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Quantifying the cooling effect of urban heat stress interventions

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Abstract: This review evaluates the existing studies of blue, green, and grey interventions based on field measurements and modelling aiming to quantify the cooling impact that reduces outdoor heat stress. Based on findings from literature, it is concluded that water bodies can reduce the mean air temperature (T_a) by 3.4°C and universal thermal climate index (UTCI) by 10.7°C, while natural vegetation can improve T_a by 2.3°C and physiological equivalent temperature (PET) by 10.3°C during summer. Vertical greenery systems (VGS) provide cooling effect of T_a up to 4°C, whereas architectural shades reduce it by approximately 3.8°C and PET up to 6.9°C under shade structure.

Keywords: interventions; urban heat stress; UHS; urban heat island; UHI; mitigation; cooling effect.

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1 Introduction

Large-scale urbanisation and the rapid population growth in big cities are contributing significantly to locally experienced impacts of climate change. A number of heat-related issues have been reported globally, especially in Europe, and all countries have begun to pay attention to this problem and the adverse effects associated with it. One example is the urban heat island (UHI) effect, a significant issue in hot summers, that affects the microclimate of the urbanised city, increasing the potential for warmer temperatures and where the air temperature (T_a) in big cities remains higher with reference to the rural surroundings (Memon et al., 2009).

Human health is adversely affected by the increase in heat driven by climate change (McMichael et al., 2006). These effects are especially serious in summer for vulnerable groups such as the elderly, people with cardiovascular disease, and young children (Reid et al., 2009). There have been particular events where the intensity of extreme heat has proven disastrous to human health, causing an increase in the mortality rate. The most common effects on the human health of the UHI and urban heat stress (UHS) are heatstroke, dehydration, fainting, asthma, heat cramps, rash, skin allergies, physical and mental stress, and respiratory issues (Luber and McGeehin, 2008).

The urban infrastructure has a high thermal capacity allowing absorption of solar energy, causing a low evaporation rate and adversely affecting air quality for inhabitants (Madlener and Sunak, 2011). The rapidly growing urban population has increased energy consumption by 75% resulting in energy dissipation as heat, which is further intensified by solar radiation. Surfaces such as roofs, pavements, and roads are composed of impervious, low albedo materials which tend to absorb and re-radiate a high amount of solar radiation in the infrared part of the spectrum. Air pollution and climate change are interlinked. The rapid growth in vehicle uses and fuel consumption is an additional contributor to the increase in temperature, with pollution from exhaust emissions increasing the adverse effects of UHI (Alsalama et al., 2021). All these risk factors have focused the attention of researchers, urban planners, and society on developing appropriate strategies for mitigating UHS. Recent studies have evaluated the techniques for mitigating the UHI effect. These have mostly focused on the implementation and effectiveness of green roofs and cool materials (Gagliano et al., 2015), urban vegetation, watered cool pavements, water bodies, and canopies (Battista et al., 2019). There is an ongoing debate on the relative effectiveness of different interventions and this paper reviews both natural and built approaches by surveying peer-reviewed papers and evaluating them to identify the best strategies to mitigate UHS, particularly in summers when the heat island effect is greatest.

The objectives of this review are:

1 to provide an overview of UHS mitigation strategies

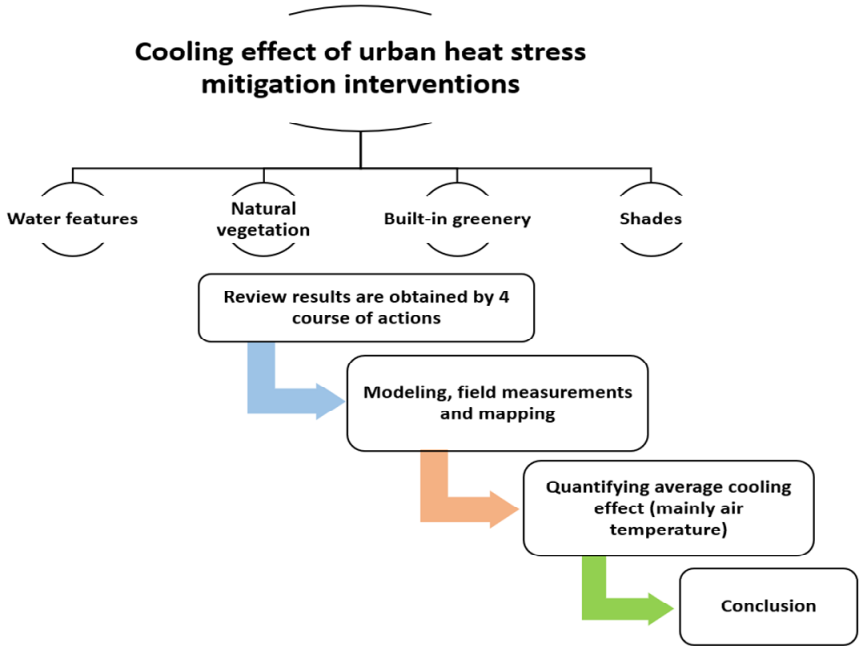
2 to quantify the cooling effect of natural and constructed features based on different indicators, mainly T_a

3 to analyse the results to determine the most efficient method to reduce UHS

4 identify the co-benefits associated with these interventions.

