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Towards Sustainable and Climate-Resilient Cities: Mitigating Urban Heat Islands Through Green Infrastructure

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Abstract: Rapidly increasing construction and agglomeration in urban areas have made the urban heat island (UHI) problem a turning point for the world, as a result of notably rising earth temperature every year. UHI and its impacts on climate are somewhat linked to weather-related matters, natural disasters and disease outbreaks. Given the challenges posed by urbanisation and industrialisation in achieving sustainability, it is crucial to adopt intelligent and decisive measures to mitigate the adverse outcomes of UHI. Greenery surfaces have long been a significant focus of scientific research and policy development, reflecting their pivotal role in combating urban heat islands and promoting sustainable urban environments. This study critically reviews the potential of green infrastructure, including green roofs, facades, shrubs, and trees, so as to minimise UHI impacts in severe urban contexts. By synthesising findings from a wide range of empirical studies, it highlights key outcomes such as reductions in surface temperatures by up to 2 °C and improvements in outdoor thermal comfort indices by over 10 °C under specific conditions. Additionally, the paper introduces a comprehensive framework for integrating greenery systems into urban planning, combining passive cooling, air quality enhancement, and energy efficiency strategies. The findings reveal that extensive green roofs, in particular, are highly effective in reducing indoor cooling demands, while strategically placed trees offer significant shading and evapotranspiration benefits. This work provides actionable insights for policymakers and urban planners to boost sustainable and climate-resilient cities whilst addressing gaps in current research related to the long-term performance and cost-effectiveness of green infrastructure solutions.

Keywords: urban heat island mitigation; green facades and roofs; sustainable cities and society

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1. Introduction

The urban population is increasing significantly due to factors such as extended life expectancy, improved healthcare services, rural-to-urban migration, and the concentration of economic opportunities in urban areas, which are often driven by technological advancements and modernisation. The United Nations report reveals that the urban population is expected to reach more than 60% of the total world population by 2050 [1]. The current scenario demonstrates that the rising urban population, along with the increase in greenhouse gas emissions, has significant adverse impacts on the urban environment and contributes to climate change [2]. Therefore, human activities directly affect global warming and climate changes. An average air temperature increase of 2 °C, representing the critical threshold until 2030, means dangerous climate changes [3,4]. Urban heat island (UHI) is a commonly observed phenomenon characterised by higher outdoor air temperatures in urban areas compared to neighbouring suburban and rural environments. This effect is primarily driven by urban structures, including heat-absorbing materials like asphalt and concrete, limited vegetation, and anthropogenic heat emissions. Whilst global warming and urban population growth can amplify the impacts of UHI, they are not their direct causes [5–9]. The term is related to the positive thermal equilibrium, which is created in the urban environment, caused by raised heat gains and decreased thermal losses [9]. The thermal balance of urban areas is affected by rising solar radiation absorption, sensible heat emitted by urban buildings, higher anthropogenic heat, decreased urban vegetation and higher infrared radiation [5,6]. The phenomenon of UHI has a strong relationship with climate change and rapid urban development. It is reported that the UHI effect is responsible for up to 8–10 K absolute temperature increase for most of the medium and large cities in the world [10]. However, current information shows that this value is close to 5.5 °C on average.

UHI reality can be observed in different regions of the world, so it indisputably comes across as well-documented evidence of climate change [10]. The facts of global warming and the UHI effect are distinct yet interconnected phenomena, both contributing to significant temperature increases in urban areas [11]. Global warming represents the planet-wide rise in temperatures due to increased greenhouse gas emissions, whereas UHI is a localised phenomenon caused by urban structures, reduced vegetation, and anthropogenic heat emissions. These phenomena act synergistically, with global warming raising baseline temperatures and UHI amplifying localised heat conditions in cities, leading to intensified thermal stress. The effects of UHI are mostly observed in cities with high populations and low environmental quality, resulting in poor thermal comfort indicators for both indoor and outdoor environments [12,13]. Moreover, UHI based air temperature rise causes important social, environmental and economic problems in cities [14]. Although the major effects of UHI are seen in summer, especially at the peak daytime hours and also at night, it has significant adverse effects such as outdoor thermal discomfort and poor air quality, high energy consumption for HVAC and high temperature related health problems in summer season and hot climatic conditions [15,16]. It is well documented in the literature that the UHI is responsible for the high energy demand of dwellings [17]. An increase in urban temperatures decreases HVAC efficiency and increases cooling energy demand. Additionally, high urban temperatures contribute to a significant decrease in natural cooling potential, an increase in pollution levels, and are linked to higher heat-related mortality and morbidity [18,19]. These rising temperatures also affect mental health, reduce cognitive performance in students, and decrease overall human productivity.

Today, countries across the globe focus on developing city models that are climate-friendly and energy-optimised [20]. Both developed and developing countries, such as the US, Canada, Australia, India, and Brazil, are actively implementing strategies to address unsustainable urban population growth and excessive car use. Cities are increasingly integrating green spaces into various parts of buildings, such as balconies, walls, and roofs, not only to reduce the effects of hot climatic conditions but also to mitigate UHI [21]. Heat mitigation technologies, including these green spaces, are expected to gain broader acceptance and see greater implementation in urban environments.

A new holistic concept has been introduced called green urbanism [22]. The idea includes plus energy urban environment based on consistent and healthy use of water, land, energy, materials, green spaces and mobility. Thus, the targets of carbon mitigation, low/zero waste and decrease in the use of energy, water and material will be achieved. The concept of low/carbon city based on green urbanism reveals a sustainable and resilient urban environment but also socially and ecologically as it is clearly seen in Figure 1 [21,22].

Figure 1. Main principles of green urbanism [21,22].

The 15 guidelines of green urbanism are detailed in Figure 1 [21,22]. It is easy to understand that innovative and comprehensive strategies need to be developed to deal with demographic and structural changes [23]. One effective strategy is to incorporate clean and low/carbon energy technologies into urban structures. This integration can significantly reduce carbon emissions, mitigate climate change impacts, and create healthier, more sustainable urban environments. Another idea that is less expensive than low/carbon technologies is to allow green plant implementation on the roofs and external walls of buildings. In cities, roofs cover 20–25% of the total area, so they have great potential to decrease the air and surface temperature of urban [24]. The idea of green roofs and facades provides a passive cooling technique that improves the energy performance of buildings. Also, considering the rapid increase in energy consumption for cooling purposes [25–27], the idea would significantly reduce HVAC-based energy demand whilst also contributing to decreased pollution and improved urban environmental quality [28,29].

In this paper, the mitigation of UHI effects through the integration of greenery systems, such as green roofs, facades, shrubs, and trees, into urban structures is comprehensively investigated. Despite the growing body of research on greenery technologies, most studies focus on isolated implementations, failing to explore how these systems can be synergised to create a unified mitigation strategy. Additionally, the long-term performance and cost-effectiveness of these solutions in diverse urban settings remain poorly understood. It aims to bridge this gap by comparing and parametrically analysing findings from a wide range of studies to develop a unified framework. The main contribution of this work lies in presenting an integrated approach to greenery systems and their potential to enhance thermal comfort, reduce urban heat, and mitigate air pollution on a large scale. By consolidating existing knowledge, the paper identifies contemporary research directions and offers actionable insights for urban planners and policymakers.

