

Outdoor thermal comfort by different heat mitigation strategies- A review

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Abstract

Due to the ongoing global warming, heat mitigation strategies are becoming implemented through practice and simulations. These efforts aim to make the cities that are dealing with the urban heat island more livable. The effect of heat mitigation strategies on climate condition and energy consumption have been studied and compared, previously. In this paper, the effect of these strategies on human thermal comfort in urban open spaces is reviewed. Specifically, the review is focused on vegetation (in the form of parks, street trees, green roofs and green walls), and highly reflective materials (on roof and on the ground level) as the most common strategies for improving the thermal conditions in cities. Several studies done by simulation or through field measurement in different countries are described. The most important finding of the review is the fact that although highly reflective materials reduce air temperature in urban open spaces, they increase the re-radiation of sun to the pedestrians. Therefore, vegetation is a better choice for improving thermal comfort in the pedestrian level.

Keywords

Outdoor thermal comfort; vegetation; highly reflective surfaces; urban heat island

1. Introduction

The air temperature in most of the cities are significantly higher than their rural areas. This phenomena which is called urban heat island (UHI) causes negative issues for urban settlers. UHI was first identified by Luck Howard, a meteorologist who measured the weather in London area for forty years (1801-1841) [1]. The UHI happens throughout the year, but it is stronger during the night when heat is absorbed by the urban surfaces with high heat capacity materials (e.g. asphalt and concrete). Apart the heat capacity of man-made materials, urban canyons reduce natural ventilation and therefore heat traps in cities. The intensity of the UHI is also related to the size and population of the city [2-5]. Oke [2] showed that UHI is approximately proportional to the fourth root of the population. This shows with the increase of urban settlers, more people are in prone to UHI. Since 2008, more than half of the world's population live in cities [6]. But, what are the consequences of UHI for citizens?

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Higher air temperature has direct and indirect effects. The most direct effect of UHI is lower thermal comfort of people in urban spaces, where there is no access to air conditioning systems [7-11]. UHI indirectly increases energy consumption for cooling [12, 13], reduces the air quality in cities [14-18], and threatens the ecosystem by warmer water flowing from the cities [19, 20].

As heat waves are the first natural cause of mortality [5, 21-25], this research focuses on the impact of UHI on thermal comfort of people in urban open spaces. During a two week heat wave in August 2003, 70,000 people passed away [22]. Heat related mortality occurs when human body absorbs more heat than it dissipates. This is more serious for elderly and people with cardio-vascular problems who have weaker thermoregulatory body system [25]. Several studies have shown strong correlations between heat waves and excess mortality [21, 23, 26]. In this way, making cities cooler seems vital for public health.

Thermal comfort is associated with environmental (air temperature, radiant temperature, wind speed, and relative humidity) and personal (clothing and metabolism) factors [7, 27-30]. Several studies have shown that radiation plays the greatest role on thermal comfort [28, 31-34]. In [35-40], the impact of urban morphology and different heat mitigation strategies on urban climate have been reviewed. Due to the significant role of radiation on thermal comfort, in this paper we focus on the heat mitigation strategies that reduce net radiation in urban spaces. Equation 1 describes the variables affecting net radiation [41]:

$$R_n = H + LE + G \quad (1)$$

where R_n is net radiation, H is sensible heat flux, LE is latent heat flux, and G is soil heat flux (all variables are in W/m^2).

Several heat mitigation strategies have been implemented in different cities to reduce net radiation. Theoretically, the lower net radiation, the lower heat in cities. Based on this principal vegetation and reflective materials are widely used as passive methods to mitigate heat in urban spaces. Here we review these strategies extensively. Therefore, the paper will focus on the most recent studies that have successfully implemented heat mitigation strategies in the world. Specifically, vegetation and high albedo materials will be studied in different form of application. The reviewed studies have used different methods (i.e. simulation and measurements).

2. Heat mitigation strategies

2.1. Vegetation in different forms

Vegetation reduces heat in three ways:

- a) by evapotranspiration,
- b) by reflecting the sun because of the higher albedo of the leaves compared to man-made dark materials;
- c) by blocking the solar radiation.

Vegetation has been used in various ways in cities. From a large to local scale, we can see vegetation in cities as parks, street trees, grass yards, and green roofs.

2.1.1. Parks

Parks probably have the biggest cooling effect for citizens. Hwang et al. [42] in a study on 10 parks in the tropical climate of Singapore showed that the air temperature in parks could be 8 to 12 °C cooler than outside. They showed the parks with more shading are more thermally comfortable. This finding becomes more important when we consider that the minimum temperature in Singapore is 23 °C [43].

