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Review Article

Causes, Modeling and Mitigation of Urban Heat Island: A Review

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Abstract: Urbanization leads to loss of vegetation and converting pervious areas into built-up and impervious areas, and consequently, urban areas expose higher temperatures as compared to surrounding rural areas, which is called Urban Heat Island (UHI). The UHI affects the urban environment and causes heat-related diseases and mortality that have increased over the last centuries. Considering the severity of the UHI problem, enormous research has been conducted and an extensive range of literature is available on this topic. This paper reviews the causes, modelling and mitigation strategies of the UHI. The urban infrastructure and anthropogenic heat sources are the main driving factors in developing the UHI in cities. Many approaches including observation and modelling techniques are used to understand the formation, causes and mitigation of the UHI. The formation and causes of the UHI largely depend on the size, shape and urban infrastructure of the cities as well as climatic conditions. Although various modelling techniques are used to study UHI, there are still lacks in all models to precisely represent the physical phenomena and complex urban infrastructure. Many UHI mitigation strategies are examined by numerous studies, while the increased urban vegetation is a more environmentally friendly solution. The study summarizes the important features and limitations of different modelling techniques and mitigation measures of the UHI. This study also identifies research gaps and proposes areas for further research.

Keywords: UHI, Modeling, Mitigation, Urban Climate, Review

1. Introduction

Climate change has a range of consequences on human health, urban temperature, and the environment. One of the well-known concerns is the increasing frequency and intensity of heatwaves linked with heat stress and increased mortality rate [1], whereas the frequency and intensity will increase in the future [2]. There are numerous definitions for heatwaves [3], most involve a variety of extremely high-temperature conditions for at least 3 consecutive days where the averages of maximum and minimum temperatures exceed the climatological 95th percentile referred to as a heatwave [4]. Summertime heatwaves have also been shown to exacerbate the UHI intensity [5, 6] and results exacerbate biophysical hazards such as heat stroke and associated health problems of the urban residents. Therefore, the UHI and heatwaves as well as increased urban expansion are considered as crucial and prominent issues for developing a sustainable city.

The UHI phenomenon can be classified according to different spatial scales. At the neighbourhood scale, the UHI of individual features/blocks (including buildings and roads) is described as the temperature differences in the intra-city and referred to as the micro-scale UHI. The local/regional scale UHI is described as variations of temperature across the entire urban and surrounding rural areas. The local/regional scale UHI is largely influenced by geographical and climatic conditions. According to the measurement altitudes, the UHI can be measured at different heights within the urban boundary layer. For instance, the surface UHI is calculated as the surface temperature differences (usually using the surface skin temperature) between urban and rural areas, which are called Surface Urban Heat Island (SUHI). The near-surface UHI can be measured as the temperature difference (air temperature difference at 2 m above the surface) between urban and rural areas, which is commonly referred to as the UHI. The urban boundary layer UHI is defined as the air temperature difference between surface and above the roof level, while the canopy layer UHI is defined as atmospheric temperature differences between the ground surface and average building height of a city [7]. The UHI at the surface and near-surface levels have been the subject of many studies [8-11]. The SUHI generally shows the highest intensity as compared to the pedestrian level UHI as the surface is directly heated by solar radiation [8, 10]. The characteristics of the UHI are strongly connected to the incoming shortwave radiation during the day. As the rapid cooling of the rural surrounding occurs at night and the higher solar heat is stored by the impervious surfaces in urban areas, the difference in air temperature at the near-surface is highest during the evening and night. Therefore, the UHI is most pronounced during the sunset and at night.

The increased urbanization is the main driving factor for losing vegetated surfaces and increasing impervious surfaces. According to a population report of [12], 50% of the world population lives in cities and this number will be increased whereby 60% of people will settle in cities by 2030. As a consequence, urbanization will be accelerated in the future. High roughness structures reduce convective heat removal and increase urban temperatures. The pervious areas are replaced by high thermal conductivity materials like concrete, bricks and bitumen. These materials in urban infrastructure absorb and store substantial solar heat during the day and emit heat at night, and this phenomenon is quite favorable in developing the UHI [13]. Urban temperatures are affected by multiple factors especially thermal conductivity and capacities of specific heat of construction materials, surface albedo, anthropogenic heat, urban geometry, lack of green spaces and limited air circulation in urban canyons [14, 15].

Considering the consequences of the UHI effects, considerable studies have been conducted to characterize the near-surface UHI using physics-based numerical climate models in different scales. Furthermore, considerable UHI mitigation strategies aiming to reduce the UHI effects have been proposed in the literature such as modification of urban geometry [16, 17] increasing emissivity and surface albedo [18, 19] increasing urban vegetation and surface shading [20-22]. Mitigation strategies aim to balance thermal energy in the city by increasing thermal energy losses and reducing the corresponding gains. The review of literature relevant to the UHI mitigation strategies revealed that the increased albedo of the urban environment and increased urban vegetation could be promising mitigation measures [23-25]. Recent studies including these mitigation techniques have shown a higher reduction of the UHI strength and provided important climatic benefits [26, 27]. The objective of the present study is to review the causes, modelling and mitigation approaches of the UHI based on the available literature. The study also suggests important research gaps for future study.

Section 2 of this article describes the causes of the UHI, while section 3 discusses the various modelling approaches of the UHI. Section 4 examines various UHI mitigation strategies adopted globally and section 5 recommends further research gaps to be explored, and finally, section 6 presents a conclusion.

2. Major Causes of UHI Generation

The presence of UHI has been studied in many cities around the world and well documented over the past decade. A wide range of factors is responsible for developing the UHI such as urbanization, industrialization, urban morphology, size of cities, meteorological factors and anthropogenic activities. The detailed causes of the UHI are discussed below.

2.1. Loss of Vegetation and Permeability

Urbanization is the major cause of the loss of vegetation and permeability. During these development processes, trees are cut, and naturally vegetated areas are replaced by paving surfaces and construction materials. The loss of vegetation in the urban areas is an important factor in generating the UHI [28]. Vegetation cover plays a crucial role in reducing the temperature by evapotranspirative and shading processes (Figure 1). A significant portion of net radiation is transformed into energy during the evapotranspirative and photosynthesis processes when a surface is covered with vegetation [29]. Within a vegetation area, energy is divided largely into the latent heat fluxes and remaining into the sensible heat fluxes (Figure 1). This phenomenon favours decreasing air temperature, and the division of energy mainly depends on available moisture flow from soil, surface and atmosphere [30]. The ambient air becomes cool during the evapotranspirative process. More loss of naturally vegetated surfaces means a higher loss of cooling in the city areas.

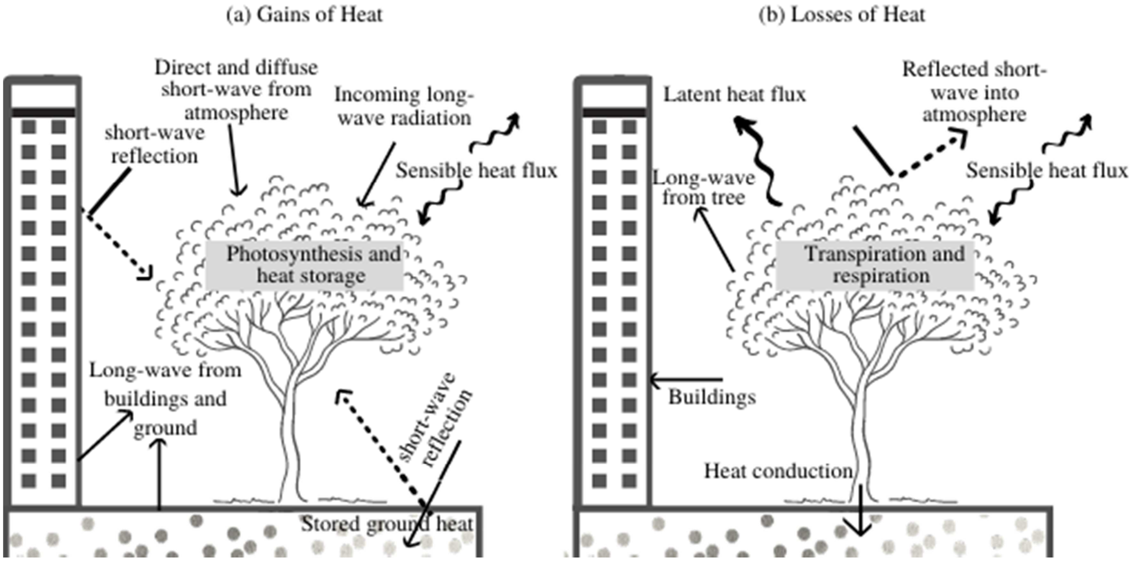

***Figure 1.** The daytime energy exchanges between an isolated tree and its street canyon environment (Adapted from [31]).*