The methodology of this review paper is explained in Section 2. The scientific works on which this article is based are summarised in the tables in Section 3. The energy demand and costs/benefits of UHS and the UHI mitigation measures are briefly explained in Section 4 and the results are discussed in Section 5. Finally, a conclusion given in Section 6.

Figure 1 Methodological framework of this review study (see online version for colours)



2 Methodology and indicators of cooling effect

This paper is a review of peer-reviewed articles on the cooling effect of various strategies. Among these, 24 articles studied water features, 31 green technologies, 13 shadings and 25 green vegetation. These studies were analysed and frequency of different indicators such as T_a, universal thermal climate index (UTCI), physiological equivalent temperature (PET), predicted mean vote (PMV), urban heat island intensity (UHII), mean radiant temperature (T_{mrt}), universal effective temperature (ETU), surface temperature of land and soil (T_s), pavement heat flux (PH_f), building heat flux (H_f), Mediterranean outdoor comfort index (MOCI), wet bulb globe temperature (WBGT), relative humidity

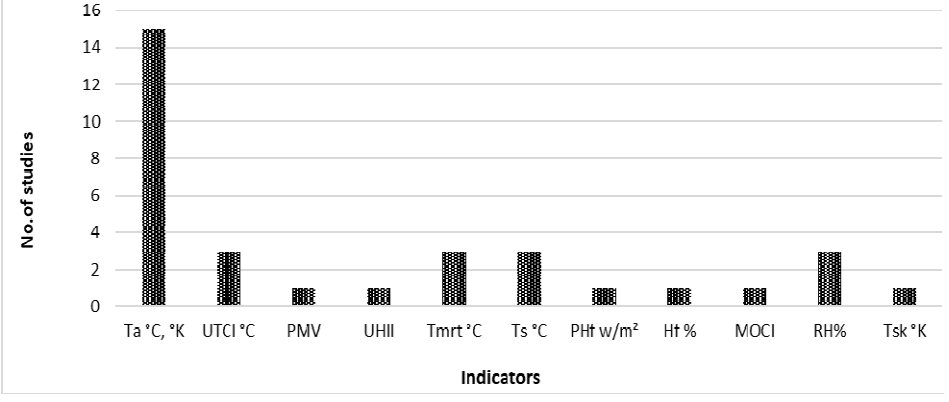
(RH), skin temperature (T_{sk}), Façade Temperature (T_f), Park Cooling Intensity (PCI), human comfort index (HCI), globe temperature (T_g), black globe temperature (T_{gb}) and wall temperature (T_w) have been used to measure the cooling effect of blue, green and grey interventions that are graphically represented in the following sections. Among the numerous indicators used in past studies, this review is focused on the cooling difference in T_a because this was the most frequently used indicator for measuring the cooling effect.

The papers were selected on a random basis from across the world and published between 2006 and 2021. These studies involved field experiments, simulations, and modelling and most experimentally validated their simulations and models. The methodology is illustrated graphically in Figure 1.

3 Interventions to mitigate heat stress

Water features, vegetation, and constructed shade are also referred to as blue, green, and grey infrastructure respectively, and are among the most effective ways to provide cooling by evaporation and shading, and so improving the urban microclimate. Blue and green features have multiple additional environmental benefits, for instance ameliorating air quality and increasing biodiversity, particularly by means of urban vegetation, and are potent ways to combat UHS (Xue et al., 2015) and UHI. They are also beneficial in increasing thermal comfort in open spaces as well as compact and dense urban areas (Lai et al., 2019). This paper presents a review of interventions from across the globe, with the three categories, water features, green spaces, and constructed shade, described separately in the following sections.

Figure 2 Measuring parameters used to evaluate cooling effect of water features



3.1 Blue infrastructure

Water areas, such as ponds, rivers, and lakes are known to significantly mitigating heat stress although cooling effect depends on the surrounding environment and atmospheric conditions (Žuvela-Aloise et al., 2016). This has led scientists to study interventions using water in different ways to reduce the environmental temperature (Gunawardena

et al., 2017). Figure 2 graphically represents the frequency of different indicators were used to evaluate the cooling effect of water features in selected papers.

3.1.1 Misting systems

One of the most attractive cooling methods is misting (Desert et al., 2020). The effect has been measured by checking skin temperature (T_{sk}) (Oh et al., 2020). The majority of studies concerned with water features were carried out in an outdoor environment; the only exceptions where one installed on a station, and another installed indoors. This review has found two different types of misting systems; water misting (Desert et al., 2020) and dry misting (Ishii et al., 2009). The greatest cooling effect from a water mist cooling system was observed in a study from Atacama (Chile) which reduced T_a by 15°C (Desert et al.,. 2020).

3.1.2 Water fountains, water pavements, and water sprays

Fountains not only minimise the effect of heat but also add aesthetic value to the surroundings, making them more pleasant and refreshing. Pavement watering has been studied for the past three decades and is considered one of the most effective techniques to improve thermal comfort. Watering surfaces can cool them to a certain extent, for instance watering pervious concrete material can reduce the T_s up to 2 °C, while watering porous bricks can reduce the T_s by 20 °C. If green areas in the urban landscape are combined with watering pavements this is particularly helpful in reducing the temperature during both the day and night (Daniel et al., 2018).