Looking at the hot and dry climate, parks seem very vital for public health. Feysia et al. [44] by measuring air temperature and humidity in 21 parks in Addis Ababa showed that plant types, NDVI (Normalized Difference Vegetation Index), and shape and size of the parks have appreciable correlations with the cooling effect. The maximum park cooling effect (PCI) they found was 6.72 °C. Moreover, they measured the maximum spatial park cooling distance (PCD), which was 240m. This means the cooling effect of a park could be felt up to 240m far from the park. By comparing different plants (i.e. *Acacia tortilis*, *Eucalyptus* spp., *Grevillea robusta*, *Cupressus lusitanica* and *Olea*), they showed *Eucalyptus* spp has the most cooling effect; while *Grevillea* and *Cupressus* have the minimum effect.

Spronken and Oke [45] studied the PCI in two cities with different climates, Vancouver (BC) and Sacramento (CA). They showed the maximum cooling effect in Vancouver was 5 °C; while irrigation of the park in Sacramento (with a hotter climate) makes the PCI up to 7 °C. They found out the trees are the most important element for the cooling effect of the parks during the day. This was due to the shading and evapotranspiration effect of the trees. During the night, the amount of moisture and surface geometry of the parks were the most important causes of PCI.

Vidrih and Medved [46] considered the effect of leaf area index (LAI) on the cooling effect of parks in Slovenia. By using a 3D CFD model, they showed that with the LAI of 3.16 (equal to 45 trees per hectare), air temperature reduction is up to 4.8 °C. In a more comprehensive and empirical study done by Hardwick et al. [47], the effect of different levels of LAI on different micrometeorological variables were studied in Malaysia. They found a strong correlation between LAI and the mean daily maximum air and soil temperatures. They also showed a higher cooling effect associated with higher relative humidity under vegetation canopies with higher LAI. They also showed a canopy with 33.7m height is 6.5 °C cooler than oil palm plantations with 5.3m height. Figure 1 shows the surface temperature of the park of the campus of Portland State University compared to the buildings.

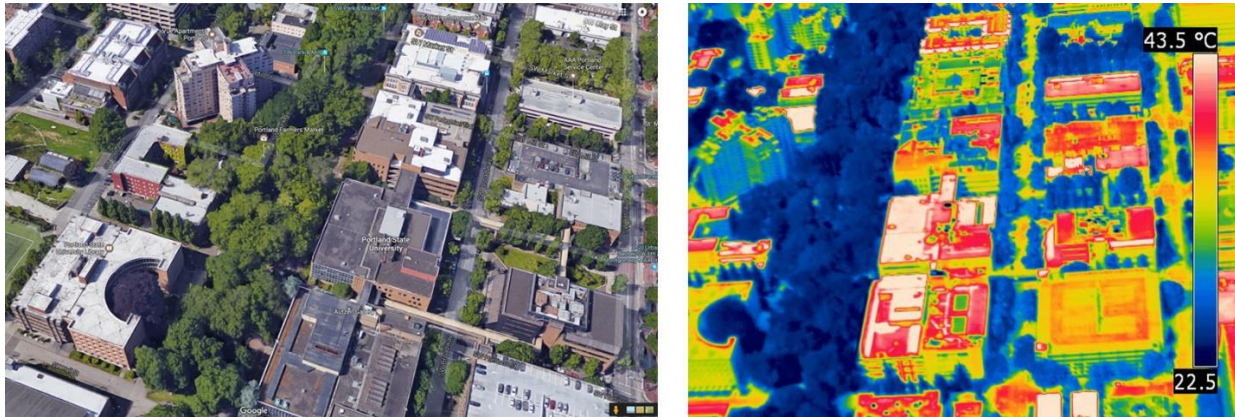


Figure 1: The surface temperature of a park compared to the surrounding buildings. Portland State University, OR, USA. 23 August 2011. Image after [48]. Thermal image is from the archive of David J. Sailor.

2.1.2. Street trees

Street trees have several environmental benefits for urban citizens. Because of our focus on thermal condition and comfort in urban open spaces, we review the most important investigations on thermal comfort. Coutts et al. [49] measured three east-west streets during heat waves in the temperature climate of Melbourne, Australia. They considered the Universal Thermal Climate Index (UTCI) for the calculation of outdoor thermal comfort within the tree canopies. The maximum UTCI reduction by the trees were 6 °C. Moreover, they reported that the maximum air temperature reduction was 1.5 °C. A similar research done in Melbourne showed that *Platanus* trees led to a PET reduction of 6.6°C during a heat wave.