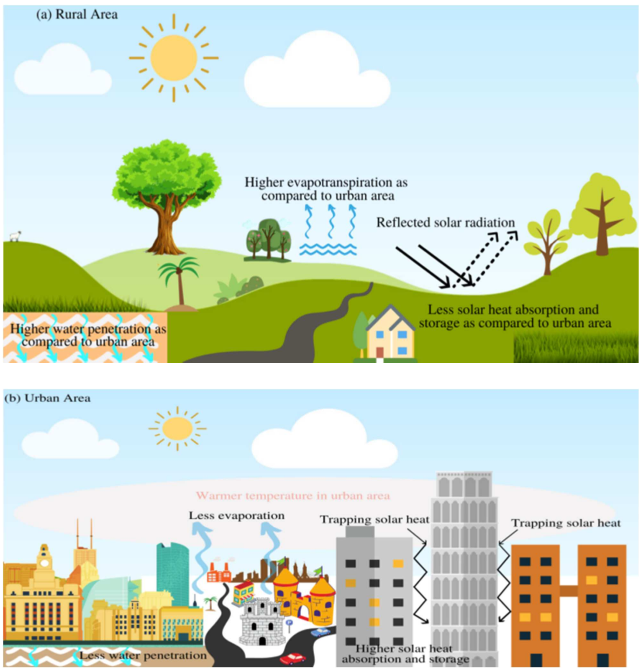

***Figure 2.** Typical characteristics of (a) rural (pervious) and (b) urban (impervious) areas in rural and city areas, and illustrates the formation of higher temperatures in city areas.*

The vegetated surfaces in rural areas display a higher rate of evapotranspiration process, whereas the stormwater runoff is higher in the urban areas due to impervious surfaces (Figure 2). Therefore, sensible heat flux increases in the urban areas due to a lower evapotranspiration process [32]. Hence, the cooling process is mostly shut down due to lack of urban vegetation and solar heat is stored in the urban surfaces during the day, and consequently, the temperature in urban areas is highly increased at night due to the emission of stored solar heat. In urban areas, the impervious surfaces prevent absorption and filtration of water through it and modify the natural pathway of stormwater [33]. Urban areas always get less moisture content than rural areas due to impervious surfaces as the construction materials seal pervious areas, which make urban areas dry (Figure 2). Sensible heat flux directly increases the temperature, while latent heat flux decreases the temperature by increasing the presence of moisture. Previous studies have found that impervious surfaces reduce 35% of water infiltration rate and increase 45% of stormwater runoff in the city areas [34]. As a consequence, the natural cooling processes such as evaporation and evapotranspiration become limited in urban areas and cannot control the raising of urban temperature [35].

2.2. Urban Morphology and Size of Cities

Urban morphology refers to the 3-dimensional form, spacing and orientation of urban infrastructure in the city areas, which has a prominent role in raising the urban temperature. Hoyano et al. [36] have demonstrated that the temperature differences between air and building surfaces vary up to 20 - 30°C during the day in summer and 5 - 10°C at night in winter. They have also found that the temperature differences between the roof and ambient air vary from 14 - 25°C during the day. Densely urban areas without vegetation can raise the UHI intensity up to 3.8°C during extreme heatwave events in subtropical cities [37]. They also obtained that decreasing vegetated cover to zero resulted in a greater increase in air temperature as compared to increasing building height. The impact of urban morphology on the UHI was evaluated by Tong et al. [38] for newly developed urban areas in northern China, and their results showed the intensity of the UHI reached up to 4.5 and 5.3 during the day and night, respectively, due to extensive building surfaces that exposed to solar radiation. Furthermore, Tong et al. [39] showed that increasing building levels and reducing street width could reduce the mean and maximum urban temperature during the day but increase at night. The urban geometry substantially influences wind flow, solar radiation, air humidity and water budget. For example, large buildings and narrow streets or openings trap the heat and it remains for a long time as it does not get adequate ventilation facility [33]. A study has shown that a building's wall thickness, aspect ratio, presence of opening and surface clutter have considerable effects on the heating and cooling of the urban surfaces [40]. The complex urban geometry predetermines multiple reflections and absorption of shortwave radiation due to lower albedo than the rural environment [28] (Figure 2). Urban structures absorb shortwave radiation (solar radiation), and consequently store more heat themselves. This stored heat is re-radiated as longwave radiation by the urban structures after the sun sets [41], and the amount of heat re-radiation depends on the nature of the underlying surfaces (e.g. geometry, albedo and color). Typical urban albedo values generally range from 0.10 to 0.20 [15]. In addition, street orientation and its geometry also influence urban surface temperatures. The ratios of buildings height and road width (H:W), and the sky view factor are two well-known factors that have considerable importance in urban geometry [42]. The sky view factor plays a vital role in reducing temperature around sunset while night-time temperature was mostly influenced by the presence of buildings [43]. The higher ratios between H:W can reduce UHI effects at the near-surface level during the day due to provide shading and create deep street canyons by tall buildings [44] (Figure 2b). High-density urban areas have a greater impact in increasing the intensity of the UHI than the geographically expanded city [45], who obtained the lower effect of the UHI in the geographically expanded urban areas as compared to the areas with taller buildings and lower height/width ratio of streets to buildings.

2.3. Properties of Construction Materials

The properties of construction materials such as thermal emissivity (energy balance), solar reflectance (albedo) and heat capacity greatly influence the formation of UHI. The drastic use of manmade construction materials and release of anthropogenic heat is the key driver in generating the UHI [46]. Thermal emissivity measures the ability of a surface to shed heat or emit long wave (infrared) radiation. Solar reflectance determines the capability of a surface to reflect the solar energy by a percentage while thermal capacity refers to a material's ability to store solar heat. Emissivity and solar reflectance represent the radiative properties and thermal capacity represents the thermal properties of a material. Low-albedo materials with high thermal conductivity raise the temperature very quickly. Solar reflectance depends on the materials of surfaces and their colors. Darker surfaces show lower reflectance than lighter surfaces. Conventional roofing materials have lower reflectance values ranging from 5 - 15% and these materials can absorb larger energy and re-radiate 85 - 95% of that absorbed energy [47]. High emissivity surfaces comparatively keep cooler as they release heat easily. Most construction materials have high emissivity except metal. Concrete and asphalt have an emissivity of about 0.90, and consequently, these materials effectively store heat and then slowly release heat energy [18]. Conventional roofs have shown lower reflectance. However, these roofs have higher thermal emissivity, while a black asphalt roof can reach surface temperature up to 74 - 85°C [47]. In urban areas, construction materials (e.g. stone, concrete and steel) show higher heat capacity as compared to the materials (e. g. sand, dry/bare soil) in rural areas, which results in double the storage heat as compared to rural surroundings [48].

2.4. Anthropogenic Heat

Anthropogenic heat notably contributes to the formation of the UHI. Heat can come from various human activities and is calculated by summing the total energy used for vehicles, heating and cooling systems, running building appliances, power plants and industrial processes. Anthropogenic heat production depends on the urban infrastructures and activity, with high energy-intensive buildings and traffic volume [49]. Traffic volume is also related to urban morphology and the vehicles have considerable influence in promoting heat as well as air pollution in urban areas [50]. Air conditioners are frequently used in cooling systems at home, workplace, public places, and even in the car to maintain human thermal comfort during hot days. The air conditioners generate substantial heat during their compression and condensation function [51]. The heat emitted from anthropogenic sources has a larger effect on UHI formation particularly in denser urban areas [52].