Most research is conducted via simulations using Envi-met and computational fluid dynamics (CFD) on models of water fountains along with water droplets, water jets, and water bodies. The addition of water jets showed a greater effect at night than during daytime. Fountains installed along with water bodies have been found to decrease the T_a, T_{mrt} by increasing the humidity and cooling of the air (Barakat, Ayad and El-Sayed, 2017).

3.1.3 Water bodies

According to research undertaken in Phoenix, Arizona (USA), the cooling effect of wetting streets, pond surfaces, and lakes was directly proportional to their surface areas, the larger the water body, the greater the cooling effect. The UHI mitigation depends upon the amount of water being used for the purpose (Gober et al., 2010). Similarly, another study shows that the T_{mrt} of the asphalt surface was much higher as compared to the temperature of the water body with significant cooling effect extending for around 0.5 metres. In contrast, other studies have found that open water surfaces can influences temperature causing it to rise. One author from the Netherlands concluded that water bodies can increase the daily maximum UHII by 95 percent at night and as, despite seasonal change water temperature remains high (Steeneveld et al., 2014) due to the absorption of heat throughout the day. Other researchers also support this seasonal variation which has a high impact on warmer days, with water remaining warm in lakes and rivers which influences the surrounding temperature (Hathway and Sharples, 2012). The papers reviewed regarding the outdoor cooling effects of blue infrastructure are summarised in Table 1.

Table 1 Literature reviewed regarding blue infrastructure

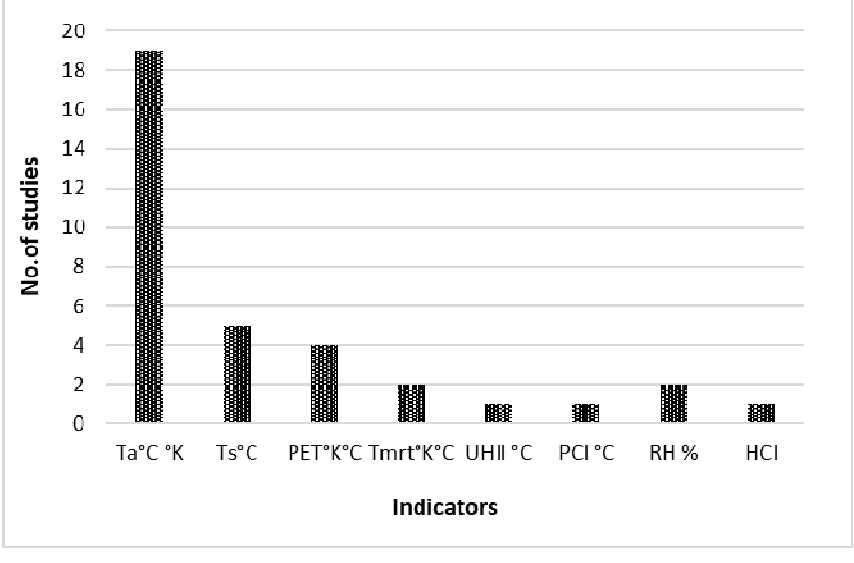
Symbol	*Type of water feature*	*Measurement method*	*Location*	*Monitoring time (summer)*	*Cooling effect*	*Indicator*	*Ref.*
a	Water misting system (cloud droplet)	Field measurements	Rome and Ancona (Italy)	Day	8.2 to 7.9°C	UTCI°C	Ulpiani et al. (2019)
b	A fountain of water spray	Field measurements and CFD simulations	Rotterdam (Netherlands)	Day	5°C/7°C	T_a °C/UTCI°C	Montazeri et al. (2017)
c	Surfaces of ponds, wetting streets, and lakes	Field measurements and simulations	Phoenix (USA)	Night	0.15 to 0.82°C/hr	T_a°C/hr	Gober et al. (2010)
d	Water pond	Field measurements	Guangzhou (south China)	Day	1.5°C/increase 6%	T_a°C/RH%	Yang and Zhao (2015)
e	Water droplets around fountains	Simulations	Korea	_	0.5°C	T_a°C	Lee (2011)
f	River	Measurements	Sheffield (UK)	Day (^)	1.5°C	T_a°C	Hathway and Sharples (2012)
g	Water misting or micro water droplets	Measurements and CFD simulations	Tokyo (Japan)	Day	2°C	T_a °	Yoon et al. (2008)
h	Prototype water mist cooling systems	Measurements	Atacama (Chile)	Day	15°C	Overall (across universal thermal climate index (UTCI), T_{mrt} and T_a recordings)	Desert et al. (2020)
i	Water pools and ponds	Measurements	London (UK)	Mainly day	Up to 7.1°K	T_a°K	Santamouris et al. (2017)
j	Dry mist	Measurements	Futamatgawa, Tokyo (Japan)	Day	1.63°K to 1.9°K	T_a°C	Ishii et al. (2009)
k	pavement watering + urban green areas	Modelling and simulations	Paris (France)	Day and night	1.1°C and 2.6°C	T_a°C	Daniel et al. (2018)
l, m	Water fountains and water jets	Envi-met simulated	Lebanon	Day and night	2°C and 4°C to 5°C	T_a°C	Fahed et al. (2020)
n	Dry mist	Field measurements and CFD analysis	Japan	Day	3°C/increase 15%	T_a°C/RH%	Yoon et al. (2008)
o	Fountains and water bodies	Envi-met Simulated	Alexandria (Egypt)	mid-day	2°C/increase 6%/5.5°C/1	T_a°C/RH%, T_{mrt}°C/predicted mean vote (PMV)	Barakat et al. (2017)

Notes: In this review, the effectiveness of most interventions presented was recorded in outdoor spaces in the summer; those also taken in winter are indicated by ~ and those in spring by ^.

