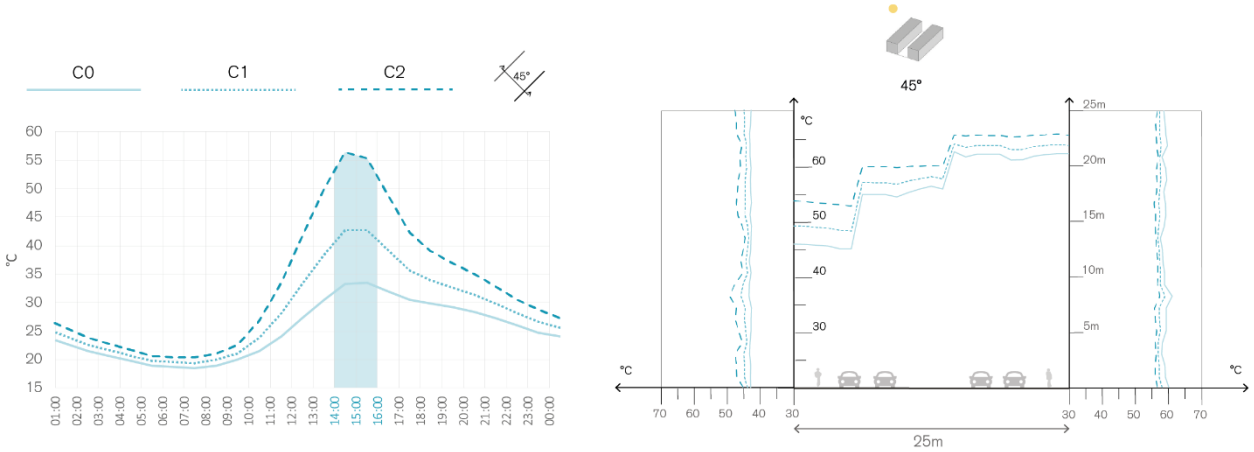


Figure 4. Solar radiation analysis (June 21st) for different orientations a) 0°; b) 45°; c) 60°; d) 90°; e) 135°; f) 150°.

After setting the geometry and orientation of the canyon, three different finishing colors, resulting in different albedo coefficients, have been analyzed: C0 - white (ε = 0.8, ρ= 0.85), C1- Grey (ε = 0.55, ρ = 0.94) and C2 - Black (ε = 0.2, ρ = 0.96). These represent the extremes and a balance option in terms of reflectivity and emissivity of the surfaces. The results have been summarized in Figure 5.

The simulations have been carried out from 13:00 to 20:00 on June 21st concerning the impact of the surface materials on temperatures level. Figure 5 b) shows the temperature level for all three selected façade colors applied to the canyon archetype. As expected, the maximum surface temperature on the façade is highly correlated to the albedo coefficient and to direct sun exposure. The higher surface temperature is reached by the C2 configuration, characterized

by high emissivity (ε = 0.96) and low reflectivity (ρ = 0.2). In fact, as presented in Figure 5, black materials (lower albedo coefficient) reach a surface temperature of around 55 °C while materials with high albedo (i.e., white color) show temperature levels 15-20 °C lower.



a) b)

Figure 5. Color effect on temperature comparison for the 45° orientation on June 21st. a) Average surface temperatures daily trend. b) Surface temperatures inside the canyon (June 21st) for different materials

Although the black material is the most critical, and such facades should be intervened promptly (unless mostly shaded), grey was chosen for the canyon archetype since it is more representative of streets and buildings. In conclusion, the canyon archetype selected for the green infrastructure mitigation potential analysis is characterized by a H/W equal to 1, orientation 45° to the east, and a general albedo coefficient of the surfaces equal to 0.5.

3.2 UHI and AP mitigation measures impact analysis

All the measures have been simulated during the summer solstice for the time period between 1:00 pm to 8:00 pm; to ensure model convergence before 2:00 pm (Most critical PET condition - Figure 5 a). However, the simulation results have been displayed considering the values calculated at 2:00 pm, representing the most critical time period for both temperatures and traffic pollution. In addition, at 2:00 pm, no shadows generated by the buildings could influence the perceived temperature values.

3.2.1 UHI impact analysis

To study UHI, Figure 6 reports the perceived temperatures measured in PET for a middle cross-section of the constructed archetype canyon, where different strategies have already been applied (G0-G7).