2.5. Synoptic Conditions, Wind Flow and Cloud Cover

The uncontrollable meteorological variables, for instance, wind flow and cloud cover, control the turbulence and radiative exchanges in and around urban areas, which greatly influence the urban temperature fluctuations [53]. The windy and cloudy weather conditions reduce the occurrence and intensity of the UHI [54], while low wind flow and little or no cloud weather conditions promote the occurrence and higher intensity of the UHI effect [53]. Morris et al. [53]. have shown that the wind flow in excess of 2.0 ms^{-1} and increased cloud cover reduces the intensity of the nocturnal UHI. Wind lessens the UHI by advection of cool air from rural to urban areas. On the other hand, the cloud provides natural insulation, which absorbs and re-emits infrared radiation, and this downward radiation is absorbed by the land surfaces and partially reduces the surface radiative loss. This absorption makes slow the radiative cooling process during the night and decreases temperature differences between urban and rural areas. The strongest UHI forms under the clear and calm and anti-cyclone (high atmospheric pressure) weather conditions. Anti-cyclone weather conditions augment the outgoing longwave radiation in the nocturnal radiation budget by providing undistributed solar radiation which is favourable for the UHI development [55]. Weaker UHIs are formed under windy and cloudy or cyclonic (low atmospheric pressure) weather conditions [56, 53]. Long-term (1961-1990) changes of the UHI investigated in Prague under different synoptic conditions [56], who obtained the increased UHI in all seasons. The trend was larger during anti-cyclonic conditions compared to cyclonic conditions. Another study has shown that the strongest UHI has been developed under anti-cyclone conditions, while a strong cyclone condition has eliminated the

UHI formation [55]. Furthermore, the intensity of the UHI has exacerbated 1.2 – 1.4°C at night during heatwaves than non-heatwaves conditions [5, 6]. In contrast, environmental factors such as wind speed & direction, surface moisture and location of the cities affect the strength of the UHI. In contrast, the impact of weather conditions was minor on the surface temperature in a high-density subtropical city in Hong Kong during the summer season [57].

3. Simulation Approaches

Numerical models have been developed to understand urban meteorological and climatological problems including the UHI phenomenon. However, major simplifications in the model are mostly required because of the complex characteristics of the UHI. Nevertheless, the computational facility has advanced extensively in recent decades and this facility allows researchers for solving mathematical models at large-scale. These numerical simulation approaches are discussed below.

3.1. Energy Balance Model

The method in calculating energy budget uses the conservation energy law for a specific volume and considers atmospheric phenomena, velocity field and turbulence fluctuations as heat fluxes. The urban energy budget was first proposed by [58] at a city scale as follows:

$$Q = Q_H + Q_E - Q_F + \Delta Q_A + \Delta Q_S \quad (1)$$

Where Q is the net radiation, Q_F represents the anthropogenic energy release within a control volume, Q_H is the sensible heat flux while Q_E is latent heat flux, ΔQ_A is the net advection through the lateral sides of the control volume, and ΔQ_S is the storage heat flux representing a mechanism for all energy storage within elements of the control volume.

The energy balance equations are used to derive the Urban Canopy Model (UCM) for a control volume such as two adjacent buildings. The model estimates the exchanges of energy between ambient and surface air in the Urban Canopy Layer (UCL). The UCM model is capable to predict ambient and surface temperatures of streets, pavements and buildings. All surface and control volumes interact with each other like electric nodes, and Equation (1) is used to each node to develop the matrix of humidity and temperatures. The numbers of humidity and temperature schemes depend on the nodes number in the walls of a building [59]. The model can be developed as one, two and three dimensional with single or multilayer schemes. A number of energy models were developed and used in the UHI studies. The summary of the most relevant energy balance models is presented in Table 1 with concluding remarks. The absence of a wind flow field is a great weakness of the energy balance model. This model is not good enough to represent the atmospheric phenomena and to determine the latent and sensible fluxes because of the lack of flow pattern information.

3.2. Computational Fluid Dynamics (CFD) Model

The CFD techniques can be applied to model flows around urban landscapes including the buildings and tree features. This is a ground-up approach considering the lowest interactions at a detailed level and buildings those up to a larger picture. The CFD technique uses mathematical models following the principle of Navier-Stokes equations, which describe the motion of the fluids. There are three different ways as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stokes (RANS) to solve the equations. These models consider all principal equations of fluid simultaneously in urban areas, while energy balance models consider temperature and velocity fields separately. The CFD models simultaneously solve all the governing equations such as temperatures, momentum and conservation of mass. Therefore, CFD models can represent more realistic information regarding the distribution of the UHI as compared to the UCM model. One limitation of CFD models is that it is impossible to model the turbulence at atmospheric and canopy scales for the same time and length scale [60]. The CFD simulations are generally divided into two scales (meso and micro) based on different studies.

3.2.1. Meso-scale Model

The average effects of meso-scale modelling encompass a wider distance or entire neighborhoods of a city. The common range of this scale is around 1 to 2 km, although the maximum range is 2 to 2000 km. The meso-scale is subdivided into three categories such as meso-α (200-2000 km), meso-β (20-200 km), and meso-γ (2-20 km) [61]. The meso-scale models are larger than the micro-scale models and smaller as compared to global-scale models. A number of meso-scale models are used in many studies, and this study presents a brief description of the most relevant models with special features (Table 1). The horizontal resolution varies from one to several hundred kilometres. The vertical depth of the model with the Planetary Boundary Layer (PBL) also varies from 200 m to 2 km. The PBL develops between the earth's surface and geostrophic wind. Large-scale interactions within the PBL are resolved in meso-scale models where the Navier-Stokes equations are used based on hydrostatic or non-hydrostatic theory including atmospheric stratification effect. The equation of motion is simplified into a balanced equation between pressure terms and buoyancy in the hydrostatic models, while the non-hydrostatic models use the equation of motion with the full Navier-Stokes equations. Planetary surface directly affects the physics of PBL, in which different physical phenomena take place and influence temperature, velocity, moisture and turbulence fields. Many PBL models are proposed in the literature [62] and most of the equations are non-linear and greatly influenced by the atmospheric interactions and land surface properties [63, 60]. Therefore, further studies are essential in this area to overcome the limitations. In addition, considerable soil models [64, 65] and moisture schemes are developed and integrated with PBL models. The interaction between radiation and cumulus is also considered for meso-scale models. Therefore, the coupling of soil, moisture, radiation, cumulus and PBL models is a wide topic for further research [60]. The meso-scale models' accuracy depends on the temperature and wind flow boundary condition obtained from observational techniques [66, 23]. Building canopies are treated as aerodynamic roughness in meteorological schemes [67]. The meso-scale models' accuracy largely depends on the land use/land cover (LULC) data availability. Another consideration of meso-scale models is homogeneous surface and estimation of surface properties such as emissivity, albedo and roughness. In the last decade, several advanced and efficient urban canopy models such as Single Layer Urban canopy Layer (SLUCM), Building Effect Parameterization (BEP), Building Energy Model (BEM), TERRA_URB, Double-canyon radiation scheme (DCEP) and Building Effect Parameterization (BEP-Tree) have been developed and coupled to the meso-scale models for UHI studies. The essential features of these schemes are the ability to parameterize surface and soil properties (e.g., albedo, emissivity, radiation, urban canyon effects, roughness length and anthropogenic heat) with high accuracy.