Regarding the cooling effect of different tree species, Doick and Hutchings [50] discuss that the lower the foliage temperature, the greater cooling effect. Monteith and Unsworth [51] argue that the leaf temperature depends on anatomical (e.g. LAI and size) and physiological (e.g. transpiration and stomatal conductance) factors. In this way, the water status (i.e. irrigation) will have a significant effect on the ability of a tree to evaporate water through the stomata of its leaves [52].

Another advantage of street trees is their impact on their adjacent. Mayer et. al [53] showed that trees reduce mean radiant temperature (T_{mrt}) even for the buildings that are not shaded by the trees. In the city of Freiburg (Germany), they showed that trees reduce T_{mrt} up to 29% at the not directly shaded site. This amount of radiation reduction is very important for the improvement of pedestrian's thermal comfort. This is mainly due to the dependency of thermal comfort on T_{mrt} [28, 32]. This reduction of radiation can improve the thermal comfort of people inside the adjacent buildings. For instance, Heisler [54] showed that a sugar maple tree reduced irradiance by its shading effect up to 80% in summer (when in leaf) and 40% in winter (leafless).

2.1.3. Green roofs

Santamouris [55] reviewed the impact of green roofs on UHI. By comparing different simulation studies, he found out that green roofs can reduce the average air temperature between 0.3 and 3.0 K when applied on urban scale. Depending on the adoption scale, the cooling effect varies. Smith and Roebber [56] studied the adoption of green roofs during a typical summer day in Chicago, Illinois. They used the Weather Research and Forecasting Model (ARW) [57] coupled with an urban canopy model. In accordance with [55], they showed that the air temperature during 19:00–23:00 is reduced up to 2-3 °C because of the higher albedo of the vegetative roofs, and the evapotranspiration effect. Figure 2 shows a green roof with its layers.



Figure 2: A green roof with different layers at Delft University of Technology, Delft, the Netherlands.

Sun et al. [58] investigated the temperature reduction over a roof (2.5 m) in Taipei. They showed the cooling effect of the green roof was more significant during day time. Comparing the green roof with a similar black roof, the green roof reduced the ambient air temperature 0.26 °C in average. The maximum cooling effect was reported 1.6 °C.

Chen et al. [59] performed simulations on the impact of high rise buildings green roofs on the pedestrian height (1.5m) thermal condition in Tokyo, Japan. For the simulations, they used coupled simulations of convection, radiation, and conduction [60]. They showed that the cooling effect of green roofs on pedestrians are negligible due to the height of the building roofs. Likewise, Taleghani et al. [61] studied the effect of different heat mitigation strategies on pedestrians' comfort in a Los Angeles neighborhood during a heat wave. They showed that the green roofs at the height 6m (two-story dwellings) did not improve street level thermal comfort. The simulated neighborhood area was 0.3 km². Comparing this area with the study on Chicago [56] (606 km²), it could be said that the size of the modification significantly affects heat mitigation.

2.1.4. Green walls

Vegetation is also used on facades, as green walls. This class of heat mitigation strategy affects building indoor environment and outdoor. Bartfelder and Köhler [62] measured the air temperature in front of a bare and a green wall in Berlin (Germany). They showed that the cooling impact of the green wall depends on the outdoor temperature. They observed that the cooling effect of the green wall was 0.4 °C and 5.8 °C during the cool and hot days, respectively.

Wong et al. [63] investigated the surface temperature of eight different green wall systems. They showed that the average surface temperature of green walls were 4.36 °C cooler than bare walls on 21st of June in Singapore. They also measured the ambient temperature in front of the walls. They observed temperature reductions up to 3.33 °C (0.15 m away) and hardly any effect was felt at the distance of 0.60 m.

In [48], the microclimate of two courtyards were measured during summer 2013. The walls of one courtyard was covered with red bricks, and the other with vegetation (Fig 3). They measured air temperature at the center of the courtyards for one week. They observed that the courtyard with green walls was up to 4.7 °C cooler than the bare one (at 16:30 PM).