2. Urban Heat Island Mitigation Strategies

2.1. Cool Pavements and Roofs

Urban Heat Islands pose a significant challenge to global sustainability efforts, exacerbating the effects of global warming by increasing energy demand and negatively impacting human health and comfort. The transformation of natural landscapes into built environments, particularly the widespread use of conventional paving materials, is a primary driver of this phenomenon. The UHI phenomenon is strongly tied to the transformation of natural landscapes into built environments. Therefore, it is essential for a habitable environment to reduce the negative effects of UHI. To reduce UHI effects, three primary techniques are commonly employed: (i) decreasing solar radiation absorption by using reflective materials and coatings, (ii) improving air flow circulation through optimized urban design, and (iii) actively and periodically cooling certain elements in the built environment using technologies such as water-based cooling systems. Each of these methods contributes to mitigating urban overheating and enhancing thermal comfort. Collectively, these techniques form part of broader UHI mitigation strategies, including sustainable urban infrastructure and vegetation-based approaches. However, the reduction of anthropogenic heat, including controlling heat production in buildings or optimising air conditioning demand, remains a complementary approach to addressing the UHI impact comprehensively [8,30]. Cool pavements are a promising solution for reducing the UHI effect. They are designed to reflect more solar radiation and release heat more effectively, lowering both surface and air temperatures. According to Ismael et al. [31], traditional pavements, which make up about 40% of urban areas, play a major role in the UHI effect due to their dark colours and high thermal inertia. These properties cause them to absorb large amounts of solar energy during the day and release it at night, keeping urban areas warmer. Several research on UHI mitigation strategies has been carried out to determine the proper way for reduction of the effects of urban microclimates. A study shows that the building materials are of vital importance for reducing energy demand while decreasing outdoor air temperature and therefore regulating indoor air temperature [16]. An experimental and numerical investigation by Battista et al. [32] is performed to evaluate the UHI effect on city of Rome. The results underline that the cool pavements provide a 0.22 °C drop in daily mean air temperature. Lawn application instead of cool pavement results in an all-day temperature decrease, with the highest air temperature drop in the evening. In another study, reflective pavements (as seen in Figure 2) are developed to decrease the ambient temperature for hot-dry regions in summer and open areas exposed to long hours of sunlight. The results show that a more durable pavement is achieved with the reflective pavement compared to the evaporative one, as well as a temperature drop of 20 °C [33,34].

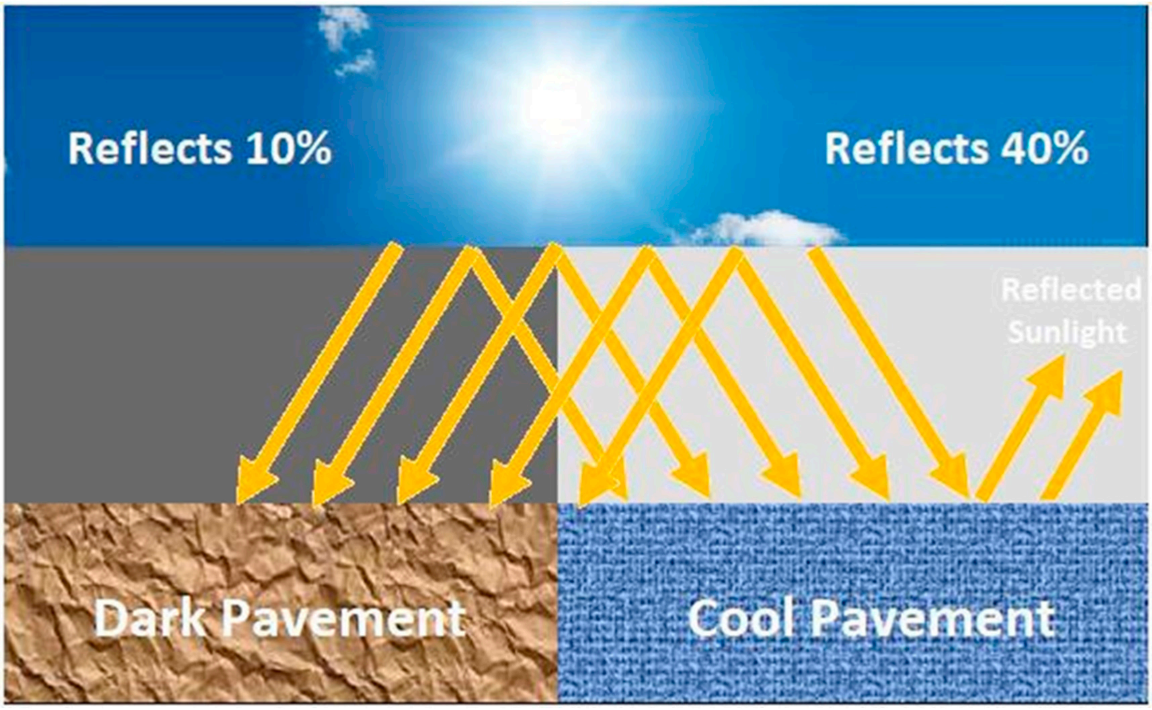

Figure 2. Sunlight reflection comparison between dark and cool pavement [33].

Pomerantz et al. [35] investigate time dependent surface temperatures of asphalt concrete pavements with different albedos measured in Concord, California. The graph in Figure 3 reveals that the surface temperature increases with decreasing albedo, as expected.

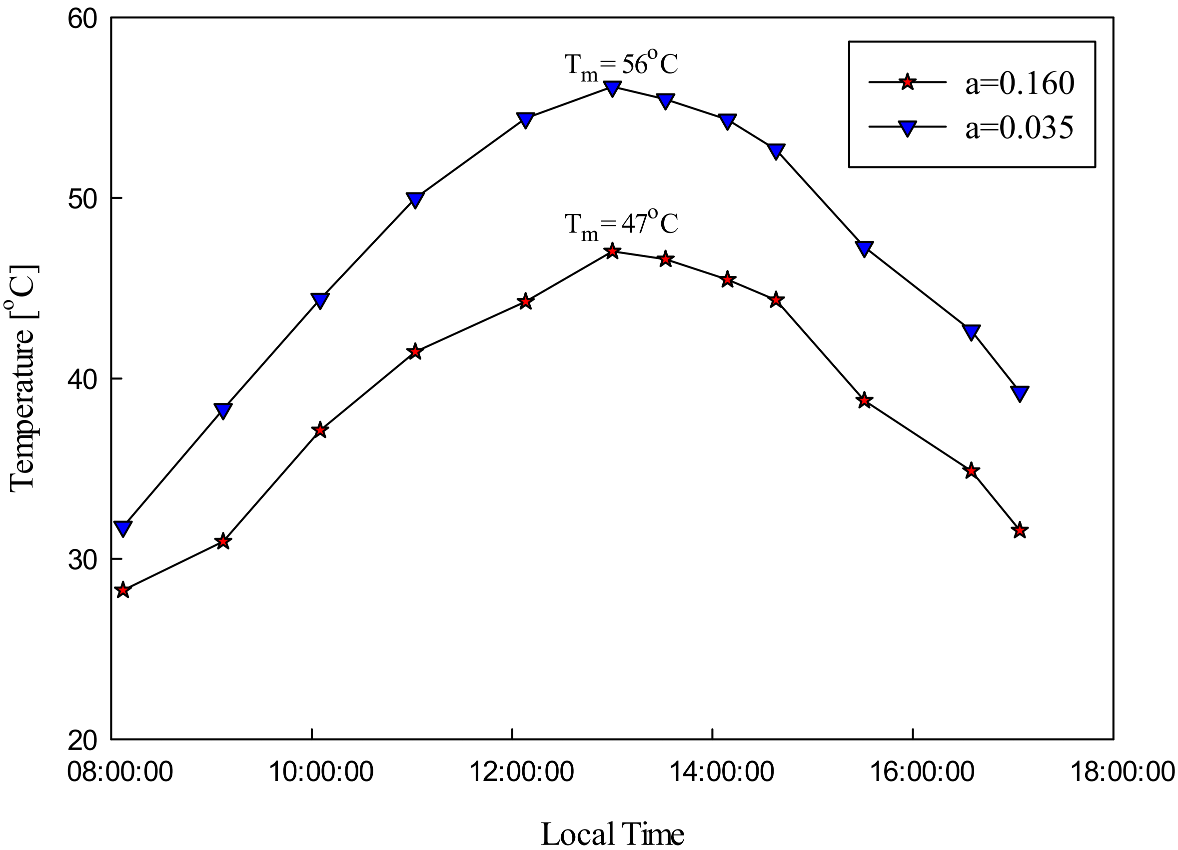

Figure 3. Measurement of time-dependent surface temperature with different albedos at different locations in Concord, California on 17th September 1998 [35].