***Table 1.** Comparison of the most relevant modelling tools for UHI studies at meso-scale.*

Reference	Modeling Tool	Type of Tool	Dimension	Equation
[68]	URBMET	Energy Balance Model	2D	Hydrostatic
[67]	HOTMAC	Energy Balance Model -CFD	3D	Hydrostatic
[69]	CSUMM	Energy Balance Model	3D	Hydrostatic
[70]	AIST-CM-MM	Energy Balance Model-CFD	1D	Hydrostatic
[71]	FITNAH	Energy Balance Model	1D	Non-hydrostatic
[72]	MC2	Energy Balance Model-CFD	3D	Non- hydrostatic
[73]	TEB	Energy Balance Model	2D	Non- hydrostatic
[74]	SUMM	Energy Balance Model	3D	Non- hydrostatic
[75]	MM5	CFD	3D	Non- hydrostatic
[76]	RAMS	CFD	3D	Non- hydrostatic
[77]	WRF-UCM	Energy Balance Model-CFD	3D	Non- hydrostatic
[78]	WRF-BEP+BEM	Energy Balance Model-CFD	3D	Non- hydrostatic
[79]	COSMO-CLM/DCEP	-	3D	Non- hydrostatic
[80, 81]	COSMO-CLM/TERRA_URB	-	3D	Non- hydrostatic
[82]	COSMO-BEP-Tree	-	3D	Non- hydrostatic

***Table 1.** Continued.*

Reference	Land Surface Scheme / Urban Canopy Model	Turbulence Scheme	Limitation
[68]	Monin-Obukhov	Drag Equation	Anthropogenic heat was only considered at the lowest level of the model. UHI effect was simulated by considering zero building height.
[67]	UCM-Monin-Obukhov	2 Equations k-1, Mellor-Yamada	The model has precise forecast capabilities in three dimensional spaces over complex terrain. Sub-grid density fluctuations neglected during mass budget calculation.
[69]	Monin-Obukhov	Drag Equation, -0 Equation	It cannot be used for complex terrain and small grid sizes. It cannot reproduce observed frontal distortions induced by urban structures.
[70]	Monin-Obukhov	Drag Equation, -0 Equation	Not considered anthropogenic heat. A small difference remained between model and obsered temperature.
[71]	Non-slip for moment and heat balance	Drag Equation	Suitable for atmospheric flow simulation over complex terrain.
[72]	Monin-Obukhov	Drag Equation, -0 Equation	
[73]	UCM-Monin-Obukhov	Drag Equation	Energy budget was divided across roofs, walls and road surfaces. Any road orientation can be considered in this scheme.
[74]	UCM-Monin-Obukhov	Drag Equation	Assumed only vertical heat conduction. No heat exchange between various constituent surfaces.
[75]	Monin-Obukhov	2 Equations k-1	It is a limited area model. Finer resolution varies between 10 to 50 km.
[76]	Monin-Obukhov	2 Equations k-1, LES	Suitable for large complex terrain. Relatively take a long time to handle the more complex physics.
[77]	UCM-Monin-Obukhov	2 Equations k-1	The heterogeneous urban landscape is considered Single layer vegetation model missed much detail urban features during latent fluxes calculation
[78]	UCM-Monin-Obukhov	2 Equations k-1	Over estimates energy in the urban canopy for tall buildings and narrow streets
[79]	DCEP	-	Further evaluation is required for cities with large building heights
[80, 81]	TERRA_URB	-	Pre-defined anthropogenic heat
[82]	BEP-Tree	-	Not precise simulation of night-time boundary layer

3.2.2. Micro-scale Model

Micro-scale urban climate modelling is a very young research endeavour. The analyses in this scale allow the resolution in detail over a short distance commonly in the order of around 1-100 meters. The CFD models at micro-scale resolve the conservation equations inside the surface layer, while the meso-scale models are assumed bulk values of different surface properties at a horizontal scale. The micro-scale models simulate those properties with actual geometry considering detailed surface layer interactions. In micro-scale models, the simulations are conducted for a small domain at a horizontal scale of some blocks of buildings (e. g., a few hundred meters). The vertical atmospheric interactions are not considered in micro-scale models and it is an appropriate technique to study the high-Rossby number problems [60]. Comparatively, more measurements are needed for parameters in micro-scale due to more complicated boundary conditions, and the measurements are highly fluctuated at the surface layer as compared to the meso-scale models [83]. A short description of the most relevant and available micro-scale models is presented in Table 2 focusing on the models' special capability and their limitations.

Table 2. *Comparison of the most relevant modeling tools for UHI studies at micro-scale.*

Reference	Modeling Tool	Type of Tool	Dimension	Equation
[89]	UCSS	CFD	3D	Non- hydrostatic
[90]	RAUSSSM	Energy Balance Model	1D	Non- hydrostatic
[91]	ENVI-Met	CFD	3D	Non-hydrostatic

Table 2. *Continued.*

Reference	Land Surface Scheme	Turbulence Scheme	Limitation
[89]	Monin-Obukhov	2 Equations k-ε	Circulation in the atmospheric boundary layer is not model in detail. Reproduction of the environment is difficult with complex terrain.
[90]	UCM	Drag Equation, -0 Equation	Only vertical atmospheric diffusion is considered. For a particular area, sometimes the one-dimensional model is not adequate to predict urban microclimate.
[91]	UCM	2 Equations k-ε	Unable to use external forcing data Model source code is required to troubleshoot modelling results.

3.3. Turbulence Treatment

Considerable theories such as Direct Navier-Stokes (DNS), Reynolds Average Navier-Stokes (RANS) and Large Eddy Simulation (LES) have been proposed in the literature for solving the turbulent dynamics [60]. DNS solves all the spatial scales within the flows, and consequently, it is usually far too computationally intense for all but the smallest simulation. LES decreases the computational intensity by low-pass filtering, which is filtering out smaller-scaled pieces of the solution and focusing more on the larger scaled pieces. Although DNS and LES can achieve high accuracy results, the application of these schemes is computationally expensive [84]. On the other hand, RANS is widely used for turbulent modelling because of its lower computational cost. RANS uses mathematical techniques to simplify the Navier-Stokes equations by separating fluctuating and averaging pieces [85]. However, this scheme was not good for high accuracy simulation of building canopies [86]. Therefore, accurate modelling of turbulence phenomena is still a research gap in CFD simulation. Furthermore, the buoyancy effect in the meso-scale turbulence model is mostly produced by the urban surface layer, which is significant as viscous turbulence. Currently, different types of multiple equations turbulent schemes have been proposed [87, 88] to consider the buoyancy effect in turbulence models.

4. Mitigation Approaches

Many mitigation approaches of the UHI, such as increasing urban vegetation cover, sustainable urban planning, changing architectural design, proper transportation system and managing natural resources are investigated according to various professional fields. This study presents the different mitigation approaches and their effectiveness in reducing UHI effects as reported in the previous studies. The mitigation approaches are classified into four main categories as follows:

1. Cooling by vegetation
2. Cooling by construction materials
3. Cooling by sustainable urban infrastructures
4. Cooling by anthropogenic heat reductions.

4.1. Cooling by Vegetation

4.1.1. Garden and Parklands

Vegetation planted around a building and specified land in urban areas are called urban gardens and parks, which can protect the urban infrastructure from solar radiation. Vegetation keeps the soil surrounding the building cooler, and protects, reflects and diffuses solar radiation [92]. In the garden and parks, evapotranspiration and shading significantly reduce temperature and even create cool islands in the city [93]. A study showed that average air temperatures in the park lands were 4°C lower than in the inner city during summer nights [94]. Parklands not only keep parks cool but also the surrounding areas and can reduce building cooling loads by up to 10% [24]. A field experiment was carried out by Ca et al. [95] to quantify the park lands effect on summer climate in Tama of New York, and a coastal metropolitan area in Japan. The results indicated that park lands reduced 1.5°C air temperatures in a busy commercial area at noon. They also proposed a park vegetation and shape index that can be used to quantify the cool island in park areas. The index values will be helpful for the urban planners to design a sustainable urban development plan by understanding the formation of the cool island. Some studies reported that park lands and green spaces reduced high temperatures in summer and stabilized the temperature fluctuation caused by building materials [96, 24]. A general conclusion was made from previous studies [97, 98] that green spaces were always cooler than spaces without any green cover. However, the cooling effect depends on the size of the park lands and solar radiation; but there is no linear relation between the cool islands and the size of parklands. A examined the effectiveness of different types of parks in mitigating the UHI, and who reports that mixed forest with grassland can reduce UHI intensity by 0.6 to 3.4°C during the night but no cooling benefit during the hottest part of the day. They also found substantial human thermal comfort during the night but not in the day [99]. Furthermore, Yan et al. [100] showed the urban park reduced 2°C air temperatures in the centre of the park. Similar results were obtained from Cheung et al. [101], who reported a maximum 4.9°C reduction in air temperatures in a larger park. They also concluded that the sky view factor, shrub and tree cover were the vital parameter in affecting air temperature. It is noteworthy that urban parklands and vegetation show slight warming effects between 9.00 am to 2.00 pm at local time [102, 99].