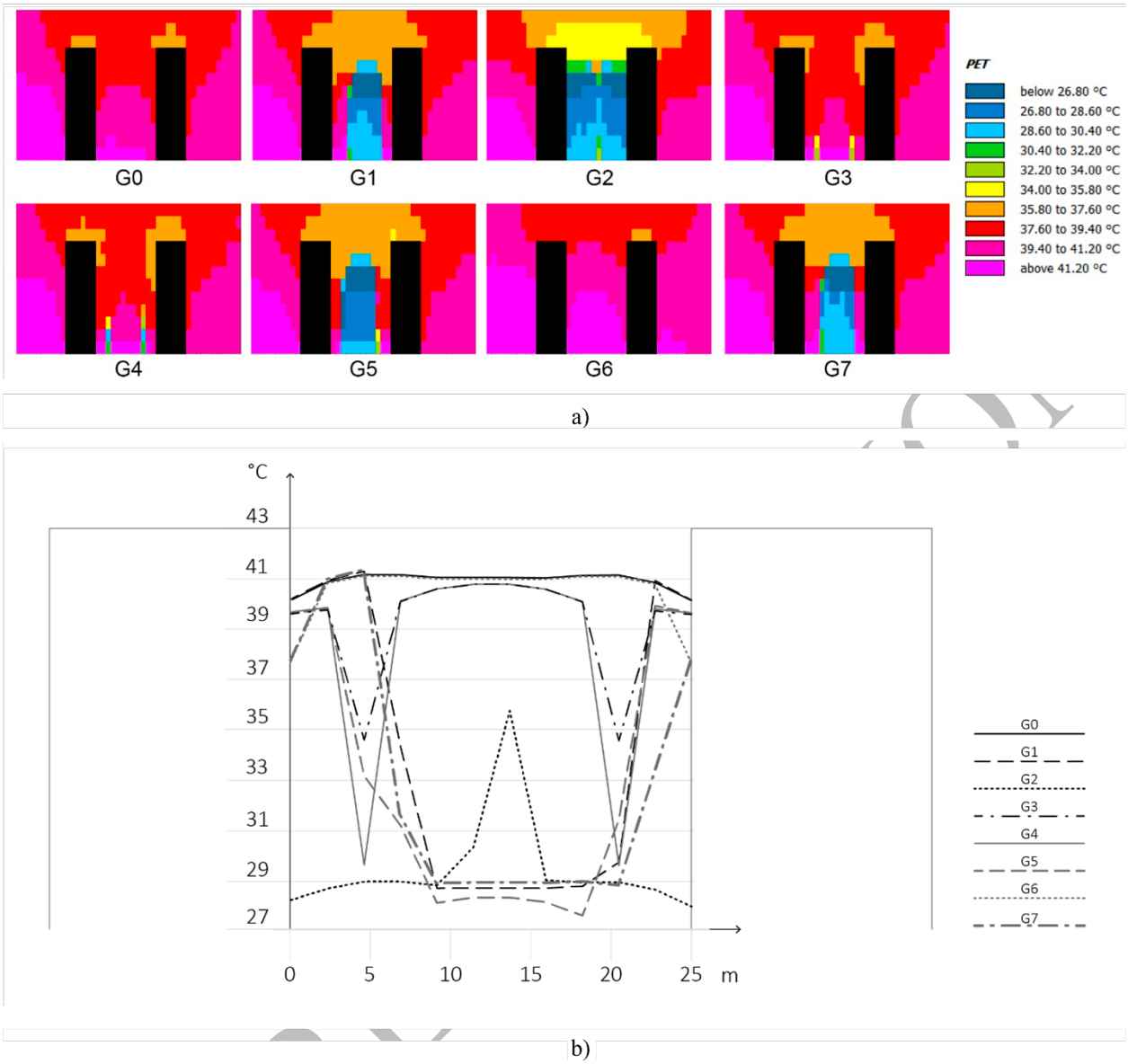


Figure 6. Simulation results of PET for all strategies inside the representative H/W=1 canyon at 2:00 pm on June 21st. a) Heat maps. b) Horizontal temperature at 1.5m height.