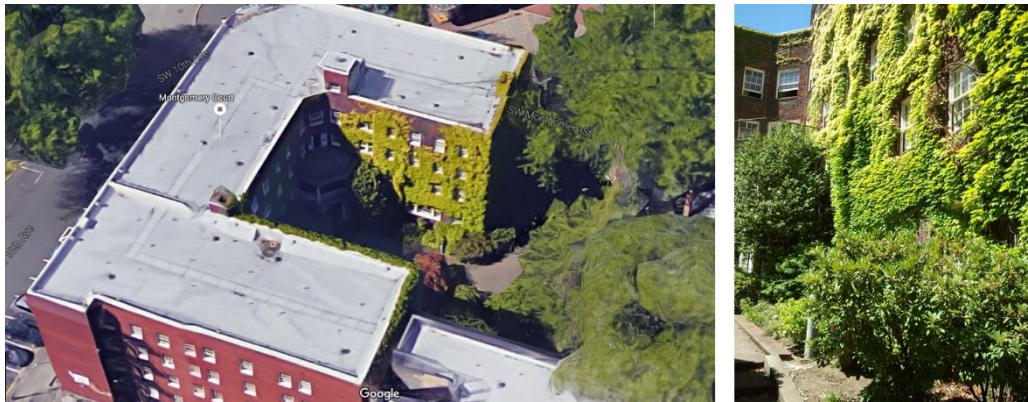


Figure 3: A courtyard building with green walls, at the campus of Portland State University (Portland, OR, USA).

2.2. High albedo materials

2.2.1. White (reflective) roofs

Reflective and white roofs have several benefits for the urban in indoor building thermal condition. Several studies have shown the impact of white roofs on indoor cooling energy saving in summer time [13, 16, 64, 65]. Others showed reduced thermal stress (and consequently higher lifetime) of cool roofs compared to the other roof types [66-69]. Furthermore, white roofs improve indoor thermal comfort for the occupants [70, 71]. Nevertheless, we will focus on the impact of white and reflective roofs on microclimate and outdoor thermal comfort.

White roofs reflect most of the short wave radiation from the sun to the sky. This leads to lower absorption of heat by the roof. During the summer time, roofs receive the largest portion of solar radiation (due to the high altitude of the sun) [72]. The percentage of re-radiating the sun depends on the albedo of the roof surface. Table 1 demonstrates the albedo of highly reflective roof materials.

Table 1: Radiative properties of high albedo materials (Table after [73-75]).

Surface material	Albedo (α)	Emissivity (ϵ)
White paper	0.75	0.95
Plaster (fresh)	0.93	0.91
Bright aluminum foil	0.85	0.04
Green pigment	0.73	0.95
Gravel	0.72	0.28

Almeria (Spain) is one of the best examples of implementing white roofs (26,000 ha). The average ambient air temperature in this city is reported 0.3 °C cooler than its rural area [76]. Figure 4 shows an aerial view of the city with its white surfaces.

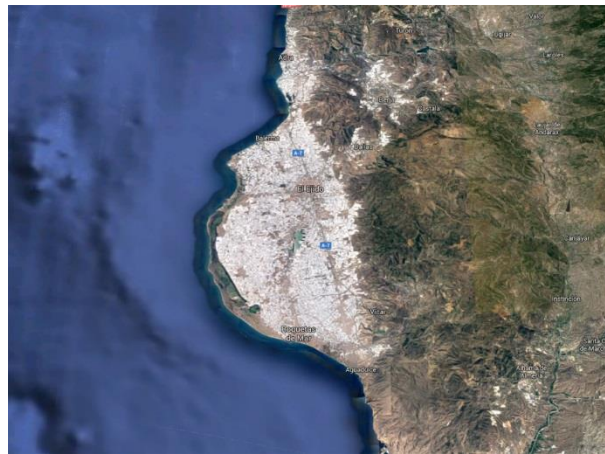


Figure 4: Almeria (Spain) with white surfaces [77].

Rosenfeld et al. [78] simulated 100,000 km² in Los Angeles to adopt cool roofs (albedo improvement from 0.25 to 0.75 for the flat roofs, and from 0.25 to 0.60 for sloped roofs). The maximum cooling effect was reported 3.0 °C at 15:00. It was also found out that the peak ambient air temperatures were reduced 2 to 4 °C.

Regarding the impact of cool roofs on microclimate, Doulos et al. [79] compared 93 pavement materials in Athens (Greece) during August 2001. They used thermal photography technic to observe the surface temperature differences. They showed the surface temperature of a white marble pavement could be up to 19 °C cooler than black granite. This cooling effect can significantly affect the local microclimate.