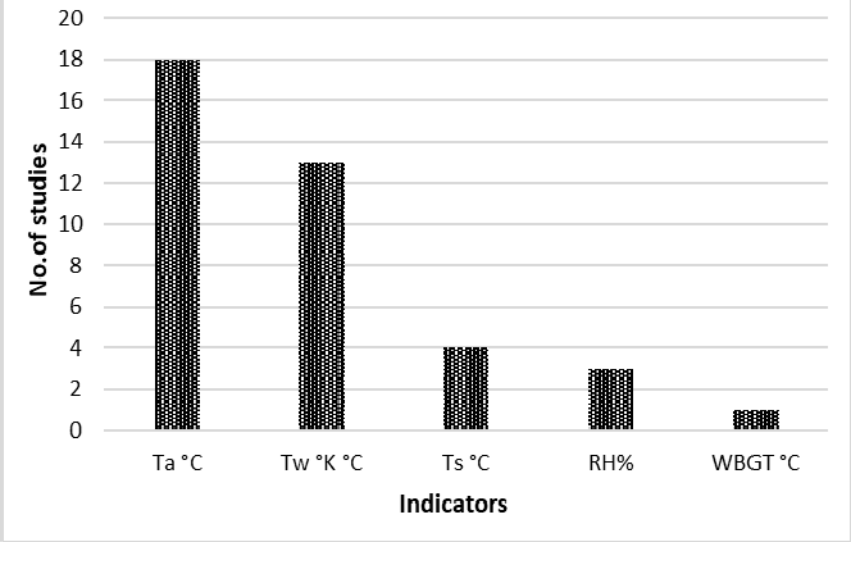
3.2 Green infrastructure

Green infrastructure refers to vegetation, such as trees, grass, and other plants and these interventions may be supported by constructed frameworks, for example, green façades and pergolas, which provide shade, or grown in containers, as in green walls.

Figure 3 Frequency of measuring parameters used to evaluate cooling effect of (a) vegetation (natural green infrastructure), (b) supported green infrastructure



(a)



(b)

Trees can trap long-wave radiation significantly enabling pedestrians to walk comfortably in their shade. Grass and shrubs lower the T_s compared to other surface materials. Climate measurements made in the centre of Athens (Greece) showed that the T_a of the green area is lower than the surroundings in the early morning (Georgakis and Santamouris, 2017). Vertical green walls or green facades, are approaches that can also ameliorate the thermal effect of urban areas.

This paper reviews research into the cooling effect of naturalistic greenery that is cheaper than constructed alternatives and can be implemented with less effort. During the screening of research articles, it was observed that different indicators have been used to quantify the cooling effect. The frequency of these indicators is graphically represented in Figure 3.

3.2.1 Types of natural green interventions

3.2.1.1 Grass

Researchers in Manchester (England) measured the difference in T_s, T_a and demonstrated the cooling effect of grass (Armson, Stringer and Ennos, 2012). Urban parks often combine dense vegetation along with water facilities (Motazedian, Coutts and Tapper, 2020). Increasing the proportion of trees increases the cooling effect and humidity (Shahidan et al., 2012). Grass alone can increase the RH (Amani-Beni et al., 2018) but this effect is greater when combined with trees (Grilo et al., 2020). A similar effect is observed with green or vegetated parking areas, where grass is grown in holes in paving or in a reinforcing mesh to create a stable surface, but this provides less cooling compared to other vegetative paved surfaces due to the convention effect when cars are parked, and thermal energy is transferred, leading to T_a drop. Thus, vegetated pavement in parking areas lessens discomfort but not as much as installed at other situations.

3.2.1.2 Trees

Trees are effective at absorbing and reflecting thermal radiation with the cooling effect depending on tree species and the planting pattern. The cooling effect of small leaved lime (Tillia cordata) was measured and an improvement in T_a was recorded during both day and night (Rahman et al., 2017). This suggests that an appropriate configuration of trees could provide a good cooling effect. Strategic placement of trees and green infrastructure has been found to not only reduce the UHI and UHS but also reduce premature human death during high temperature events (Doick and Hutchings, 2014).

Parks with a high density of trees experience reduced temperature and increased RH particularly during summer and can influence temperature and RH as far as 60 metre away (Grilo et al., 2020). Different numbers of trees have been compared and the most effective daytime cooling results were found with 50% tree cover (Aboelata and Sodoudi, 2019). In a study in Kaohsiung (Taiwan) five strategies were tested, the results showing that increasing the green coverage ratio (GCR) in the street up to 60%, in the park up to 80%, and GCR on the roof of building up to 100% can reduce T_a (Huang and Chen, 2020). The papers reviewed on the cooling effect of vegetation in outdoor spaces are given in Table 2.