4.1.2. Trees

Street trees can be planted in two ways such as planting a tree directly in the ground and using cell structures, which facilitate the required development of roots under a partial asphalt covering. But the installation cost of cell structures is higher than direct tree planting in the ground and needed skilled personnel. Some researchers determined the effects of trees on building design and urban planning [103, 104] and proposed a new type of architectural planning for greening in urban areas, where the aim was to find out the optimal percentage of greeneries ratio based on various land use categories. The optimal greeneries were compared to existing levels of greenery of each type of land use, and their study suggested a leaf area index of 1.36 to 10 for the shrubs, lawns and full-grown and dense trees. These values were helpful to recompense for the loss of green spaces stemming from urban development. Akbari et al. [105] conducted a study and reported that shading of trees reduced the building surface temperatures as effective as wind flow. Surfaces shaded by trees and vegetation can be 11 - 25°C cooler than the peak temperatures on unshaded surfaces on a sunny day [52].

A study found a negative effect of trees and vegetation on urban microclimates of four cities in the USA in four different climatic conditions [106]. Their study highlighted Sempervirens
plants such as Conifers, which increased heating cost up to 21% in a cold climate, whereas deciduous trees (leafless) were less important. On the other hand, dense shade on all surfaces decreased cooling costs by 53 - 61% per year and peak cooling loads by 32 – 49%. They reported that if trees and vegetation are not strategically placed, this could impact wind flow. For instance, the 50% reduction of wind flow decreases the heating costs 8% per year in the Salt Lake City of USA, whereas cooling costs were increased by 11% per year because of the obstruction of summer breezes. Thus, it is imperative to have good knowledge about plant species and local climatic conditions.

The effect of trees and vegetation was monitored, modelled and simulated in many studies [107-115, 93]. Most of the studies were case studies and conducted at city-scale or individual building scale. These study results showed that trees and vegetation reduced air temperatures in the range of 0.28 to 4°C while the shade factor provided 80% of the cooling effect during the summer [93]. Furthermore, the cooling benefit of trees was experimentally investigated by several studies [116-119], who concluded that trees provided notable cooling benefits ranged from 1.2 to 4.1°C during the day with a substantial increase in human thermal comfort. However, the research findings from these studies cannot be applied to other regions due to different city and building characteristics. Therefore, further studies are required for developing a framework including a set of fundamental features based on different climatic conditions and geographical locations.

4.1.3. Green Roofs

Green roofs reflect solar radiation by shading and consume energy via evapotranspiration and photosynthesis processes [120]. In summer, green roofs absorb 70 to 90% energy of the sun by leaves during the photosynthesis process and the remaining energy is reflected back into the atmosphere [121]. Green roofs decrease the substantial amount of heat transferred from the roofs to the inside of buildings by shading and evapotranspiration. The roofs' vegetation also extends the roofs' life span by protecting UV radiation, bad weather effects, and temperature fluctuations [122]. Quantitative thermal impacts of green roofs have been investigated through field experiments and mathematical approaches by some studies [123-126]. The interesting conclusion of the study by [123] was, green roofs act as an insulation layer rather than cooling the roofs, while the conclusion made by Eumorfopoulou and Aravantinos [124] was, green roofs were able to improve the thermal performance of buildings but not able to replace the insulation layer. About 30% of green roofs could reduce the surface temperature by up to 1°C in the Baltimore-Washington metropolitan area, where the performance of green roofs is slightly affected by soil moisture [8]. Their study also illustrated that the surface UHI during the peak temperature of the day was further reduced by 0.55°C (when a soil moisture control limit was 0.45 m^3 m^{-3}) and 0.27°C (when a soil moisture control limit was 0.35 m^3 m^{-3}). On the other hand, when the soil moisture was near the wilting point (0.15 m^3 m^{-3}) for a dry condition, the cooling benefits from green roofs were almost zero. Furthermore, some specific factors, for instance, geographic location, solar exposure, growing medium and moisture availability also influence temperature over green roofs [121]. A study was conducted by Rosenzweig et al. (2006) in the city of New York to test UHI mitigation scenarios by using the climate model MM5. Although their study did not explicitly represent the buildings in the MM5 model, it assumed the presence of buildings through the boundary layer which controls the transportation of heat and moisture in the surface layer. Their study found that vegetation had greater impacts in reducing urban temperature than urban geometry. They also obtained that 50% of green roofs covered with grass reduced urban surface temperatures up to 0.1 - 0.8°C, while in Toronto in Canada 50 km^2 green roofs reduced local ambient air temperatures by up to 0.5 – 2°C [127]. Thermal benefits of green roofs were quantified through the field measurement data by Wong et al. [128] for the tropical environment in Singapore. They obtained that the cooling effect of plants was responsible for the highest reduction (4.2°C) of ambient air temperature. Another experimental study for 20 years of a permanent survey of the cooling effect of the extensive green roof was conducted by Kohler and Kaiser [129], who showed a stabilization cooling effect of 1.5°C and a constant temperature within the growing media in the green roof as compared to a traditional roof.

Regional climate models offer a real solution for evaluating the benefits of green roofs at city scale by parameterization of urban canopy accounting effects of green roofs on sub-grid scales. The coupled WRF-UCM modeling systems are widely used to investigate the effectiveness of green roofs for UHI mitigation. The major studies considered only albedo adjustment and increased moisture availability rather than directly parameterized green roofs for detail physical processes. Smith and Roebber [130] investigated green roof efforts in Chicago using the WRF-UCM model but they did not directly parameterize the green roofs. Rather, they assumed a uniform increase of moisture availability and adjusted albedo within the entire urban domain at the roof level. Furthermore, a few studies used practical approaches to parameterize the physics processes of green roofs in the numerical model. A more efficient modeling approach for evaluating the performance of green roofs was applied by Li et al. [8] in the metropolitan areas of Baltimore-Washington DC. They developed and used the Princeton UCM coupled with the WRF including well-tuned physical processes in the urban areas for investigating changes in surface and near surface UHI effects. A physical-based green roofs algorithm in the coupled WRF-UCM model has been employed, which was another solution for assessing green roof impacts in reducing UHI effects [131, 10]. Their study found that temperature, wind and relative humidity were changed in the lower atmosphere due to UHI reductions, as green roofs reduced vertical mixing and boundary layer depth during the day.

Finally, although considerable research has been conducted to investigate the effectiveness of green roofs in reducing the urban temperature, few studies have quantitatively determined the cost and intangible benefits of green roofs [132], and added them into the urban design process. The key challenges in installing green roofs are the higher construction and maintenance costs and leakage problems in the roofs [133]. Therefore, the cost-effective and sustainable quality green roof design is a demand of time. Further efforts should be made to transfer research results into real project design so that society can benefit.

4.1.4. Green Walls

Green walls are designed as vertical vegetation systems and classified into green facades and living walls. Plants are planted in the ground in a green facade system and the plants climb on the wall up to 30 m. A living wall is a combination of plants planted in a growing medium attached to a wall, and it is a comparatively complex structure and needs a particular impermeable membrane to protect the wall from water damage [134]. These green walls are possible to install on any buildings and also on fences. But precaution must be considered for supporting the weight of the vegetation by the walls and for the type of vegetation and potential colonizers. Maintenance of the green walls includes pruning, weeding and inspection of the supporting walls. Green walls develop a microclimate environment and can substantially reduce the temperature on buildings and energy efficiency as well [134]. Green walls also provide other additional benefits such as capturing the suspended particles, protecting the building from UV radiation and protecting walls from graffiti.