Taleghani et al [48] measured the mean radiant temperature and air temperature above two different roof surfaces. The measurement campaigns were done at the campus of Portland State University (OR, USA) during summer 2013. They compared a black roof (albedo 0.37) with a white roof (albedo 0.91). It was found that the white roof led to 2.9 °C higher T_{mrt} above the surface, but reduced 1.3 °C T_a . While the roof is not a commonly used area, it should be noted that this increase of T_{mrt} by the high albedo surface can cause thermal discomfort above the roof.

2.2.2. Reflective ground pavements

A large portion of urban surfaces is covered by low albedo pavements [78, 80]. In [61], T_{mrt} and T_a at 1.5m height were simulated in a residential neighborhood during summer 2014. It was shown that the temperatures above the asphalt pavement was the highest in the neighborhood. They showed that T_{mrt} above an unshaded asphalt could be 30 °C higher than vegetation. This amount of re-radiation from the asphalt pavement caused discomfort for the pedestrians at the sidewalks. Figure 5 shows how the surface temperature of an asphalt roof can be risen by sun.

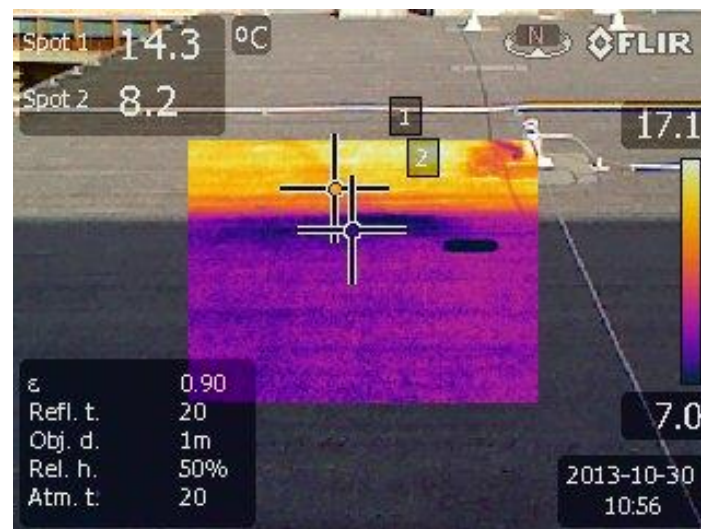


Figure 5: The comparison of the surface temperature of shaded and unshaded asphalt pavement at 10:56 on 30 October 2013.

In [81], the effect of ground surface albedo on the microclimate and pedestrians' thermal comfort were studied. Micrometeorological simulations were performed to see the impact of improving the albedo from 0.1 to 0.3 and 0.5. The simulated area was an urban square in Toronto, Canada. It was found that the increase of albedo made the square 0.5 and 1.0 °C cooler at 15:00 (by albedo 0.3 and 0.5, compared to 0.1 albedo, respectively). Although the increase of albedo reduced T_a , it increased T_{mrt} and caused discomfort for the pedestrians.

Santamouris et al. [36] through "the largest application of cool pavements in urban areas in the world" investigated the impact of 4500 m² reflective pavements in Athens. The maximum cooling effect that

they observed was 1.9 K during a summer day. By using a thermal camera, they also showed that the surface temperature was decreased by 12 K. They concluded that the cool pavement improved significantly the pedestrians' thermal comfort in an urban open space.

Most of the reviewed studies showed that the asphalt pavements cause discomfort for pedestrians. Carnielo and Zinzi [82] tested asphalt pavements with different surface colors. They measured the surface temperatures in Rome, Italy, during August 2011. Five painted asphalt were compared with the conventional asphalt at the campus of Italian National Agency for New Technologies. The maximum surface temperature differences between the control asphalt (dark) and the colored ones were 6.2, 7.8, 7.9, 10.0, and 19.3 °C, for the red, green, blue, grey and white asphalts, respectively. This experiment showed how a simple change in surface color can cause significant cooler surface temperature; while keeping the rest of the pavement properties (such as heat capacity) the same.