The literature discusses different types of cool pavements and how they work. Reflective pavements, which have a higher albedo, reflect more sunlight and stay cooler [36]. This can be achieved with reflective coatings, infrared-reflective paints, thermochromic materials, or by using alternatives like slag in concrete [37]. Permeable pavements take a different approach, using evaporative cooling to lower heat by allowing water to evaporate and absorb thermal energy [38]. Another option is adding phase change materials, which store and release heat, helping to regulate temperature changes [39]. Research on cool pavement technology continues to advance, with efforts centred on enhancing material characteristics, refining design and application methods, and assessing durability and cost-efficiency over time. Incorporating cool pavements within wider urban planning and design initiatives, alongside complementary UHI mitigation measures, is vital for fostering sustainable and resilient cities.

A unique, non-white, near-infrared reflective coating technology has been developed by American Rooftile Coatings. The innovation can be easily applied to clay tile or pitched concrete roofs [40]. As it is clearly seen in Figure 4 that a remarkable temperature decrease is obtained with the use of cool tile coatings while outside temperature and horizontal global solar intensity are measured to be 27 °C and 820 W/m^2, respectively.

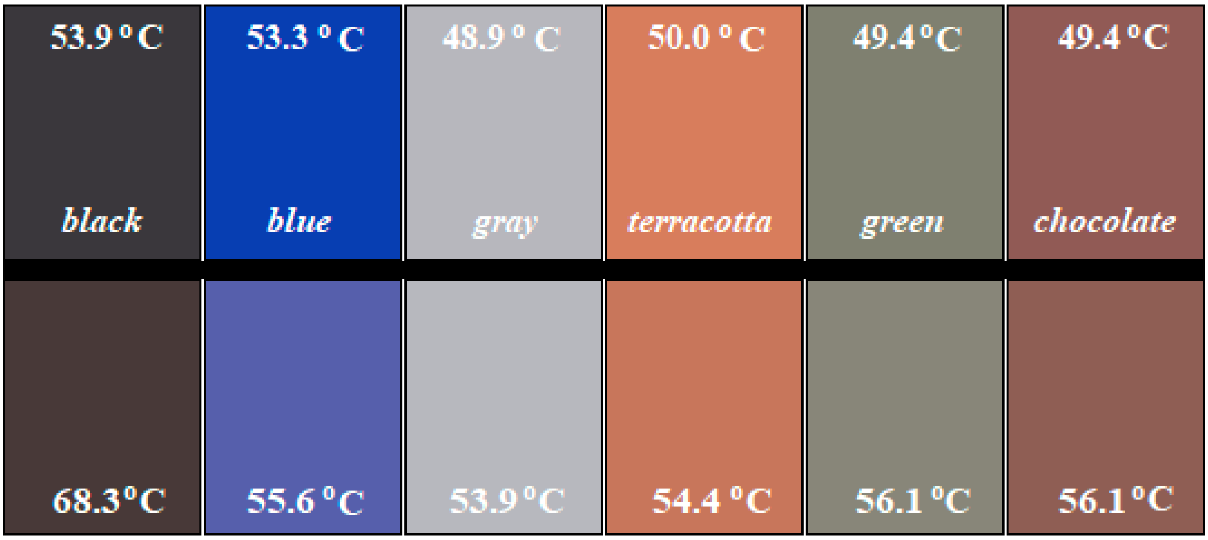

Figure 4. Range of colours having and surface temperatures of cool tile coatings (**top**) designed similarly to standard colour coatings (**bottom**) [40].

On the other hand, Aggarwal and Molleti [41] highlight several drawbacks associated with cool tile coatings, including concerns related to durability, maintenance, aesthetics, cost, microclimatic effects, and moisture problems. One significant issue is the durability and maintenance of these coatings. Over time, factors such as dust accumulation, biological growth, and UV degradation can reduce their solar reflectance, which diminishes their effectiveness. This degradation requires regular cleaning and maintenance to ensure optimal performance, a process that can be both expensive and inconvenient for homeowners. Another drawback relates to aesthetics. Whilst advancements in cool-coloured coatings have increased the variety of options available, the range of colours may still fall short of meeting all preferences. Additionally, lighter colours, which generally provide higher solar reflectance, may not align with certain architectural styles or regional preferences, limiting their appeal in some contexts. Cost is also a notable concern. The initial expense of applying cool tile coatings is typically higher than that of traditional roofing materials. Although these costs can be offset by energy savings in the long term, the upfront investment may act as a barrier for some individuals or households. The potential impact on local microclimates represents another consideration. While cool roofs can help reduce the urban heat island effect, they may also lead to increased heating demands during winter in colder regions. This trade-off underscores the importance of tailoring cool roof strategies to specific climatic conditions. Lastly, moisture-related problems can arise in certain environments. In regions with high humidity or frequent rainfall, the lower temperatures of cool roofs can increase the risk of moisture accumulation, potentially leading to issues such as mould growth or structural damage. These drawbacks illustrate the complexity of implementing cool tile coatings and emphasise the need for careful planning to balance their benefits with potential challenges.

Tables 1–3 [40] illustrate the colour pair trial parameters, and the reduction of temperature and heat flux measured in each of six colour pair trials. Thanks to this technology, while reducing the tile temperature, heat gain and cooling energy requirement, the appearance of the roof is also improved.

Table 1. Solar reflectance and measurement program as trial parameters of colour pair [40].

Colour	$\rho_{standard}$	ρ_{cool}	$\Delta\rho$	Trial Dates	Clear Sky, A/C On	Clear Sky, A/C Off
Terracotta	0.33	0.48	0.15	6 June 2003–1 July 2003	15 June 2003	30 June 2003
Chocolate	0.12	0.41	0.29	6 July 2003–15 July 2003	6 July 2003	10 July 2003
Grey	0.21	0.44	0.23	17 July 2003–6 August 2003	27 July 2003	31 July 2003
Green	0.17	0.46	0.29	8 August 2003–19 August 2003	16 August 2003	8 August 2003
Blue	0.19	0.44	0.25	21 August 2003–3 September 2003	22 August 2003	31 August 2003
Black	0.04	0.41	0.37	4 September 2003–6 October 2003	14 September 2003	5 September 2003

$\rho_{standard}$ is solar reflectance values of standard tiles. ρ_{cool} is solar reflectance values of cool tiles. $\Delta\rho$ is solar reflectance increase which is equal to solar absorptance decrease, $\Delta\alpha$.

Table 2. Reduction in temperatures and heat flux due to a clear sky day with A/C [40].

Colour	$\Delta\rho = \Delta\alpha$	I [W/m^2]	$\Delta T_{surface}$ [K]	ΔT_{attic} [K]	$\Delta q_{ceiling}$ [W/m^2]	Trial Date, A/C On
Terracotta	0.15	873	4.6	1.9	1.0 (13%)	15 June 2003
Chocolate	0.29	778	8.6	3.7	1.7 (17%)	6 July 2003
Grey	0.23	817	6.7	2.8	1.4 (15%)	27 July 2003
Green	0.29	834	9.6	3.9	2.0 (17%)	16 August 2003
Blue	0.25	822	8.2	2.3	1.1 (13%)	22 August 2003
Black	0.37	734	13.8	5.5	2.1 (21%)	14 September 2003

$\Delta\rho$ is solar reflectance increase which is equal to solar absorptance decrease, $\Delta\alpha$. I is peak horizontal solar irradiance. $\Delta T_{surface}$ is peak temperature drop in tile surface. ΔT_{attic} is peak temperature drop in attic air. $\Delta q_{ceiling}$ is peak heat flux drop in ceiling.

Table 3. Reduction in temperatures and heat flux due to a clear sky day without A/C [40].

Colour	$\Delta\rho = \Delta\alpha$	I [W/m^2]	$\Delta T_{surface}$ [K]	ΔT_{attic} [K]	$\Delta T_{interior}$ [K]	Trial Date, A/C Off
Terracotta	0.15	863	5.5	3.0	0.8	30 June 2003
Chocolate	0.29	847	9.4	4.0	1.0	10 July 2003
Grey	0.23	848	6.8	2.8	1.1	31 July 2003
Green	0.29	856	11.0	4.5	1.1	8 August 2003
Blue	0.25	794	8.2	2.4	0.7	31 August 2003
Black	0.37	766	13.5	7.2	1.8	5 September 2003

$\Delta\rho$ is solar reflectance increase which is equal to solar absorptance decrease, $\Delta\alpha$. I is peak horizontal solar irradiance. $\Delta T_{surface}$ is peak temperature drop in tile surface. ΔT_{attic} is peak temperature drop in attic air. $\Delta T_{interior}$ is peak temperature drop in interior air.