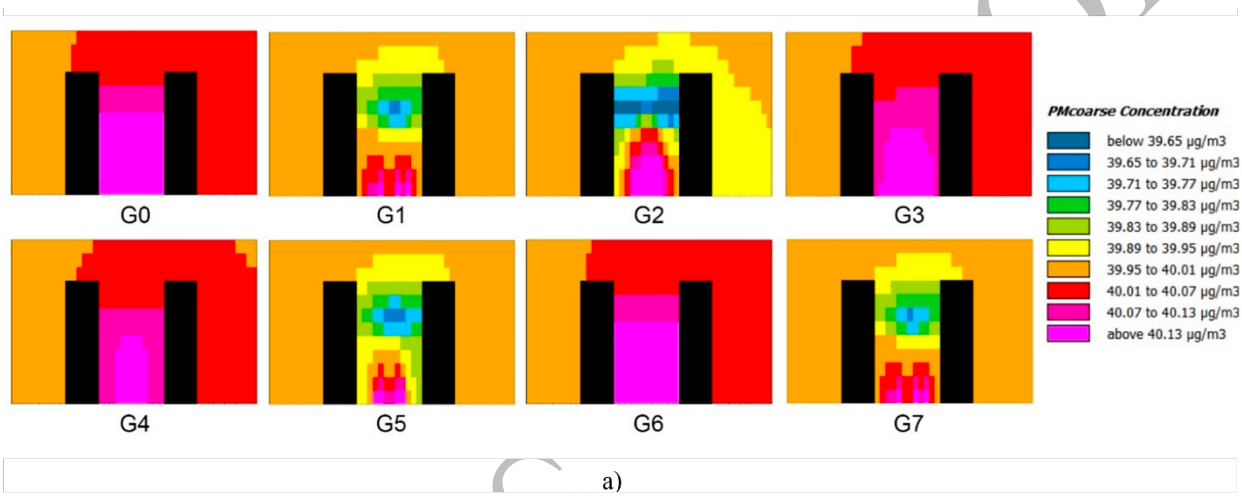
The perceived air temperature trend at a height of 1.5 m along the canyon section has been presented in Figure 6 b). The G0 configuration represents the base case where no vegetation is present in the canyon, used as a reference for comparing the different scenarios. In that case, the temperature level is homogenously high, with PET values close to 41 °C. The MS certainly led to different results; some have a clearly localized impact (e.g., G3 and G4) compared to others (G2, G5, G7). In fact, registered temperatures may vary from 27°C to 41 °C. For instance, looking at the values reported across the canyon section base, the results obtained for G1 simulation have a completely different trend compared to G0: on the edge of the street, temperatures are still around 40-41°C, but in the center, under the area of influence of the tree canopy, temperatures drop by more than 10°C potentially increasing the comfort level. Increasing the number of tree lanes and locating them closer to the canyon sidewalks (G2), the simulation results show a temperature level trend characterized by an extended lower and homogenous temperature area in proximity of the trees (28-29°C) with a punctual peak in the unshaded street center (35.7°C), evidently out of the area of influence of the trees. The temperature trends are different for the cases where the greenery is represented by hedges (1.5 m high for case G3 and 3m high for G4), having a very localized PET drop on the exact location where the hedges were placed. Probably given the low shading that these provide. The results show that in the area where hedges were applied, temperatures drop by 5°C for G3 and 10°C for G4 cases. The combined use of trees and hedges was studied in case G5. Such presence of multiple greenery leads to lower perceived temperatures with a minimum of 27.6°C found in the middle of the street, with a similar trend as G1, confirming a low spatial contribution of hedges against UHI. G6 and G7 cases combined the presence of 5 m high green walls, respectively, with and without a central row of trees. In general, as shown by the simulation results, the green wall (G6)

decreases the perceived temperature level on the sides of the canyon. In the G7 case, temperatures are lower than G6 due to the presence of tree canopy that contributes to diminishing temperatures also in the central part of the canyon, thus confirming the considerable effect of high-level greenery MS, the low effect of low-level greenery MS and suggesting a negligible impact of green facades for pedestrians regarding UHI.