Table 2 Literature review of natural green infrastructure

S	*Natural green infrastructure*	*Measurement method*	*Location*	*Monitoring time (Summer)*	*Cooling effect*	*Indicator*	*Refs.*
a	Grass	Experimental measurements	Manchester (UK)	Day	up to 24°C/0°C to 3°C	T_s °C/T_a °C	(Armson et al. (2012)
b	Green coverage (grasslands and broad-leaved trees)	Envi-met simulations	Freiburg (Germany)	Day	up to 43°K/22°K/3.4°K	T_{mrt} °K/PET°K/T_a°K	Lee et al. (2016)
c	Park grass	Experimental Measurements	Beijing (China)	Day	0.6°C/up to 2.44%/1.00	T_a°C/RH%/HCI	Amani-Beni et al. (2018)
d	Parks with trees and grass	Meta-analysis (Studies)	_	Day	0.94°C	T_a°C	Bowler et al. (2010)
e	Tree type Tilia cordata	Morphological Measurements	Munich (Germany)	Day and night	3.5°C and 0.5°C	T_a°C	Rahman et al. (2017)
f	10% increase in vegetation	Field measurements	Shenzhen (China)	Day and night	0.05°C to 0.15°C and 0.16°C to 0.55°C	UHI (Difference of T_a°C)	Yan et al. (2020)
g	Tree shade	Field measurements and Simulations	Putrajaya (Malaysia)	Day	up to 2.7°C	T_a°C	Shahidan et al. (2012)
h	50% tree cover	Envi-met simulations	Cairo (Egypt)	Day	0.5°K to 1°K/4°K	T_a°K/PET°K	Aboelata and Sodoudi (2019)
i	Green coverage ratio in street rises by 60% and park to 80 % set the GCR on the roof of building up to 100%	Envi-met simulations	Kaohsiung (Taiwan)	Day	2°C	T_a°C	Huang and Chen (2020)
j	Street trees	Envi-met simulations	Montreal (Canada)	Day	up to 0.3°C/0.6°C to 2.1°C/1.1°C to 3°C	T_a°C/PET°C/T_{mrt}° C	Wang and Akbari (2016)
k	Leaf area index = 45 trees per hectare	Measurements and CFD modelling	Slovenia	Day	up to 4.8°C	T_a°C	Vidrih and Medved (2013)
l	Parks	Measurements	Melbourne (Australia)	Day	1°C	T_a°C	Motazedian et al. (2020)
m	Urban parks (Tree shade)	Measurements	Taipei (Taiwan)	Mid-day	0.64 to 2.52°C/3.28°C to 8.07°C	T_a°C/soil T_s°C	Lin and Lin (2010)
n	Parking area with grass	Measurements	Kobe (Japan)	Day and night	0.1°C	T_a°C	Takebayashi and Moriyama (2009)
o	Strategic placement of trees	Studies analysis	UK	Day	2°C to 8°C	T_a°C	Doick et al. (2014)
p	Parks	Measurements	London (UK)	Night	1.1°C to 4°C	T_a°C	
q	Parks with a high density of trees	Arc map	Lisbon (Portugal)	_	1°C to 3°C/2% to 8%	T_a°C/RH%	Grilo et al. (2020)
r	Green area	Measurements	Athens (Greece)	Morning	2°C	T_a°C	Georgakis and Santamouris (2017)
s	Vegetation	Review study	_	Day	13°K	PET°K	Lai et al. (2019)
t	Green ground	Envi-met simulations and measurements	Padua (Italy)	Day and night	3°C and 1.4°C	T_a°C	Noro et al. (2015)

Table 3 Literature review of constructed green infrastructure

S	*Constructed green technologies*	*Measurement method*	*Location*	*Monitoring time (Summer)*	*Cooling effect*	*Indicator*	*Refs.*
a	Green wall and specially Stachys and Hedera	Measurements	UK	Day	3°C and special species up to 7°C	T_a °C	Cameron et al. (2014)
b	Green wall/facade	Measurements	La Rochelle (France)	day and night	up to 4°C	T_a °C	Djedjig et al. (2015)
c	Green wall	Envi-met simulations	Colombo	Day	1°C to 2°C	T_a °C	Herath et al. (2018)
d	Green wall	Microscale modelling	Riyadh (KSA)	Day	up to 1.2°C to 9.3°C	T_a °C	Alexandri and Jones (2008)
e	Vertical greenery systems	Measurements	Singapore	Day	3.3°C/4 to 12°C	T_a°C/T_w °C	Wong et al. (2010)
f	Vertical wall with green vegetation	Experimental measurements and C-M simulations	Thessaloniki (Greece)	Night	1.5°C/0.58°C to 3.5°C	T_a°C/T_w °C	Kontoleon and Eumorfopoulou (2010)
g	Green walls and green roofs	Measurements	Rio de Janeiro (Brazil)	Day and night	2.8°C to 8.1°C/increase 2%	T_a°C/RH%	Castiglia Feitosa and Wilkinson (2018)
h	Vertical green wall	Measurements	Steinach am brenner and tyrol (Austria)	Day	0.9°C/increase 4.5%/18.9°C	T_a °C/RH%/T_w °C	Medl et al. (2017)
i	Green walls using C. hyssopifola H.B.K species	Experimental measurements	Thailand	Day (~)	1.7°C	T_a°C	Charoenkit and Yiemwattana (2017)
j	Green facade	Measurements	Madrid (Spain)	Day	2.4°C to 2.9°C	T_a°C	de Jesus et al. (2017)
k	Vertical Green wall	Measurements	Shanghai (China)	Day	5.5°C	T_a°C	Yang et al. (2018)