The effects of vertical greeneries on the buildings in reducing temperature and saving energy were evaluated by Wong et al. [135], who found that increasing 100% green cover on vertical glass facade building reduced the mean radiant temperature between 0.32 and 1.0°C with cooling load reduction of about 10 to 31%. Their results also showed that there was a linear relationship between leaf area index and shading coefficient. Furthermore, their study suggested that the shading coefficient should be lower to reduce the demand for cooling energy. According to their study result, 50% vertical greeneries and a shading coefficient of 0.041 decreased the envelope thermal transfer value of a glass façade up to 40.68%. The increased vertical greeneries were very effective to reduce air temperatures throughout a large area. Wong et al. [136] analyzed different green facades in Singapore, a climate similar to Amaravati. They found that in the best case scenario the reduction in temperature from the green façade could only be felt 60 cm away from the wall. Beyond that, there was no difference in temperature.

4.2. Construction Materials

Two parameters of construction materials play an important role in reflecting solar radiation. The first is albedo which refers to the ratio of incoming solar radiation to reflective solar radiation and it is represented on a scale of 0 to 1. The second is emissivity and it measures the effectiveness of a material in emitting solar energy as thermal radiation at specific temperatures and wavelengths. Emissivity is also represented on a scale of 0 (perfect reflector) and 1 (perfect emitter). Albedo and emissivity indicate the radiative properties of construction materials. The higher value of albedo and emissivity of materials indicates that they are less likely to store heat and reflect into the atmosphere [15]. Urban temperature distributions are affected by the radiation budget over urban areas. The incoming solar radiation is absorbed by major urban surfaces including streets, roofs, building surfaces, squares, and transformed into sensible heat [137, 102, 8]. This storage heat is re-radiated as long wave radiation, whereas the wave intensity depends on the albedo, emissivity, thermal inertia and percentage of visible surfaces to the sky. Further urban infrastructure made of different construction materials and associated UHI is described in the following subsections.

4.2.1. Cool Roofs

Cool roofs have two most important features such as higher albedo (indicates reflectance of solar radiation) and thermal emissivity, which plays a substantial role in reducing temperature. The materials of cool roofs should reflect solar energy above 70% and solar emissivity 80% [138]. According to the findings of Gartland [138], cool roofs heat up to 40 - 60°C. The differences between surface and ambient air temperatures were greatly varied between cools roofs and traditional roofs, where the differences were 50°C for traditional roofs and 10°C for cool roofs [92, 139, 28, 140]. Synnefa et al. [140] experimentally investigated 14 different reflective coatings for thermal performance and optical properties. Temperature sensors, data logging systems and infrared thermography procedures were applied to their experimental study. Their study results showed cool coating reduced 4°C surface temperature during summer conditions and 2°C during the night. Also, the statistical analysis from their study showed that the thermal behavior of cool coatings and cool materials was affected by thermal reflectance during the day and by emissivity during the night, which affects the performance of the cool coatings and cool materials. Furthermore, Synnefa et al. [141] conducted an experimental study for measuring the temperature differences between 10 conventionally pigmented coatings and 10 prototype cool colored coatings. The highest surface temperature difference was 10.2°C during summer against the solar reflectance of 0.22 while the temperature difference was 1°C during winter. Therefore, cool colored coatings avoid any heating penalty. A study was carried out by the Lawrence Berkeley National Laboratory and the Oak Ridge National Laboratory to investigate the properties of various color pigments, and the study discovered certain color pigments could reflect around half of the solar radiation of close infrared radiation [142]. The smooth white coatings can increase the lifespan of cool roofs and albedo values from 0.04 to 0.80 as compared to roofs covered by black asphalt surfaces [27]. Cool roofs require regular cleaning and maintaining otherwise, their reflectance will be reduced. For a white cool roof, solar reflectance was reduced from 0.80 to 0.60 due to biomass and dust deposits [143]. An experimental study was carried out by Watkins et al. [144] in London to investigate the effectiveness of reflective walls (albedo = 0.50), where the study result revealed that reflective walls reduced surface temperature approximately 3 to 4°C at the hottest time of the day. Extensive field experimentation and modelling studies on cool roof penalties were conducted in the United States, Canada, Japan and various parts of Europe. Indeed, considerable further studies are needed to address the cool roof penalties in hot vs. cold conditions based on different geographical locations. A few studies focused on the decrease in reflectivity of cool roofs because of weathering, microbial growth and accumulation of dirt and showed that regular washing of cool roof could restore 90 - 100% of the initial reflectivity [145, 146, 112]. The bioclimatic architectural building design is a very effective approach to protect the building from overheating in summer, in which a special effort is required to ensure thermal comfort for the residents [147]. Susca [148] conducted a study to assess the life cycle of black and white roofs, and it was found that the life cycle of white roofs is longer than black roofs. Cool roofs are an environmentally friendly and cost-effective UHI mitigation strategy [149].

The performance of 5 colors of thin layer asphalt was examined by Synnefa et al. [150] using computational fluid dynamics modelling tool PHOENICS-CFD. The modelling tool was developed based on Navier Stokes equations and it is an efficient tool for simulating fluid flow. Their study found the daily surface temperature fluctuation was 18°C for black asphalt and 8°C for colored thin layer asphalt [150]. A review on cool roofs for mitigating UHI effects and improving thermal comfort revealed that the cool roof materials were responsible for decreasing the flow of heat flux into the buildings and reducing the high temperatures [27]. Some cool roof materials such as cementitious or elastomeric cool coatings, cool shingle–ply roofing systems made by various materials and clay shingles ensuring higher albedo were suggested to use in cool roof system [138]. Recently, modelling studies have extensively evaluated the effectiveness of cool roofs in mitigating UHI [131, 8, 10]. Li et al. [8] have reported the increasing albedo (up to 0.9) of 50% cool roofs have a substantial impact in reducing surface UHI (2.5°C) over Baltimore-Washington metropolitan area. Imran et al. [131] found that cool roofs can reduce roof surface temperature by 2.2 to 5.2°C for increased albedo 0.50 to 0.85°C during the day in the city of Melbourne while the maximum roof surface temperature reduced by 8°C in the high intense urban areas in Chicago Metropolitan areas in the USA for 100% cool roofs [10]. In addition, this study summarizes the UHI mitigation by cool roofs in Table 3.

4.2.2. Cool Pavement

Cool pavements reflect a substantial amount of the solar radiation away from the urban surface to the atmosphere because of higher albedo. Albedo is defined as the ratio of reflected radiation from a surface to incident radiation. Albedo value indicates how much energy is absorbed or reflected from the surface of a material. The higher albedo values indicate the higher energy is reflected into the atmosphere and lower energy is absorbed by the material. Therefore, it is very important to select materials properties for new construction or retrofitting of buildings to mitigate UHI effects [151]. Air temperature in summer is reduced by up to 4°C by increasing surface albedo from 0.25 to 0.40 [15]. A substantial number of studies examined the capabilities of cool pavements in reducing the urban temperature by increasing albedo [152, 107, 153-157]. Their studies showed that cool pavements can reduce surface temperature by up to 10°C when albedo increased by 0.25 [152, 107]. Climate models revealed that the infrared radiation from cool pavements was absorbed within 200m of the planetary boundary layer, and thus it affects near-surface temperature [15]. A study carried out by Pomerantz et al. [155] showed that cool pavement reduced air temperature by 0.6°C if reflectance of pavement has increased from 10% to 35%. Recently, high performance roof coating materials such as light color gravel and tiles, elastomeric and polyurea membranes have been developed by the roofing materials industry in which all products have a higher albedo than ordinary materials [142]. Furthermore, a brief summarized mitigation strategy of the UHI by cool pavements is presented in Table 3. Urban paved areas such as roads, parking areas and school yards are frequently covered with asphalt or other types of dark materials which can contribute to reaching surface temperatures of 60 - 80°C on hot days in summer, and these infrastructures make a significant contribution to developing the UHI [153]. The paved areas can occupy up to 45% area of a city [52]. In order to minimize these effects, the following mitigation measures can be taken:

Reflective pigments can be added to concrete (e.g. colored concrete) and asphalt (e.g. colored asphalt) to increase the reflectivity.