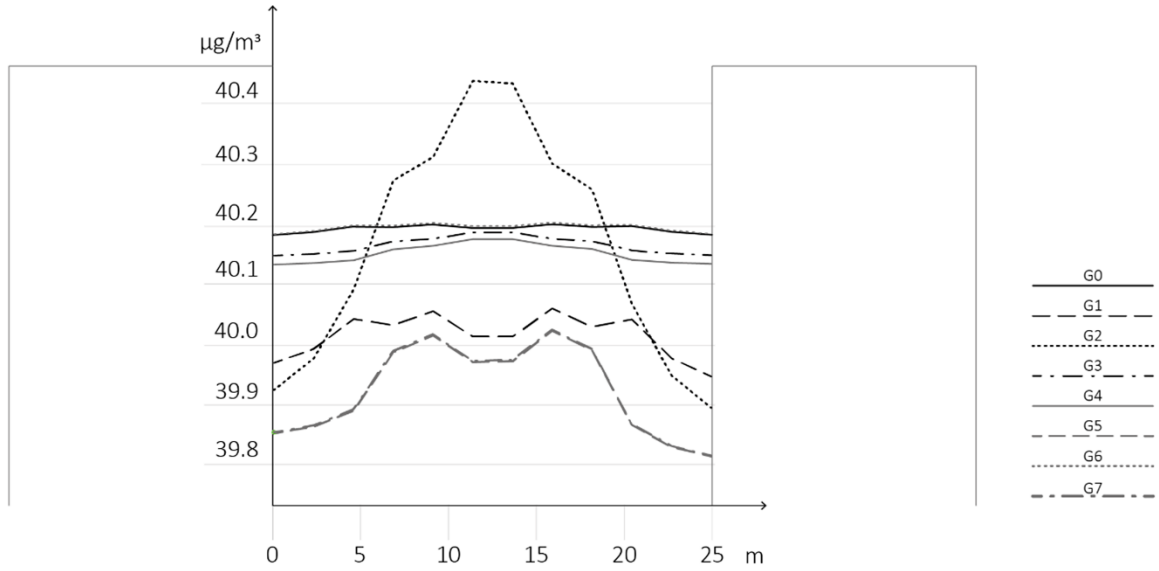
3.2.2 Air pollution impact analysis

The same mitigation measures applied for lowering the UHI (G0-G7) are tested in terms of PM and NOx concentration. Both are screened given their high impact on human health, which can result in respiratory disease and/or cardio-circulatory system affections.

Figure 7 resumes the simulated PM concentrations in a middle section of the canyon. Such distribution follows the evidenced vortex generated by the north wind on an urban canyon with a 45° orientation, in which the pollutants dispersion is minimum in the middle upper part, where the primary vortex surges, and the leeward side. It is noteworthy to mention the small variations within the canyon, with an approximate amplitude of 0.48 µg/m3.



a)



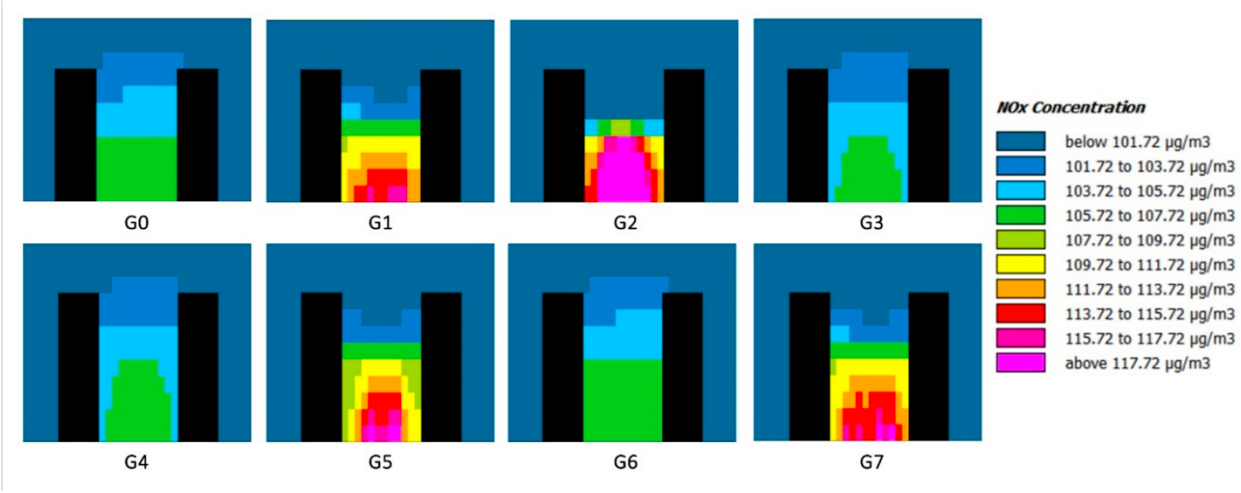
b)

Figure 7. Simulation results of PM coarse concentration for all strategies inside the representative H/W=1 canyon at 2:00 pm on June 21st. a) Heat maps. b) Horizontal temperature at 1.5m height.