Table 4 Literature review of constructed grey (shades) infrastructure

S	*Type of constructed shading*	*Measurement method*	*Location*	*Monitoring time (Summer)*	*Cooling effect*	*Indicator*	*Refs.*
a	Optimised awnings	Measurements	Central Italy	Day	2.5°C	PET°C	Rossi et al. (2020)
b	Sun sails	Measurements	Pecs (Hungary)	Day	5.8°C to 10°C	PET°C	Kántor et al. (2018)
c	Black and white sun sails	FEM simulations	Cordoba (Spain)	Day	up to 3°C/12°C	T_a/T_s	Garcia-Nevado et al. (2021)
d	Overhead shaded structures	Measurements	Milan (Italy)	Day	0.8°C/6.1°C/8.2°C/ 5.3°C	T_a°C/T_{gb}°C/PET °C/UTCI°C	Lee et al. (2020)
e	Architectural shading	Envi-met simulations	California (USA)	Day	1.6°C to 1.7°C	T_a°C	McRae et al. (2020)
f	Deep canyons	Measurements	Fez (Morocco)	Day	6°K to 10°K	T_a°K	Johansson (2006)

3.2.2 Green interventions involving support

3.2.2.1 Vertical greening

Vegetation that is supported by constructed frameworks or built structures to grow are referred to as vertical greenery systems (VGS). In this study we considered two types of VGS; green façades, comprising climbing plants growing in the ground but supported on the walls of buildings (Lepp, 2008), and green walls, which are vertical built structures consisting of containers of growth medium, such as soil or substitute substrate, in which the plants are grown, as well as an integrated hydration system. These types of greening offer numerous co-benefits, including aesthetics and biodiversity. An attractive solution is the application of vegetated facades, which help reduce heat by the phenomenon of evapotranspiration as well as mixing air vertically, lowering the temperature in the surroundings and reducing UHI by providing fresh air (Johnston et al., 2004).

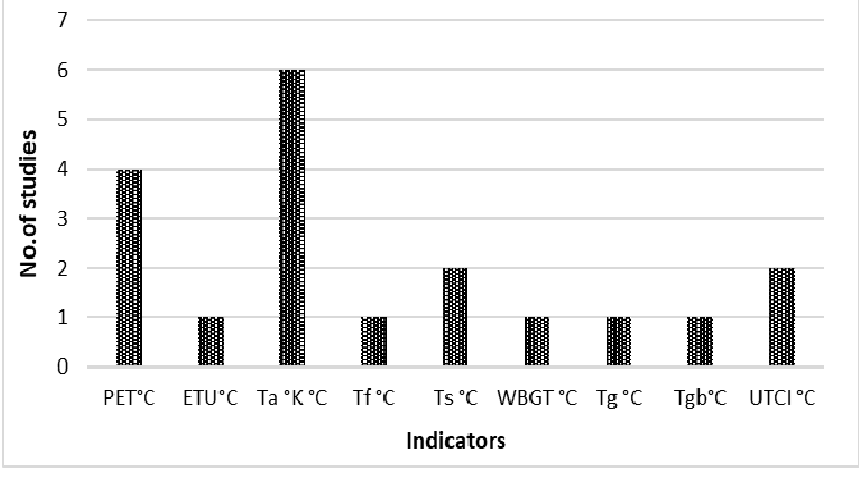
3.2.2.2 Plant species in vertical greening systems

Different plants showed different efficiency, plants with woody branches and the smallest leaves appeared to be the most efficient in cooling effect during summer (Charoenkit and Yiemwattana, 2017).

The efficiency in reducing T_s and T_w of species ranged from 1°C to 5.6°C, with Sword bean (*Canavalia gladiate*) the most efficient plant. In the UK, the cooling effect was considerable when the outdoor T_a evaluated with the extent to which temperature was affected different according to species (Cameron et al., 2014).

Below are some reviewed studies for constructed greenery referring to cooling effects in outdoor spaces given below in Table 3.

Figure 4 Measuring parameters used to evaluate the cooling effect of constructed grey infrastructure



3.3 Grey infrastructure (Constructed shading)

Thermal stress in hot weather can limit outdoor activities. Outdoor spaces can be shaded in different ways; via shading devices (Yıldırım, 2020), sun sails (Garcia-Nevado et al., 2021), architectural shading (McRae et al., 2020), shade pavillons or optimised awnings (Rossi et al., 2020), parasols, deep canyons (Johansson, 2006), textile canopys, and other overhead shade structures Lee et al., 2020). Figure 4 graphically represents the number of times different parameters have been used to evaluate the cooling effect of constructed shading in papers.

The papers reviewed s referring to cooling effects of shade structures in outdoor spaces is given in Table 4.