3. Conclusions

This paper reviewed the impact of different heat mitigation strategies on the pedestrians' thermal comfort in the context of urban and microclimate. It should be noted that the magnitude of UHI varies in different climates. Consequently, in each climate, a specific heat mitigation strategy is needed. Most of the previous studies have investigated the changes of meteorological variables (such as air temperature deviations) by heat mitigation strategies. Among different heat mitigation strategies, vegetation and high albedo (reflective) surfaces as solutions for improving outdoor thermal comfort in urban spaces were investigated in this paper. Vegetation was studied in the forms of parks, street trees, green roofs and green walls. High albedo materials were then studied while they are used on the roofs (as white roofs) and on the ground surfaces. Through several examples in different countries and climates, it was shown that urban surfaces play an important role on the thermal comfort of pedestrians. Vegetation and high albedo surfaces showed appreciable reduction of air temperatures within urban open spaces. However, mean radiant temperature affects human thermal comfort more than the other meteorological variables. Therefore, using high albedo materials on the ground surface causes re-radiation of solar radiation to pedestrians and leads to thermal discomfort (in spite of reducing air temperature). So, this paper concludes that using vegetation in urban open spaces is a better choice for improving thermal comfort in the pedestrian level. Given the importance of the UHI phenomena, it is recommended for future research projects to investigate the effect of heat mitigation strategies in urban scale on local pedestrian comfort. Furthermore, as UHI varies in different climates, finding a correlation between heat mitigation strategies and different climates and latitudes would be very interesting to investigate.

Appendix

Table 2: classification of the reviewed studies.

Strategy	Method	Reference	Study year	Studied climate	Main finding
Vegetation	Parks	[42]	2015	Singapore, Singapore	8 to 12 °C cooler air temperature
		[44]	2014	Addis Ababa, Ethiopia	Maximum PCI of 6.72 °C
		[45]	1998	Vancouver, BC, Canada Sacramento, CA, USA	Maximum cooling effect of 5 °C in Vancouver; PCI up to 7 °C in Sacramento
		[46]	2013	Slovenia	Air temperature reduction up to 4.8 °C
	Street trees	[49]	2016	Melbourne, Australia	UTCI reduction of 6 °C; air temperature reduction of 1.5 °C
		[50]	2013	UK cities	the lower the foliage temperature, the greater cooling effect
		[51]	2013		Irrigation has a significant effect on the ability of a tree to evaporate
		[53]	2008	Freiburg, Germany	Trees reduce T_{mrt} up to 29% at the not directly shaded site
		[54]	1986	State College, PA, USA	A sugar maple tree reduced irradiance by its shading effect up to 80% in summer (when in leaf) and 40% in winter (leafless)
		[47]	2015	Malaysia	6.5 °C cooler air temperature in a vegetated canopy
	Green roofs	[55]	2014		Green roofs can reduce the average air temperature between 0.3 and 3.0 K when applied on urban scale
		[56]	2011	Chicago, Illinois, USA	The air temperature during 19:00–23:00 is reduced up to 2-3 °C
		[58]	2012	Taipei, Taiwan	A green roof reduced the ambient air temperature 0.26 °C in average
		[59]	2009	Tokyo, Japan	The cooling effect of high rise buildings with green roofs on pedestrians are negligible due to the height of the roofs
		[61]	2016	Los Angeles, CA, USA	The green roofs at the height 6m (two-story dwellings) did not improve street level thermal comfort
	Green walls	[62]	1987	Berlin, Germany	The cooling effect of a green wall on outdoor environment was 0.4 °C and

					5.8 °C during the cool and hot days, respectively
		[63]	2010	Singapore, Singapore	the average surface temperature of green walls were 4.36 °C cooler than bare walls
		[48]	2014	Portland, OR, USA	A courtyard with green walls was up to 4.7 °C cooler than a bare one (at 16:30 PM)
High albedo materials	White (reflective) roofs	[76]	2008	Almeria, Spain	The average ambient air temperature in Almeria is reported 0.3 °C cooler than its rural area.
		[83]	1997	Los Angeles, CA, USA	The peak ambient air temperature in the city was reduced 2 to 4 °C by adopting 100,000 km ² cool roofs
		[79]	2004	Athens, Greece	The surface temperature of a white marble pavement could be up to 19 °C cooler than black granite
		[48]	2014	Portland, OR, USA	A white roof (albedo 0.91) led to 2.9 °C higher T _{mrt} above the surface than a black roof (albedo 0.37), but reduced 1.3 °C air temperature
	Reflective ground pavements	[61]	2016	Los Angeles, CA, USA	T _{mrt} above an unshaded asphalt could be 30 °C higher than vegetation
		[36]	2013	Athens, Greece	Air temperature reduction of 1.9 K and surface temperature reduction of 12 K by application of 4500 m ² cool pavements
		[82]	2013	Rome, Italy	The maximum surface temperature differences between the control asphalt (dark) and the colored ones were 6.2, 7.8, 7.9, 10.0, and 19.3 °C, for the red, green, blue, grey and white asphalts, respectively

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