A detailed examination of Table 1 reveals that cool tiles exhibit higher solar reflectance (ρ_{cool}) values compared to standard tiles ($\rho_{standard}$), with a corresponding increase in solar reflectance ($\Delta\rho$), which is directly linked to a reduction in solar absorptance ($\Delta\alpha$). For instance, black tiles demonstrate the highest increase in reflectance (Δρ = 0.37), indicating their potential effectiveness in mitigating heat absorption. In Tables 2 and 3, the cooling benefits of increased solar reflectance are quantified under conditions with and without A/C. Table 2 shows that black tiles, with the highest Δρ, lead to a significant surface temperature drop of 13.8 K and a peak heat flux reduction of 2.1 W/m^2 (21%) under clear skies with A/C. Similarly, Table 3 highlights that, even without A/C, black tiles achieve a notable reduction in surface temperature (13.5 K) and attic air temperature (7.2 K). This demonstrates the potential of cool tiles in reducing cooling loads and indoor heat stress in both active and passive cooling scenarios. These findings suggest that incorporating cool tile technology can be an effective strategy for diminishing UHI effects, improving thermal comfort, and decreasing energy demands, particularly in regions with high solar radiation.

2.2. Grass, Green Roofs and Facades

Green surfaces, such as vegetation or specially designed coatings for urban cooling, are often associated with high solar reflectance and thermal emissivity. However, these properties can vary significantly depending on the specific characteristics of the surface, such as colour, material composition, and texture. High solar reflectance and thermal emissivity contribute to keeping green roofs and facades cool, particularly by minimising heat absorption during the daytime and facilitating heat dissipation at night. However, during the daytime, evapotranspiration plays a dominant role in cooling by releasing moisture into the atmosphere [21,42]. A study shows how trees and grass effect the outdoor thermal comfort in hot and arid climatic conditions [43]. The results indicate that up to 2 °C outdoor temperature decrease is achieved. A computer simulation model is used by Srivanit and Hokao [44] to evaluate the cooling effect of greening on microclimates. In the related study, the largest ambient air temperature drop is calculated to be 2.29 °C. Shahidan et al. [45] use a similar simulation method to estimate the optimum cooling potential of the combined tree and ground physical material. The average temperature reduction is found to be up to 2.70 °C. It is underlined that the use of these combinations can mitigate the UHI effect, especially in tropical climate conditions. In terms of thermal comfort evaluation, the highest physiologically equivalent temperature (PET) drop is obtained as to be 4 °C [46], and 3.90 °C [47] by turf application. Roof applications of grass have been found to surpass ground-level applications in terms of their effectiveness in mitigating human heat stress and enhancing microclimate conditions. This is primarily attributed to the increased exposure of roof surfaces to solar radiation, where grass can reduce surface temperatures more significantly through evapotranspiration and shading effects [48,49]. Moreover, the elevated position of green roofs enables improved airflow and greater thermal insulation, which collectively contribute to better regulation of urban heat and microclimatic improvements [50]. Combined applications can be used to improve microclimate and thermal comfort. Two comprehensive studies mentioned above show that the combination of trees and grass provides a reduction in ambient temperature of up to 2 °C [43] and 2.29 °C [44]. In addition to these results, a maximum of 10 °C PET is observed in terms of thermal comfort with the use of tree and grass combinations [46]. These applications are ideal not only for the summer season but also for the winter season. A recent study [51] reveals that a wider application of deciduous trees and grass for public parks has great potential to increase the ambient temperature for the high thermal comfort of cities.

With roofs occupying 20–25% of urban settings [24,52], they represent a significant opportunity for mitigating global warming's adverse impacts. A green roof is an extension of the existing roof which generates a layer for planting vegetation over a waterproofing system. Green roofs are also called as vegetative or eco-roofs [53]. Green roofs are classified as intensive and extensive type green roofs (as seen in Figure 5). Intensive green roofs are mostly preferred for commercial buildings where owners need large spaces to integrate different types of plants. The application can also include paths and walkways to generate an extra relaxing and interaction natural work environment for employees. Extensive green roofs are more preferable for single and multi-family residential buildings. In this application, walking area is limited and mostly used for maintenance purposes. The application has thermal advantages and provides high performance in water usage while reducing the roof weight, especially compared to the intensive one [54]. In addition to this, the cooling potential of extensive green roof structure is found to be higher than intensive green roof type [55]. As shown in Table 4, it highlights key differences between extensive, semi-intensive, and intensive green roof systems. Extensive green roofs, characterised by minimal soil depth (5–13 cm) and lower dry weight (4.5–11.5 kg), offer the lowest initial investment cost and require minimal operation and maintenance. These features make them highly suitable for applications prioritising cost efficiency and reduced structural load. In contrast, semi-intensive and intensive systems involve greater soil depth and higher dry weights, with intensive systems supporting a wider variety of vegetation, including large shrubs and trees. However, these systems demand higher initial investment costs and routine maintenance, which may limit their feasibility in cost-sensitive projects. Furthermore, the added weight and structural demands associated with intensive systems necessitate careful consideration in building design and retrofitting. Similarly, in a study that analysed the quantitative costs of green roofs and green walls, it is revealed that these types of designs are generally more costly than conventional systems when installation cost, operation and maintenance, and disposal costs are taken into consideration [56]. However, their longer lifespan and additional benefits, such as mitigating the UHI effect through natural vegetation and soil, make them more logical and sustainable choices in the long run [56]. From these findings, it can be concluded that the choice of green roof system should be aligned with the specific requirements of the building and its intended use. Extensive green roofs are particularly advantageous in lightweight structures and cost-sensitive residential applications, whereas intensive systems are more suitable for projects aiming to maximise green space and vegetation diversity. Additionally, green roofs have also the ability to reduce effect of UHI through natural vegetation and soil [57].

Figure 5. Green roof systems as intensive (**left**) and extensive (**right**) [57].

Table 4. Comparison of different types of green roof systems [57].

Features	Extensive	Semi-Intensive	Intensive
Types of Plants	Moss, sedum, grass	Moss, sedum, grass, shrubs, herbs, flowers	Moss, sedum, grass, large shrubs, trees
Soil Depth	5 cm to 13 cm	13 cm to 20 cm	20 cm to 76 cm plus
Dry Weight	4.5 kg to 11.5 kg	11.5 kg to 18 kg	18 kg to 45.5 kg plus
Types of System	Built-up, tray	Built-up, tray	Built-up
Operation and Maintenance	Minimum	Rare/routine	Routine
Initial Investment Cost	Low	Medium	High

According to studies, green roofs enhance indoor air quality [58,59] through their cooling effects, achieved via evapotranspiration and thermal insulation. These mechanisms reduce indoor air temperatures [60], which in turn lowers the cooling demand of buildings and decreases energy consumption. By mitigating heat and reducing reliance on air conditioning, green roofs contribute to a healthier indoor environment. In summer, by covering 30% of the total roof area with green plants, a decrease of 0.06 °C in surface temperature is achieved as can be clearly illustrated in Figure 6 [60]. The data obtained shows that 2–5 °C cooling potential can be achieved during the daytime by using green roof systems. At the same time, green roofs can be 3–6 °C warmer than ambient temperature during the night-time.