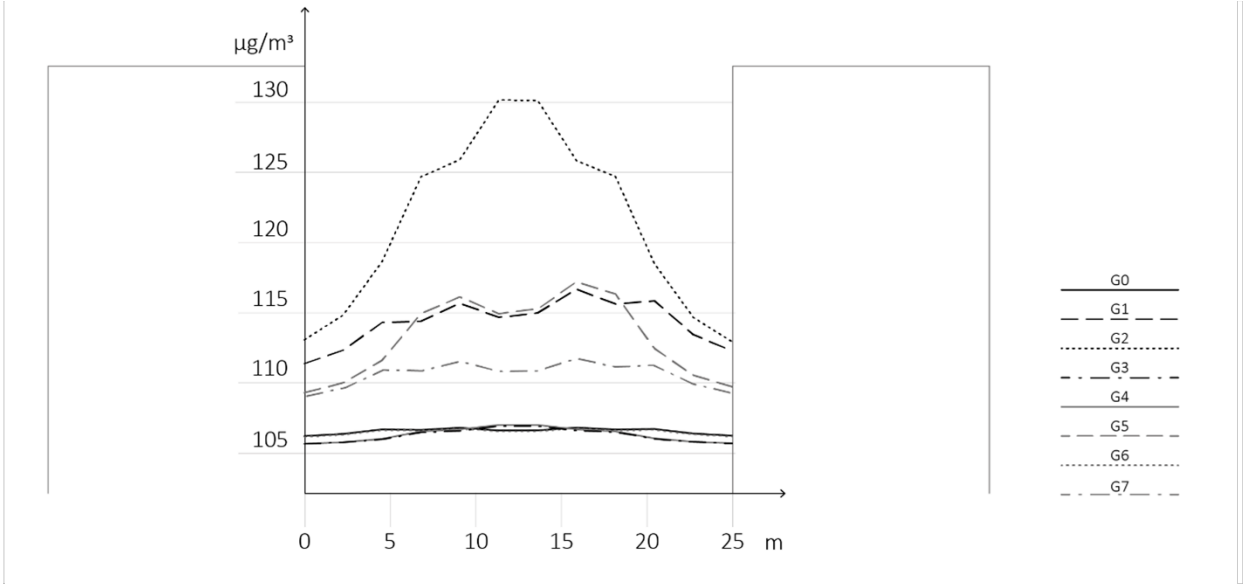
As expected, different greenery configurations led to different PM concentration trends. The base case (G0) shows little variance in PM concentration in the contained air volume with values around 40.20 µg/m3. The configuration with one tree inside the street (G1) shows a moderate reduction of the PM concentrations throughout the section (vertical and

horizontal), with the minimum horizontal values on the street sides equal to 39.95 µg/m3, while the lowest values present right above the tree canopy 39.65 µg/m3. In the configuration with two tree lanes (G2), the increased canopy density seems to reduce the PM dispersion in the atmosphere under the tree canopy height while reducing PM concentrations above it. The curve of MS G3 and G4 results show mutual similarity with the slightly reduced PM concentration on the sides of the street, indicating that the hedges might act as barriers insufficiently protecting sidewalks from the more polluted road. Nevertheless, the protection against road pollution is higher proportionally to the height of the greenery. Case G5, representing the combined use of trees and hedges, shows the lowest pollutant concentration at the canyon's sidewalks with levels between 39.8 and 40,0 µg/m^3, which could be attributed to the air pollutant entrapment at street level, generated by the low-level greenery acting as vertical barriers and the high-level greenery canopy acting as a horizontal obstruction. For case G6 (green walls only), the PM concentration is similar to G0 because the PM moves within the canyon before being deposited by the green wall. The case in which the green walls are applied together with one row of trees (G7) shows a PM reduction similar to the G1 (single tree lane) and G5 configuration (hedges plus trees) where even though there is a single row of trees, the correct ventilation of the canyon is not obstructed, and green barriers absorb the pollutants underneath canopies. Therefore, it is possible to deduct that there is also a considerable effect of high-level greenery MS, a localized and low effect of low-level greenery MS, and a negligible impact of green facades for pedestrians regarding AP. Although, the integration of different types of vegetation (high and low-level greenery MS – Trees plus hedges (G5)) is welcome and helps further increase the PM reduction for a more livable built environment for pedestrians.