4 Energy-saving benefits of interventions

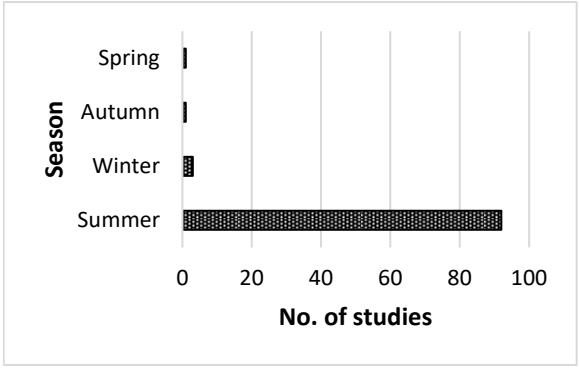
Nowadays, energy consumption is an important issue and the focus of attention for many scientists and researchers. For both cooling and heating, different technologies and electronic appliances are used, and various methods are applied by different countries in order to balance demand and consumption. The natural and constructed options discussed in this paper to improve thermal comfort in urban areas can reduce energy consumption, cost and ultimately lead to sustainable city planning. Natural greenery reduces PET, particularly when combined with shading in summers (Müller et al., 2014). Trees can decrease outdoor T_a and building cooling load by 29% (Shahidan et al., 2012) which ultimately reduces indoor air conditioning cost by around 25 Egyptian pounds, equivalent to 1.25 euro/day (Aboelata and Sodoudi, 2019). Another study showed that there was an annual saving of about 1.5 million US dollars because the urban forest, of about 100,000 trees, decreased the demand for energy and water (Moore, 2016). Specifically in July, at the peak of summer, the installation of green facades can reduce building energy demand by up to 20% (Haggag et al., 2014).

There are other shading technology options that not only provide pedestrian thermal comfort but also reduce energy demand. For an instance, the installation of sun sails in Mediterranean city streets can reduce cooling demand up to 46% (Garcia-Nevado et al., 2021). Other shading devices in street canyons can reduce yearly heating load up to 18% during winter (Evins et al., 2014). These interventions include green walls, suburban parklands and ceiling sprays (Narumi et al., 2009) not only effective outdoor but also for the indoor environment.

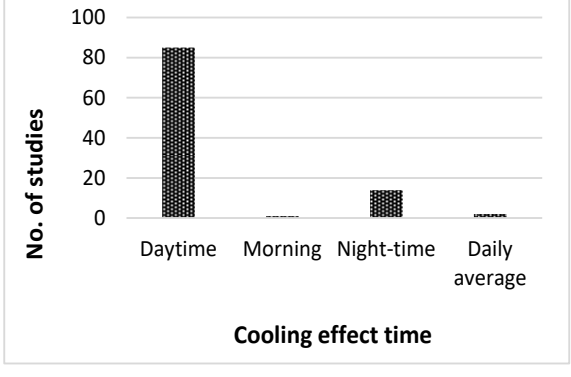
5 Results and discussion

The overheating of urban areas has negative impacts on human health and contributes to increased morbidity and mortality in cities. Different interventions have been the subject of experiments and found to contribute to improving thermal comfort in outdoor open spaces, with most research conducted during the daytime in summer, as shown in [Figures 5(a) and 5(b)].

Figure 5 No. of studies were monitored in (a) season and (b) measurements time



(a)



(b)

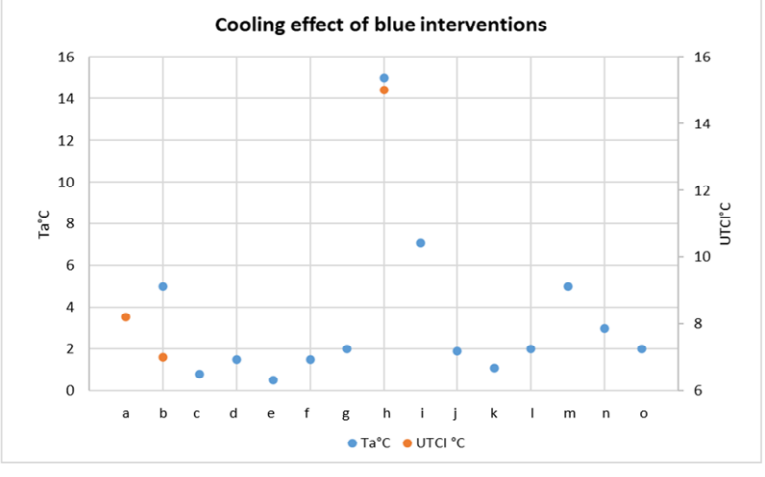
The literature on all four categories of interventions (water features, naturalistic and constructed green infrastructure, and shading) were carefully analyzed, and cooling estimation for all categories of interventions are discussed as follows:

- Blue infrastructure: It has been found that mist nozzles are effective but need to be combined with fans to provide cooling relief. Spraying water on the pavement can cool by 628 W/m² for 1mm/h of sprinkled water due to evaporation, and 12–18 W/m² of cooling for 1mm/h due to advection. Water misting systems are effective in reducing UHS by decreasing mean T_a by around 3°C and UTCI by up to 10°C. Thermal comfort achieved by different methods can be seen in Figure 6(a).
- Natural vegetation: This can create have significant – and multiple– impacts on the environment. For example, measurements taken over grass alone were beneficial, but when combined with trees, showed a greater cooling effect. Grass contributed significantly to mitigating the UHS by reducing PET by at least 10°C while making a slight decrease in the T_a of approximately 2°C. Outdoor cooling effects of different type of natural vegetation are plotted in Figure 6(b).
- Supported green infrastructure: Green walls and facades improve both indoor and outdoor thermal comfort. The average air temperature (T_a) can decrease by up to 4°C