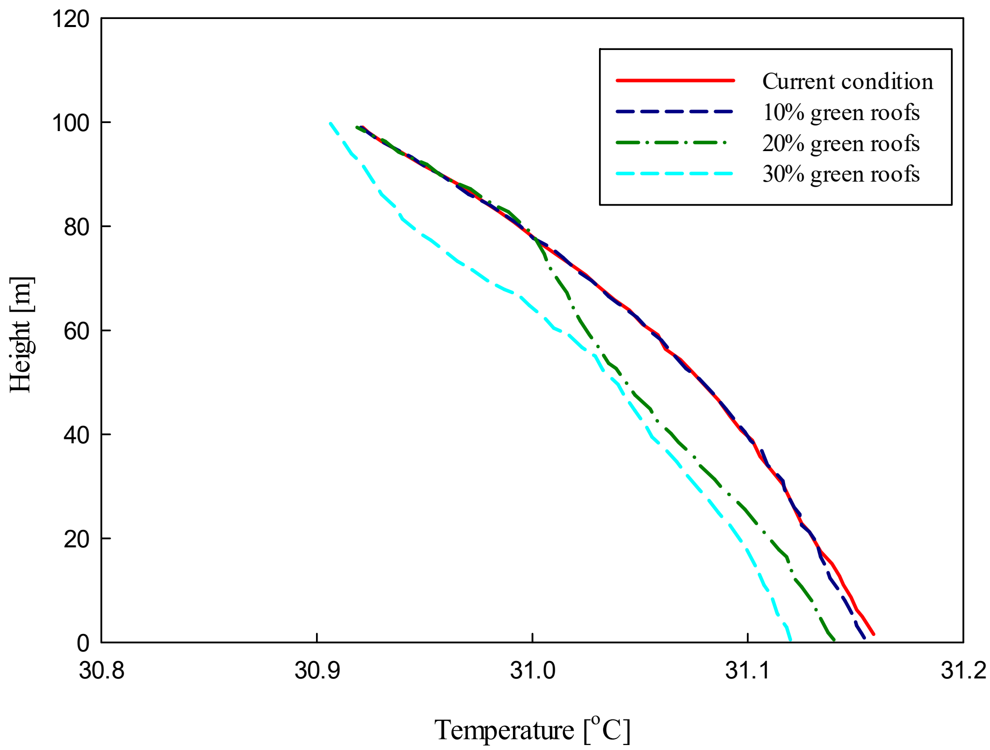

Figure 6. Comparison of different scenarios by covering the top of the building with green roof systems at different rates [60].

Herath et al. [61] report that 50% and 100% coverage of the green roof and 50% coverage of the green wall applications lead to a temperature drop of 1.76, 1.79 and 1.86 °C, respectively. Another study says that street trees and green roofs are widely recognised as effective strategies for mitigating urban heat, each contributing uniquely to cooling the urban environment. Figure 7 presents a meta-analysis comparing their cooling potential based on findings from [62]. Street trees are shown to reduce peak air temperatures by 0.2 °C to 5 °C, primarily through shading and evapotranspiration. However, this effect is localised, with the greatest temperature reductions observed directly beneath or near the tree canopy. While this localised cooling enhances pedestrian comfort, it may not significantly affect overall urban temperatures. Moreover, extreme planting densities, which achieve greater cooling effects, are often impractical for urban implementation. Green roofs, by contrast, exhibit a more modest cooling effect, with air temperature reductions averaging around 0.3 °C. Their impact is often limited to the immediate rooftop area, as the cooling benefits from evapotranspiration diminish with height and do not significantly influence street-level temperatures in dense urban areas. Nevertheless, green roofs effectively lower roof surface temperatures, reducing building cooling loads and indirectly contributing to urban heat mitigation. The analysis highlights notable variability in the reported cooling effects, reflecting differences in study methodologies, urban contexts, and climatic conditions. Furthermore, it underscores the necessity of standardised evaluation metrics to facilitate more robust comparisons. While street trees are more effective in directly cooling the pedestrian environment, green roofs contribute to wider energy efficiency and thermal regulation objectives. An integrated approach combining both strategies could offer greater potential for sustainable urban cooling and microclimate improvement.

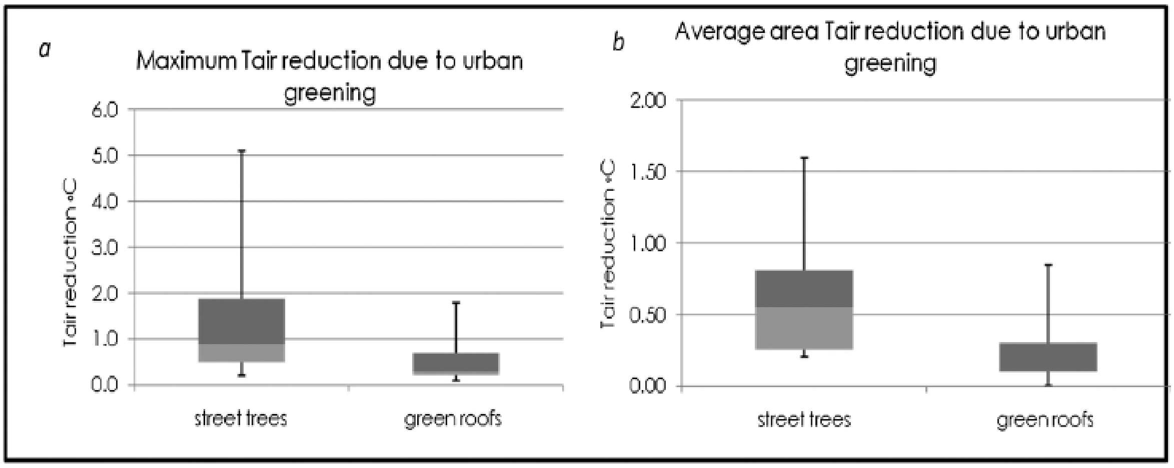

Figure 7. Comparison of the cooling potentials of street trees and green roofs with respect to (**a**) the maximum, and (**b**) the average area T_{air} drop due to urban greenery [62].

2.3. Shrubs and Trees

External physical properties help to distinguish between shrubs and trees. Shrubs have several stems that grow from the ground whereas a tree has one trunk. A study carried out by Rui et al. [63] state that the effects of vegetation on microclimate and air quality are not only related to green cover, but also to the vegetation types and tree placement. In this study, CO_2 absorption efficiency ratio is also investigated, and the results show that the efficiency ratio between grass, shrubs and trees is 1:15:30 as clearly discussed in Table 5. It is also emphasised that the effect of vegetation on air quality and microclimate should be analysed using various indices which take into account both the total area covered by vegetation, the settlement pattern and the degree of clustering. Shrubs are capable of decreasing the surface temperature of soil [63]. As clearly discussed in Table 5, vegetation plays a crucial role in mitigating CO_2 emissions over extended periods. The data in the table provides a comparative analysis of different vegetation types based on their CO_2 absorption capacity and the depth of soil cover required. For instance, coniferous trees and small broad-leaved trees can capture up to 600 kg/m^2 of CO_2 over a 40-year period, significantly outperforming shrubs and grasses, which absorb 300 kg/m^2 and 20 kg/m^2, severally. The variations are largely attributable to differences in canopy density, root structure, and overall biomass accumulation. It is important to consider the spatial distribution and clustering of these vegetation types, as the overall effectiveness of CO_2 sequestration depends on these factors. For example, shrubs require at least four plants per square meter to achieve their potential CO_2 absorption rate. Similarly, the depth of soil cover also directly influences the health and growth of vegetation, with trees necessitating a depth of over 1.0 m, whilst shrubs and grasses thrive in shallower soils of >0.5 m and >0.3 m, respectively. To analyse the effect of vegetation on air quality and microclimate comprehensively, it is essential to employ diverse indicators. These should account not only for CO_2 absorption but also for variables like soil temperature regulation, albedo changes, and evapotranspiration rates. For instance, as noted, shrubs are capable of decreasing soil surface temperatures, which may contribute to localised cooling effects and improved microclimate conditions. Indicators must also reflect settlement patterns and vegetation clustering, as dense vegetative clusters can amplify cooling effects and enhance pollutant dispersion [63].

Table 5. The quantity of CO_2 captured by different plant species over a span of 40 years [63].

Type of Vegetation	The Amount of CO_2 Absorption [kg/m^2]	Depth of Soil Cover
Tree (coniferous trees, small broad-leaved trees)	600	>1.0 m
Shrub (at least four plants per square-meter)	300	>0.5 m
Grass (natural weeds, aquatic plants, grass garden, lawns)	20	>0.3 m

Edmondson et al. [64] indicate that in the non-domestic green area, the combination of shrubs and trees decreased the daily average maximum surface temperature of the soil by 5.7 °C in summer compared to the herbaceous vegetation as it is clearly given in Table 6. In addition, shrubs and trees help to reduce negative effects of urbanisation on the microclimate and human health.