Generally concrete has good albedo values (0.30 - 0.40), thus a concrete layer (2.5 cm to 10 cm) can be applied on the top of an asphaltic pavement in good condition. This strategy can keep the surface cooler and be able to accommodate different types of vehicles [141].

Currently, asphalt roads are composed of around 85% mineral aggregates including 15% bitumen. The albedo value of bitumen can be increased by the reverse process of the paving system, i.e. applying thinner layer bitumen on the surface of high albedo aggregates placed on the road. However, this pavement is only suitable for low-speed and light-weight vehicles.

Several studies focused on the cost associated with cool pavements construction [107, 92, 155, 158]. A few studies examined the cost for individual cool roof technology, which depends on several factors including climate type, geographic location, and pavement size and design life. Therefore, further research is required on a cost analysis that highly depends on a range of these complex factors. The cost analysis of cool pavements indicated that the construction cost of cool pavements increased up to $10 psqf compared to traditional asphalt pavement [155]. Most studies emphasized the range of benefits and drawbacks (e.g. costing) which need to be accounted for cool pavements.

4.2.3. Permeable Pavement

The primary cooling mechanisms of permeable pavements are heat resistance, evaporative cooling and reflection if reflective materials are used [159-161]. One of the promising applications of permeable pavement is parking lands. The parking areas are generally paved with asphalt and low-albedo materials that absorb solar heat and increase the surface temperatures. Parking areas can be covered and shaded by planting vegetation around the perimeter and entire surfaces providing different modular systems consisting of concrete or PVC or other construction materials that permit plant growth. All these modules are installed on a pervious soil layer for promoting the natural percolation of storm water into the groundwater systems. A study conducted by Doulos et al. [154] considered 93 pavement materials that are used very often in urban areas to reduce ambient air temperatures. Their study determined that the albedo factor of each material was mainly responsible for the variation of average daily temperature. It was also found that dark and rough surfaces in the urban areas absorbed more solar heat than smooth light-colored and flat surfaces. Permeable pavements strategy is a good solution for stormwater management and can be used to reduce UHI and improve a comfortable thermal environment for the urban residents by evaporative cooling. Table 3 additionally summarizes different studies on permeable pavement and the UHI. This cooling efficiency depends on the evaporation rate, which is significantly affected by higher water availability near the surface or large moisture exposure to the atmosphere [8]. A surface with good permeability and increased air voids is a good way to increase moisture in the atmosphere to maintain the evaporative cooling process.

4.2.4. Thermal Inertia

Thermal inertia indicates its ability to absorb and store heat and defer a certain time period for its release, known as a lag phase. Inertia is measured by the penetration (diffusivity) speed of heat into a material and ability of the material to absorb or release (effusivity) heat. The higher diffusivity allows more rapidly passing heat through the thickness of the material. The higher effusivity materials absorbed more heat without substantially warming up. High inertia materials absorb and store excess heat and prevent heat from being transmitted to the ambient air and, consequently, improving thermal comfort [162]. It is necessary to place the high thermal inertia walls where there is sunshine, and a minimum of 50% of the walls of a building should have higher inertia to get the maximum cooling benefits [163].

Table 3. *The most effective UHI mitigation approaches in the literature.*

Reference	Location	Mitigation Approach	Modeling Tool
[10]	Chicago metropolitan area	Green and cool roofs	WRF-UCM
[8]	Washington, USA	Green roofs	WRF-PUCM
[101]	Hong Kong	Urban Parks	Experimental
[128]	Singapore	Rooftop garden	Statistical Analysis

Reference	Location	Mitigation Approach	Modeling Tool
[140]	Athens, Greece	Reflective coatings	ANOVA F-Statistical Analysis
[131]	City of Melbourne, Australia	Green and cool roofs	WRF-UCM
[164]	City of Melbourne, Australia	Vegetated patches	WRF-UCM
[118]	Hong Kong	Woodland	Experimental
[158]	Los Angeles, USA	Vegetation, cool roofs and lighter color pavement	DOE-2 and CSUMM
[102]	City of Melbourne, Australia	Vegetation and cool roofs	WRF-PUCM
[117]	Hong Kong	Trees	Experimental
[165]	Los Angeles, USA	Increased vegetation and albedo	CSUMM
[159]	California, USA	Permeable asphalt pavement	DBOLS-Statistical Analysis
[23]	Hong kong, China	Planting and vegetation	MM5
[129]	University of Applied Sciences Neubrandenburg	Green roof	Experimental
[116]	Melbourne	Trees	Experimental
[24]	Singapore	Park lands	ENVI-met
[119]	Hong Kong	Trees	Experimental
[166]	Tokyo, Japan	Green walls	Coupled MM-CM-BEM
[167]	City of Vienna, Austria	Green and blue spaces	MUKLIMO_3
[135]	Singapore	Vertical green walls	STEVE Model
[168]	Putrajaya, Malaysia	Vegetation and water body	WRF-UCM
[169]	London, UK	Stack ventilation	3TC Model
[170]	Tokyo, Japan	Photovoltaic Canopies	Numerical PV-panel Heat Balance Model
[171]	Nevada, USA	Reflective Roofs	Regression Analysis
[172]	Spain, Madrid	Green roofs	Sima Pro-LCI
[173]	Qatar	Green roof and walls	GCM and CCWorldWeatherGen tool
[174]	Tokyo, Japan	Humidification and albedo increase at building-wall surfaces	Coupled CM-BEM
[115]	Kobe, Japan	Green roof and high reflection roof	Numerical Equation
[175]	Arizona, USA	Photovoltaic Canopies	Statistical Analysis
[115]	Kobe, Japan	Green roof and high reflection roof	Numerical Equation

Table 3. *Continued.*

Reference	Max^m Air Temp. Reduction	Max^m Surface Temp. Reduction	Max^m Energy Saving
[10]	-	8.34°C and 10.09°C	
[8]	1°C and 0.7°C	~7°C for both roofs	-
[101]	4.9°C	-	-
[128]	-	4.2°C	-
[140]	-	4°C	-
[131]	1.4°C and 1.6°C	3.8°C and 5.2°C	
[164]	3.7°C	4.2°C	-
[118]	4.1°C	-	-
[158]	3°C		10%
[102]	~ 2.4°C and 1°C	-	-
[117]	2.1°C	-	-
[165]	2°C		10%
[159]	0.45°C	1.6°C	-
[23]	1.6°C		-
[129]	1.5°C	-	-
[116]	1.5°C	-	-
[24]	1.3°C		10%
[119]	1.2°C	-	-
[166]	1.2°C		40%
[167]	1°C		-
[135]	1°C		-
[168]	0.53°C		-
[169]	Significant		10%
[170]	-		10%
[171]	-		31-39 (Wh/m^2/day)
[172]	-		10%
[173]	-	-	3%
[174]	Significant		3%
[115]	Significant		-
[175]	Significant	-	-
[115]	Significant		-

4.3. Sustainable Urban Infrastructure

4.3.1. Urban Design and Solar Radiation

Urban areas are composed of building surfaces, roofs, and pavements that store short wave solar heat during the day and re-radiate as longwave radiation during the night. Capturing solar radiation, light exploration and protection systems are important urban design considerations to reduce energy demand, environmental pollution and UHI effects [176, 177]. The changes in building design, orientation and urban geometry have affected solar access [178]. Mesa et al. [179] suggested that the optimum separation ratio between the buildings and their heights is from 0.67 to 1. Densely urban morphology enables interior spaces to achieve a lower level of natural illumination quality and intensity [179]. Modified buildings reduced the temperature effect and improved the thermal comfort of buildings for the residents [180]. The effects of design, geometry and orientation of buildings with respect to capturing solar radiation and using them for energy in building facades and roofs were analyzed [181] who illustrated that the 30% and above 50% area of the facade and roof were suitable for passive and active solar techniques application, respectively. The relation between built forms, density and solar potential was examined by [182], who suggested that the optimum design was those with randomness in the vertical and horizontal layout with less site coverage. Another study established a relationship between building height and width [183], who showed an increased building width decreased the influence of the orientation of lower height buildings.