Figure 8 resumes the simulated NOx concentrations in a middle section of the canyon. Besides a significant variation amplitude of approximately 16 µg/m3, the resulting air pollutant concentration follows the PM distribution trend.



a)



b)

Figure 8. Simulation results of NOx concentration for all strategies inside the representative H/W=1 canyon at 2:00 pm on June 21st. a) Heat maps. b) Horizontal temperature at 1.5m height.

As experienced for PM coarse concentrations, not all greenery solutions act similarly. Compared to PM concentration, the scale of NOx concentrations is larger because traffic is more strongly linked with NOx emissions than PM.

All MS involving trees (G1, G2, G5, and G7) generally reach higher NOx concentrations. This is probably due to the presence of tree canopies that can obstruct the wind flow and thus the natural dissipation of the air pollutants emitted by traffic, resulting in air stagnation, hence the higher concentration of pollutants below naturally generated canopies. Meanwhile, G3 and G4 (low-level greenery MS) performed best, creating a barrier from traffic on the street towards the pedestrians on the sidewalks. Green facades (G6) showed no noticeable difference from the baseline scenario. This can be attributed to their low effect of them on wind flow dynamics and the low air pollutant deposition capacity of the selected species. Considering NOx only, high-level greenery MS has a rather detrimental effect than low-level greenery MS.

Aggregating PM and NOx results, the implementation of hedges will efficiently protect users on sidewalks from traffic emissions. At the same time, trees with low foliage density could also be used to guarantee correct canyon ventilation, facilitating NOx dispersion and PM protection.

4. Conclusions

The present study has been carried out to identify and quantify the potential UHI and AP mitigating effects of typical greenery solutions applicable in urban canyons of dense BE. Through computer-aided simulation, the proposed method has been proven useful and verified that natural-based solutions (i.e., vegetation) could positively impact both perceived temperatures and air pollution concentration, but not in all cases as it is commonly expected. Some measures positively impact mitigating the effect of both UHI and AP, while others mitigate only one of them. Therefore, because results depend on many factors, interventions in the built environment shall be studied and tailored for the specific case, and it is impossible to establish a unique optimal strategy for all cities and critical areas. Hence, identifying, utilizing, and investigating a canyon archetype allows for standardizing the process and predicting the potential effects of vegetation that must be considered progressively more in the urban design process. Despite there might be levels of uncertainty in this analysis due to the considered scale, the results partially confirmed what has been stated in the literature. In general, from the results of the H/W=1 urban canyon, the following considerations can be made:

- The use of trees is a promising option to tackle the UHI effect. The canopies can decrease the PET by 9-15°C and benefit users' well-being.
- Green walls have, in general, a lower impact on PET reduction. The low albedo of the foliage can sometimes increase the outdoor temperature level.
- The tree canopy can reduce airflow into the canyon, reducing pollutants dispersion. Proper tree distribution and foliage density must be carefully considered.
- Considering NOx, the integration of hedges represents a good strategy for containing traffic pollution in the road section. From the perceived temperature point of view, the hedges are locally useful if they are sufficiently high. A 3m hedge, with its shade, can diminish PET up to 6°C. However, a high hedge is a visible obstacle inside the canyon that might not be visually appealing.
- Trees and hedges were proven to be valid options when dealing with UHI and AP.

Nevertheless, the results hereby presented are incomplete and could differ; thus, more research is foreseen to complement them. For instance, the analysis was mainly performed on a single day with the highest solar angle, but it might not be the hottest day. Also, the analysis carried out considering the contribution of wind was limited as a single wind speed and direction was set.

5. Author Contributions

Conceptualization of the research, G.S. and E.Q.; conceptualization of the paper, G.S, J.D.B.C, and M.C.; methodology, G.S, J.D.B.C, and M.C.; investigation, G.S. J.D.B.C.; data curation, M.C. and G.S.; writing - review and editing, G.S, J.D.B.C, M.C., and E.Q.; data visualization M.C.; supervision, G.S.; project administration, G.S., and E.Q.; funding acquisition, G.S., and E.Q. All authors have read and agreed to the published version of the manuscript.

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