Table 6. Average, minimum and maximum daily temperature values in May, June, July across land-use and vegetation classes [64].

		Domestic		Non-Domestic	
		Shrub and Tree	**Herbaceous**	**Shrub and Tree**	**Herbaceous**
Minimum Temperature	Average	13.7	14.6	13.0	14.4
	Minimum	5.1	5.6	4.6	6.2
	Maximum	20.7	20.1	21.2	21.1
	Range	15.6	14.5	16.6	14.9
Average Temperature	Average	15.2	16.6	14.1	17.2
	Minimum	7.5	9.0	7.1	9.4
	Maximum	24.7	24.2	24.2	26.9
	Range	17.2	15.2	17.1	17.5
Maximum Temperature	Average	17.3	19.5	15.2	20.9
	Minimum	8.1	9.2	7.1	10.2
	Maximum	32.2	35.7	27.7	36.2
	Range	24.1	26.5	20.6	26.0
Sample Size		11	8	41	19

Trees are more effective than shrubs at lowering air and surface temperature owing to their greater shading effect [52,65]. It can also be underlined that trees are more effective than grass in improving the microclimate [48] and reducing human heat stress [50]. The ENVI-met modelling study reveals that even in temperate suburban areas, a 5% increase in the population of mature trees and new trees is able to lower the mean hourly surface temperature by 1 °C and 0.5 °C, respectively [65]. In addition to this, when all existing vegetation is replaced with asphalt, a significant increase in surface and air temperatures is observed, up to 4.7 °C and 3.2 °C, respectively. The application of trees to the curb leads to a 1.87 °C reduction in ambient air temperature [61]. Research done by Gill [66] presents that every 10% increase in green vegetation results in a 1.5 °C drop of surface temperature. In another research, a maximum temperature reduction of 2.5 °C is achieved in a courtyard decorated with shady trees and grass as it is seen in Figure 8 [67].

Figure 8. Courtyards with bare pavements and shading nets (**left**), grass and trees (**right**) [67].

The air temperature changes are presumably related to the combined effects of shading and evapotranspiration [67,68]. The cooling efficiency increases with increasing air change rate as it is clearly shown in Figure 9. The concept of cooling efficiency inherently assumes positive values, yet in certain scenarios, such as when landscaping strategies induce net heating (e.g., grass under shading meshes), negative efficiencies may emerge. This highlights the importance of defining and contextualising cooling efficiency within realistic parameters. Furthermore, while very high air exchange rates can artificially produce exaggerated efficiency values, these scenarios are unlikely to occur in practical applications. Such unrealistic outcomes underscore the need for caution when interpreting data and stress the importance of aligning results with feasible operational conditions. A systematic exploration of these limitations, coupled with a discussion of alternative cooling strategies or complementary methods, can provide a more balanced understanding of the findings.

In the city of Colombo, it is reported that a reduction in air temperature of 1.9 °C is achieved by combining all the options (trees, green roofs, green walls) that could be used as a strategy to improve the thermal comfort of the city residents [61]. Duarte et al. [69] prove that in urban areas decorated with trees, there can be a temperature drop of 0.30–1.5 °C in ambient air temperature. It is also possible to reach a 2.27 °C air temperature reduction by increasing the amount of trees by about 20% [44]. Salata et al. [70] study on different strategies to mitigate the effects of the urban microclimate on the campus of Sapienza University in Rome. Trees have the highest potential for air temperature decrease, followed by green roofs and grass. In the urban area, an ambient temperature drop of 2–3 °C is possible to achieve using existing mitigation technologies [71]. According to data gathered using ENVI-met, urban renovation with additional street trees and cool pavements is another way to lower the air temperature by up to 1.5 m elevation [72]. On the other hand, trees have a positive effect on indoor thermal comfort of building occupants. For instance, a 20.8% improvement in indoor thermal comfort is observed by planting 17% more trees in Manchester [73]. The minimum, maximum and average surface urban heat island intensity in city of New Delhi between the years of 1991 and 2018 is calculated as to be 1.26 °C, 4.6 °C and 1.18 °C, respectively, resulting in a noticeable decrease in thermal comfort [74]. A significant temperature drop of 2.07 °C is achieved by adding trees to the curb sides in the Colombo metropolitan area, so green infrastructure is found to be the most appropriate way to improve the thermal comfort conditions of the urban environment [75]. A CFD (Computational Fluid Dynamics) modelling using ENVI-met shows that trees are able to decrease ambient air and surface temperature by 0.2 °C and 0.5–0.8 °C, respectively. On the other hand, if the combination of tree, grass and green roof is applied, a reduction of 0.1–0.3 °C in air temperature is observed, while a reduction of 0.4–1.1 °C in surface temperature is obtained [76]. Changes in air temperature, temperature humidity index and surface temperature over time are given in Figure 10a–f. Figure 10a,b illustrate that during the early morning hours, when the air is cooler, temperatures across both configurations remain on the colder scale. However, as midday approaches, the temperature rises more noticeably in the other configurations, whereas the green roof scenario maintains relatively lower temperature levels. This trend persists throughout the entire time interval around midday. Similarly, Figure 10c,d suggest that approaching midday, thermal comfort levels are more likely to be achieved with green roofs. Finally, Figure 10e,f focus on surface temperatures. The authors note that the surface temperature of the green roof could not be measured. However, they observe that areas with buildings surrounded by trees remain cooler. Additionally, they assert that, had measurements been available, green roofs would undoubtedly exhibit lower surface temperatures compared to other cases. Overall, these findings highlight the significant role of green roofs in mitigating urban heat and enhancing thermal comfort, particularly during peak daylight hours. Teshnehdel et al. [77] present a numerical simulation approach using ENVI-met v4 software to investigate the impact of heat reduction strategies on thermal comfort. The results indicate that a decrease in air temperature is possible through water body evaporation with no trees. However, this technique increases the specific humidity of air, which can offset the cooling effect and potentially reduce thermal comfort. In contrast, the combination of water bodies and trees demonstrates superior performance in improving thermal comfort and regulating the microclimate.

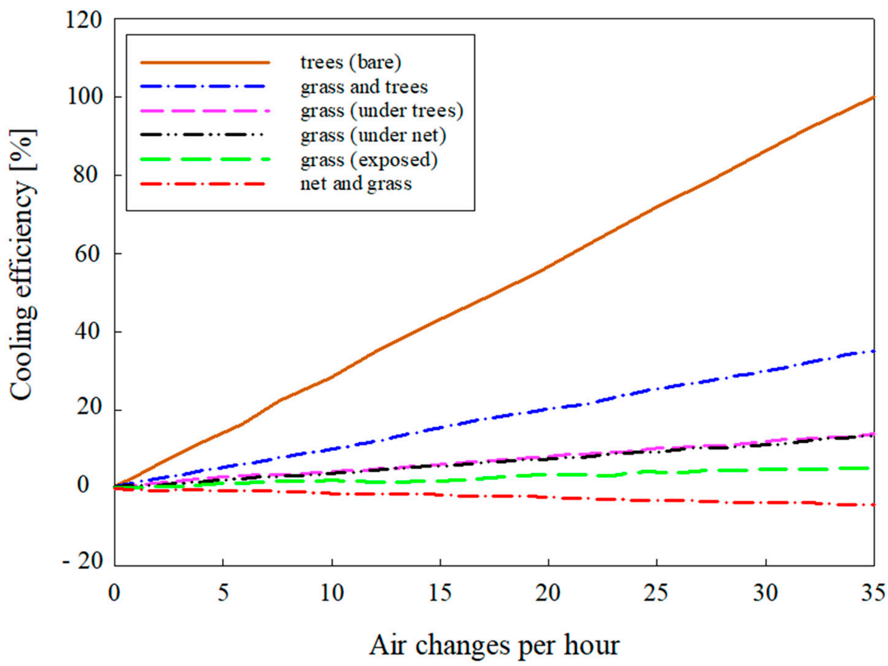

Figure 9. The effect of different assumed air change rates in the courtyards on the calculated cooling efficiency, leaving all other measured inputs unchanged [67].