4.3.2. Urban Design and Air Flow

Urban canyon illustrated by taller buildings and narrow streets is responsible for creating multiple reflections of the solar radiation when solar heat incidents on the top of the canyon during the day (Figure 2b). After that, the reflected energy was attracted by the exterior walls, and as a result, it decreased the overall albedo in the city and raised the air temperature at the top canyon [184]. In addition, this narrow urban canyon reduced wind velocity and prevented free air circulation at night, and consequently, generated nocturnal UHI effects [185]. On the other hand, tall buildings provided shelter for the lower canyon during the day and reduce air temperatures 3 - 5°C at the near-surface level as compared to the corresponding top canyon [184]. Therefore, the height and density of buildings substantially affect the UHI. Furthermore, roughness length plays an important role in estimating the wind flow over urban canyons. Wind flow and pollutants dispersion are greatly affected by canyons' geometry (height to width ratio) [186, 187]. The high degree of pollutants mixing needs higher turbulence. Therefore, it is better to orthogonally orient a building towards the wind flow to control the turbulences and wind at street level [188]. Therefore, wind speed and direction also play a vital role in influencing the UHI effects.

4.3.3. Windows of Buildings

Windows control the thermal insulation of a building during summer and winter. Windows reduce the temperature difference between the inner and outside of the buildings and reduce the UHI intensity in the building. Smart low e-windows can reduce gaining solar heat inside buildings. These windows can adapt to seasonal variation and the inclination angle of the incident of solar radiation. It limits solar radiation in summer and allows light to pass during winter [189]. Double and triple glazed windows have 16 to 20 mm air space which provides higher insulation capacity by conduction and convection processes and hence reduces UHI intensity for the residents in the building. According to the findings of a study, self-adhesive plastic films show excellent performance, which can reduce 98% of UV radiation and 75% of thermal solar heat [190]. Their study also illustrated that the use of low solar gain windows saved heating and cooling costs by 8-10%, whereas high solar gain windows reduced by up to 13-17%. In addition, lower and higher solar gain windows can resolve the overheating in summer.

4.4. Anthropogenic Heat Reduction

4.4.1. Reduction of Air Conditioner Heat

Solar cooling systems can be an excellent alternative to air conditioners. Solar collectors gather solar energy and act as a low-temperature (80 to 120°C) source using absorption machines [189], which are potential alternatives to traditional compression machines generally used in conventional air conditioning systems. As a result, this solar cooling system will be able to reduce the UHI by absorbing solar heat and additionally, heat emission will be reduced from air conditioners. Furthermore, ground source heat pumps or geothermal heat exchangers can be used as very effective energy savers throughout the year for building cooling and heating operations [191]. The system uses ground energy rather than fossil fuel for the cooling and heating operations of the buildings, which helps reduce carbon emissions and consequently reduces urban warming. Geothermal heat exchangers can reduce air temperature up to 5 - 8°C while solar air conditioning reduces from 7 - 12°C [189]. Therefore, the use of air conditioners can be reduced by using alternative cooling options, which will result in a reduction of anthropogenic heat and the UHI effects.

4.4.2. Reduction of Urban Vehicles

Anthropogenic heat contributed to raising the UHI up to 2 - 3°C in the CBD of a city both during the day and night [15]. Building appliances and vehicles also contribute to generating UHI effects. Halogen and incandescent bulbs produce considerable heat which is absorbed and stored by building walls and materials inside them. Therefore, natural ventilation (e.g. windows, walls with air vents) should be designed in such a way where buildings will need less energy for lighting and cooling systems. The more practice of public transport and less practice of individual cars can reduce temperatures in cities. Motorized vehicles emit heat in the lower atmosphere. A car uses more than four times as much energy per person per kilometre as a bus and twice as much as a train [189]. Heat emission by vehicles is trapped in poorly ventilated urban canyons and promotes to form of urban smog and increases global warming [144]. The CNG (Converted Natural Gas) can be better fuel for cars instead of diesel and petrol for reducing air temperature and pollution as well [33]. Therefore, an appropriate urban transportation system is important to minimize the heat resulting from motorized vehicles. Therefore, more energy-efficient and lower polluting public transport services can reduce UHI effects and improve air quality [192]. In addition, the development of an active transport infrastructure offers easy access for people to travel around by bicycle and on foot which reduces not only anthropogenic heat production by motorized vehicles but is also helpful for human health.

5. Research Gaps

The UHI problems are manifold. It has substantial effects on the urban environment, climate, services, public health and national economy. Considerable studies have been carried out to model urban climate and evaluate the effectiveness of various mitigation approaches in reducing UHI effects. Increased vegetation cover has been considered the most beneficial and sustainable mitigation approach among all mitigation strategies. However, the present study has identified the following research gaps on UHI studies for future research:

1) Further research should be conducted to find out the effective techniques to integrate the meso-scale and micro-scales models.
2) Further improvement is still needed in representing the physical processes in the urban canopy layer in the Physics-based climate models.
3) The coupling techniques of radiation, soil, moisture, cumulus and PBL models are possible topics for further research.
4) Observational studies are still limited because of time and costs. The total life cycle analyses of different types of urban forest are necessarily based on local construction practices, ecosystem, and climatic factors.
5) Further research should be carried out to quantify the life-cycle cost and benefits of green and cool roofs in improving quality of life, ensuring biodiversity and sustainable ecology, and promoting recreational use at different climatic and geographic locations.
6) Field experiments should be done to collect observed climate data for more refinement of climate models to estimate the direct and indirect benefits of green roofs.
7) Research should be carried out to characterize the complex set of variables such as green roof cover ratio, tree size, tree type, orientation, climate types and geographical locations in developing UHI mitigation strategies.
8) Research should be carried out to examine the effectiveness of trees for UHI mitigation considering a complex set of variables: trees size, species of trees, trees health, locations and climatic conditions. Still, there is a need for further research on cost-benefit analysis in terms of the life-cycle of different types of trees in mitigating UHI in urban areas.
9) Many studies highlight only the cooling potential of green walls and vertical greeneries. Still, there is scope for further studies on the cost-benefit analysis.
10) Further research should be carried out by focusing on the effectiveness of cool pavements and their benefits at a large city scale, considering complex urban settings (e.g. building materials and sky view factors).
11) Research should be conducted to development of low thermal conductivity materials and their impacts on the environment.

6. Conclusion

This review presents basic concepts, various modelling techniques and mitigation strategies in relation to the UHI phenomenon. The major factors and their significance have been discussed for generating and mitigating the UHI. Solar radiation and anthropogenic heat due to urbanization play a key role in generating the UHI in cities. Currently, researchers are focusing on the simulation approaches due to advanced computing systems. However, recently developed modelling tools have some limitations such as complexity of urban details, theoretical weakness, high computational cost and shortcomings of high-resolution model inputs. A combination of different models and further development of modelling tools would be a better way to overcome these shortcomings. Furthermore, urban greeneries are a very effective and sustainable UHI mitigation strategy for compact cities marked by taller buildings and paving covers. The key mechanism was shading and evapotranspiratve cooling. The larger size of urban parks and a greater percentage of urban vegetation provide substantial cooling benefits and human thermal comfort as compared to smaller parks. Green and cool roofs show notable performance in reducing UHI effects, but fewer studies investigated green walls' cooling benefit and life-cycle cost-benefit analysis. It is recommended to combine several UHI mitigation strategies (e.g., parks, trees, cool pavement, and green roofs) rather than an individual mitigation strategy. It is also concluded that further studies are still needed in developing sustainable UHI mitigation (e.g. increased vegetation cover) considering cost-benefit analysis with long-term real measurements at micro and meso-scales. Cities in the world are vastly different. Therefore, the mitigation measures should meet the requirements of the individual city worldwide.

Conflict of Interest

All the authors do not have any possible conflicts of interest.

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