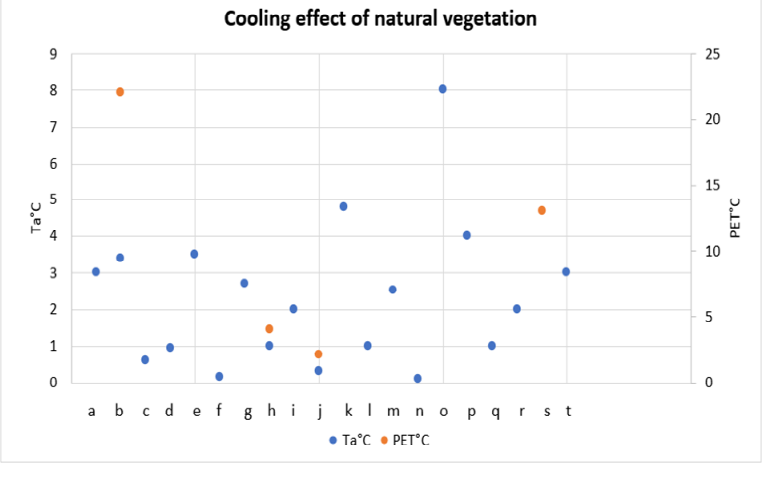
during the daytime in the summer season. Results of air cooling obtained by different studies are illustrated in Figure 7(a).

- Grey infrastructure: Sun sails and other shading device are beneficial due to their maximum cooling effect. Most studies support the idea that people prefer to walk on the streets because of overhead shading as it reduces the heat intensity (Nam-Hyong and Chun-Seok, 2018). The shades enhance pedestrian comfort in summer but during winter it causes cold stress and increases the heating requirement. Overall artificial shading structures provide a cooling effect with a decrease of the T_a by approximately 4°C and PET by 7°C. Results obtained with different types of shading are presented in Figure 7(b).

Figure 6 Cooling effect of (a) blue interventions and (b) natural green interventions achieved by different studies (see online version for colours)

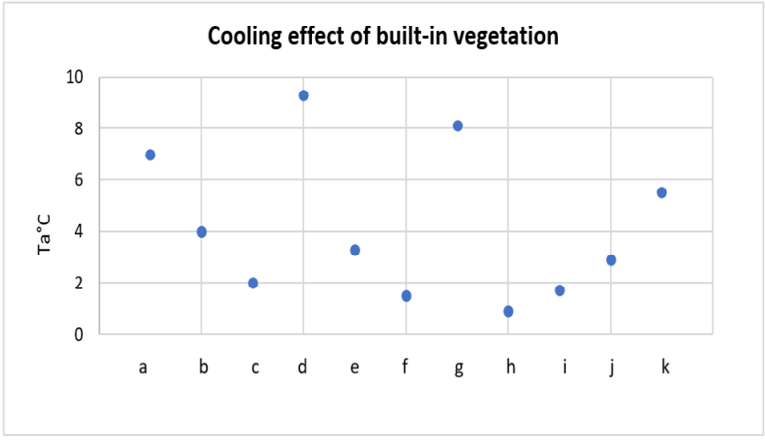


(a)

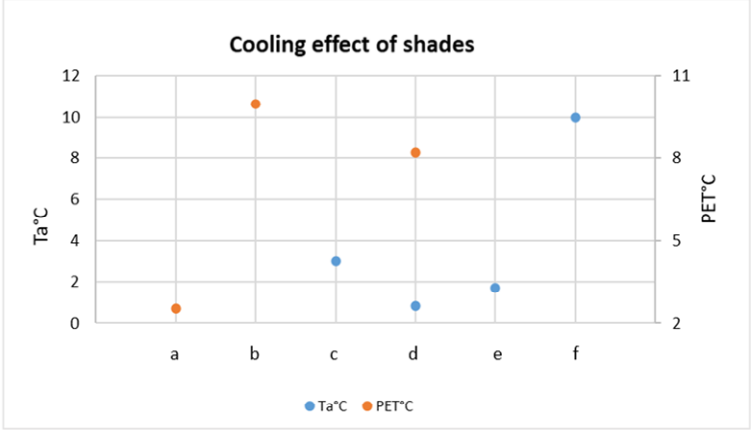


(b)

Figure 7 (a) Cooling effect of built-in green interventions achieved by different studies (b) Cooling effect of built-in shades achieved by different studies (see online version for colours)



(a)



(b)

6 Conclusions

The reviewed interventions not only contribute to the physiological health of citizens but also have a psychological impact. When the environmental conditions are extreme with intense solar radiation, and heat levels rise, one must consider preventive actions and resources to implement cooling interventions in urban settings. When selecting the most appropriate heat resilience strategy, important criteria should be considered such as cooling effect, cost, maintenance, and public acceptance.

All the types of mitigation measures that are reviewed in this study provide cooling, but the effect depends on the local climate and geography. Future investigations should focus on developing a practical decision support tool that can help decision-makers to

select an adaptation measure based on the characteristics of the proposed site, local social and economic circumstances, and constraints.

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