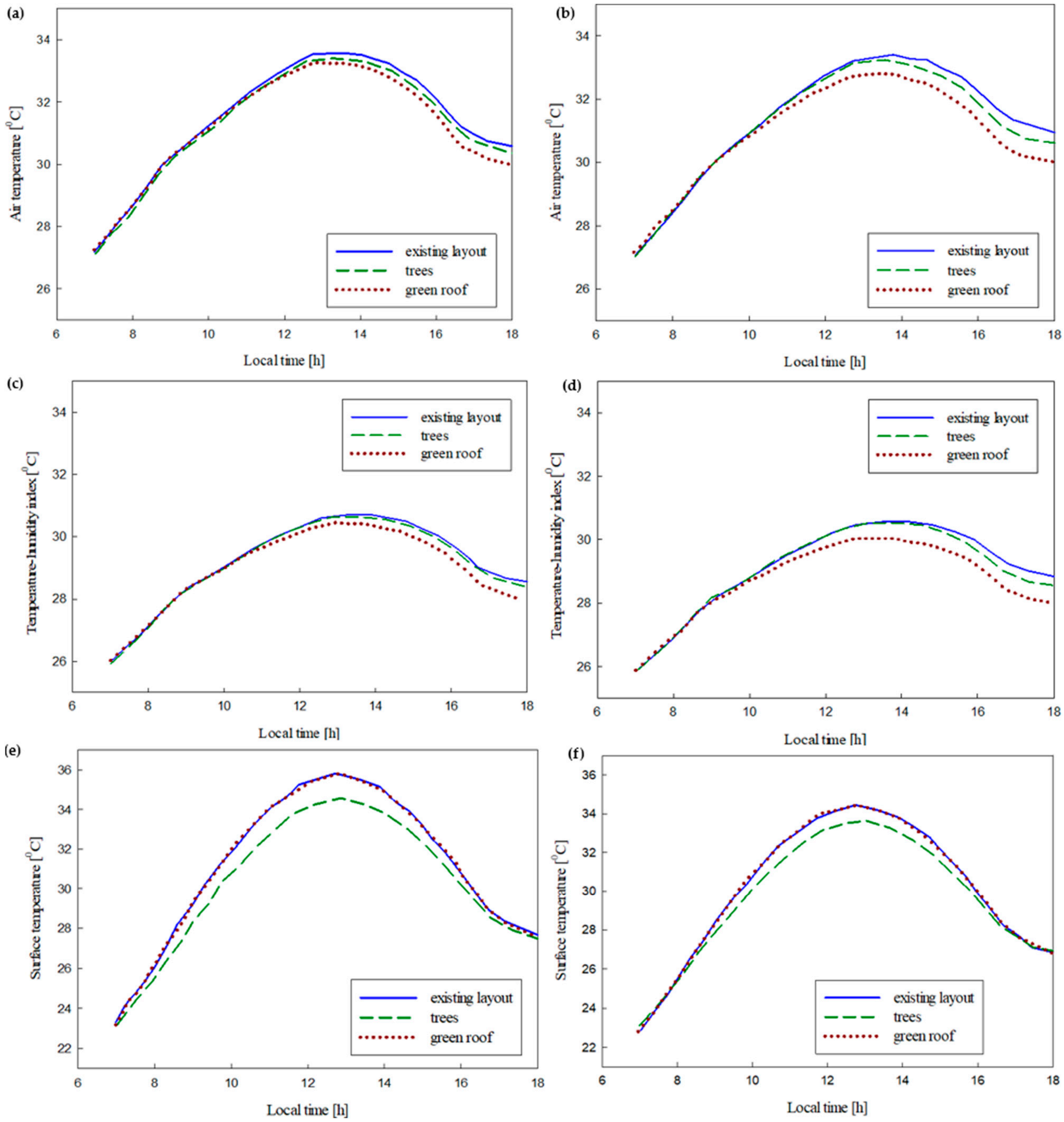

Figure 10. (**a**) Air temperature variation with time in selected Sub-area 1, (**b**) Air temperature variation with time in selected Sub-area 2, (**c**) Temperature-humidity index (THI) variation with time in selected Sub-area 1, (**d**) Temperature-humidity index (THI) variation with time in selected Sub-area 2, (**e**) Surface temperature variation with time in selected Sub-area 1, and (**f**) Surface temperature variation with time in selected Sub-area 2 [76].

3. Impacts of UHI

3.1. Environmental Effects of UHI

Global temperature increase is directly related to climate change, which causes the formation of microclimates in urban areas [78]. One of the effects of climate change is the UHI, which is seen as the main reason for urban microclimate development. The UHI results in increased cooling energy demand in the urban environment [79], thus increasing the rate of greenhouse gas emissions and pollution [78]. For instance, a study shows that in the City of Athens, the energy requirement and peak energy load for cooling purposes increase by twofold and threefold, respectively [80,81]. However, UHI effects are not limited to cooling demands. While heating loads in dwellings decrease by 30% during the winter season [81], the overall energy balance of urban areas can vary depending on the local climate, building infrastructure, and seasonal temperature variations. Beyond energy considerations, UHI negatively impacts outdoor and indoor air quality due to the accumulation of pollutants exacerbated by limited air circulation. Additionally, rapid temperature changes and fluctuations pose a threat to natural habitats and wildlife, which are highly sensitive to such disturbances [78]. Other notable impacts include increased thermal stress on human populations, changes in precipitation patterns, and heightened risk of extreme weather events. These interconnected effects highlight the urgent need for comprehensive strategies to mitigate the adverse consequences of urban microclimates and climate change.

3.2. Effects of Urban Heat Island on Human Health

It is a fact that ground-level pollution increases in the areas affected by UHIs. This phenomenon exacerbates air quality issues and contributes to higher concentrations of pollutants, such as ground-level ozone, which can aggravate respiratory conditions. Especially during periods, exposure to high temperatures may result in heat stress on the human body, causing weakness, various ailments, consciousness disorders, cramps, heat stroke, fainting and triggering pre-existing chronic diseases [78]. Vulnerable populations, including the elderly, children, and individuals with pre-existing chronic conditions, are at higher risk of heat-related illnesses [82]. Studies have shown that the increased urban heat during extreme heat events can significantly worsen cardiovascular and respiratory diseases, while also triggering mental health issues like anxiety and fatigue [83]. Therefore, it is clear to say that increasing mean temperature due to UHI threatens the human health [84]. In Beijing, 4.6 °C temperature difference is observed between urban and surrounding area of the city centre. This situation, which causes extra hot days, directly affects the human health and wellbeing [84,85]. Increasing urban mean temperature associated with UHI triggers the thermal stress [86–88], resulting in rising human mortality [87]. For instance, between June and August 2022, Europe experienced its deadliest meteorological events in the form of intense heat waves, which led to more than 20,000 deaths linked to high temperatures. Looking ahead, the global need for air conditioning is predicted to grow at an accelerated rate, with estimates indicating that by 2100, electricity consumption for cooling will be 40 times greater than in 2000 [89]. This growing concern over the increased demand for cooling systems and the associated energy consumption highlights the importance of exploring alternative solutions. Recent studies have explored the benefits of green infrastructure in mitigating UHI effects. For example, green roofs are found to provide thermal regulation of air while also promoting human health in an environmentally sustainable and cost-effective manner [90,91].

4. Thermal Comfort Parameters

Four thermal comfort definition models are used to measure comfort level of the living space [92]. A model called apparent temperature (AT) is developed by Steadman [93–96] and used by Australian Bureau of Meteorology (ABM) [97] for Australian climatic conditions. The model is a combination of solar radiation, wind and heat transfer [92,93]. The model is given as follows:

$$AT = T_{\infty} + \frac{3.3e_{RH}}{1000} - 0.7v_{10\ m} - 4 \quad (1)$$

$$e_{RH} = (RH/100)e_{sPa} \quad (2)$$

where T_∞ is ambient air temperature (°C), and e_{RH} is vapour pressure (Pa) which is calculated using relative humidity (RH) in percentage. e_{sPa} is given as saturated vapour pressure (Pa). v is defined as wind velocity (m/s) is measured at 10 m height.

A heat index (HI) equation [86,94,98] is introduced to predict heat stress for early warning, which is directly responsible for human climate-related disturbances. The aforementioned equation is given as follows:

$$\begin{aligned} HI = -42.379 + \; & 2.04901523T_\infty + 10.14333127RH - 0.22475541T_\infty RH - 6.83783 \times 10^{-3}{T_\infty}^2 \\ & -5.481717 \times 10^{-2}RH^2 + 1.22874 \times 10^{-3}{T_\infty}^2 RH + 8.5282 \times 10^{-4}T_\infty RH^2 - 1.99 \times 10^{-6}{T_\infty}^2 RH^2 \end{aligned} \quad (3)$$

Some assumptions in the model are: A walking male, weighing 67 kg, wearing shorts and a T-shirt, not exposed to direct sunlight [92,98]. All relevant assumptions applied to the above model can be seen in the paper written by Rothfusz [98]. After the calculation of HI, collected data is evaluated. Table 7 shows level of heat stress according to data from National Weather Service (NWS), US [86].

Table 7. Human stress level data range according to US National Weather Service [86].

Heat Stress Level	Temperature (°C)
Risk	<27
Caution	27–32
Extreme Caution	33–39
Danger	40–51
Extreme Danger	≥52

Other thermal comfort model named Humidex (HUMIDEX) is developed to qualify the feels like temperature of people [99] and it is used by Meteorological Service of Canada (MSC) [92]. In original form of the equation, dew point temperature is preferred instead of specific humidity. A unitless HUMIDEX equation [99] is given as follows:

$$HUMIDEX = T_\infty + \frac{5}{9}\left(\frac{e_{RH}}{100}\right) - 10 \quad (4)$$

Remarkable thresholds are given in Table 8 [99] according to the evaluation of data obtained from computational results.

Table 8. Remarkable thresholds according to the computational results [99].

Heat Stress Level	Threshold
Discomfort	30
Dangerous	46
Close to heatstroke	54

Another unitless index called Temperature Humidity Index for Comfort (THIC) is utilised for livestock industry [92,100]. The model is a modified version of the Temperature Humidity Index (THI) and is calibrated with the thermophysical properties of pigs [92,101]. Mentioned index is given below:

$$THIC = 0.72T_{wb} + 0.72T_\infty + 40.6 \quad (5)$$

where T_{wb} is wet-bulb temperature (°C). Behavioural changes of physically large animals are defined using this index. The equation is still in use by livestock farmers to measure the heat stress level [90,102]. According to data gathered with the use of equation, 3 threshold levels are classified as it is seen in Table 9 [92].

Table 9. Qualitative threshold levels for physically large animals [92].

Heat Stress Level	Threshold
Alert	75
Dangerous	75–83
Very dangerous	≥84

Empirical equations (Equations (6) and (7)) are developed to examine the impact of green spaces on thermal comfort, focusing on mean radiant temperature (MRT) and predicted mean vote (PMV) [63]. MRT represents a key meteorological factor for assessing thermal comfort, influenced by radiation absorbed by the human body, as well as urban geometry and surface materials. PMV, ranging from −4 (very cold) to +4 (very hot), estimates overall thermal sensation by considering the energy balance of the body, incorporating meteorological elements like temperature, humidity, wind speed, and personal variables such as clothing and activity level.

$$MRT = \left[\frac{1}{\sigma_b}\left(LE_t(z) + \frac{\alpha_{sa}}{\varepsilon_p}(SE_t(z) + SSE_t(z))\right)\right]^{\frac{1}{4}} \quad (6)$$

$$\begin{aligned} PMV = \left[0.028 + 0.303 \times e^{((-0.036)\times\frac{RM}{A_{Du}})}\right] \times \left[\frac{WE}{A_{SS}} - E_{dif} - E_{sw} - E_{lhl} - SHL - R - C\right] \\ = PMV\ (T_{air},\ T_{mr},\ V_w,\ RH,\ M,\ I_{cl}) \end{aligned} \quad (7)$$

where for Equation (6), the Stefan-Boltzmann constant, symbolised as σ_b, equals 5.67×10^{-8}. $LE_t(z)$, $SE_t(z)$, and $SSE_t(z)$ correspond to incoming longwave energy, direct shortwave energy, and scattered shortwave energy, respectively. The human body's shortwave absorption rate, α_{sa}, is established at 0.7, whilst its emissivity factor, ε_p, is determined to be 0.97. For Equation (7), RM represents the rate of metabolism, while WE denotes the external workload. A_{SS} signifies the skin's surface area. E_{dif} and E_{sw} refer to the heat expelled through moisture diffusion and sweat evaporation, respectively. E_{lhl} and SHL account for the latent and sensible heat losses through respiration, respectively. R and C indicate radiant and convective heat exchanges, respectively. The air temperature is indicated by T_{air}, and T_{mr} denotes the mean radiant temperature. Wind speed is shown by V_w, and RH signifies relative humidity. Finally, I_{cl} is used to describe clothing insulation.

5. Conclusions

This review examines a novel approach to mitigating the UHI effect by integrating various greenery systems into urban environments, emphasising the synergistic benefits of combining green roofs, facades, trees, shrubs, and grass. The main findings of this paper highlight the importance of a holistic evaluation of these greenery strategies as interconnected systems rather than isolated technologies. By reviewing and comparing a wide range of empirical studies, this work introduces a unified framework that enhances our understanding of how integrated greenery can reduce UHI impacts on a large scale. The paper also identifies key factors such as thermal comfort, air quality improvement, and passive cooling as the primary advantages of these systems. Beyond consolidating existing knowledge, the work also provides a foundation for future efforts to optimise urban greenery strategies and develop climate-resilient cities. By synthesising findings from a diverse range of studies, it highlights the multifaceted benefits of greenery systems in urban contexts. Notably, integrating green roofs, facades, and vegetation into urban structures has demonstrated up to a 2 °C reduction in ambient temperatures and improved thermal comfort indices by over 10 °C under specific scenarios. These outcomes reinforce the pivotal role of green infrastructure not only in mitigating UHI impacts but also in reducing cooling energy demand by approximately 15%. Furthermore, strategic tree placement along pavements contributes to localised shading and evapotranspiration effects, enhancing both pedestrian comfort and overall energy efficiency. These findings underline the critical importance of prioritising green infrastructure within urban planning frameworks to foster sustainable, climate-resilient cities. Consequently, the main contribution lies in presenting a comprehensive, integrated methodology for assessing and implementing greener solutions, offering practical guidance for urban planners and policymakers to address UHI effects effectively.

- Green roofs and facades significantly contribute to UHI mitigation by improving energy efficiency, reducing air pollution, and offering passive cooling, especially in high-density urban areas.
- A study reported that average daily air temperature and MRT decreased by 0.5 °C and 22 °C, respectively, leading to a PET of 23 °C on the hottest days, aligning with comfort zones.
- The combination of water bodies with trees shows notable cooling potential, with PET index values falling from 37.5 °C (without greenery) to 23 °C (with greenery and water bodies), a substantial improvement in thermal comfort on the hottest days.
- Critical thresholds for human health indicate core temperatures of 38.5 °C for heat exhaustion and 42 °C for heat stroke, stressing the importance of UHI mitigation for public health.
- Cool pavements and reflective surfaces have been shown to reduce air temperature by up to 0.22 °C and surface temperature by up to 20 °C, respectively, providing additional UHI mitigation options.
- Urban greenery (trees, shrubs, and grass) provides shading and evapotranspiration effects, which can reduce outdoor temperatures by up to 2 °C in hot, arid climates.
- Extensive green roofs, ideal for residential areas, reduce cooling loads and indoor temperatures, while intensive green roofs with larger vegetation are more suited to commercial environments.
- Strategically placed greenery, such as trees along pavements or near buildings, effectively reduces surface and air temperatures, with cooling effects reaching up to a 1.87 °C reduction in ambient air temperature.
- Comprehensive strategies that incorporate green urbanism principles, water management, and renewable energy integration offer sustainable pathways for UHI mitigation and urban climate adaptation.
- In the future, expanding green spaces and integrating innovative green infrastructure solutions accelerate cities' transition towards climate-friendly environments, supporting the development of more sustainable, liveable, and resilient urban areas. Broad-scale implementation of green roofs, cool pavements, and afforestation strategies particularly strengthens resilience against climate change and safeguards public health.

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