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REVIEW

Optimized greenery configuration to mitigate urban heat: A decade systematic review

Jiawei Fu [a,*], **Karine Dupre** [b], **Silvia Tavares** [a,c], **David King** [a], **Zsuzsa Banhalmi-Zakar** [a]

[a] *College of Science and Engineering, James Cook University, Townsville 4811, Australia*
[b] *School of Engineering and Built Environment, Griffith University, Gold Coast 4215, Australia*
[c] *School of Law and Society, University of the Sunshine Coast, Sunshine Coast 4556, Australia*

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Abstract Urban vegetation is a nature-based solution for cooling cities. Under global warming and urban population growth, it is essential to optimize urban vegetation configuration in the urban area to bring maximum cooling benefit. This paper reviews 85 optimized urban vegetation configuration studies published from 2010 to 2020 to provide an insight into the most effective vegetation configuration for urban heat mitigation. Patterns and preferences in methods and the optimized greenery configurations are comprehensively analyzed. The results indicate that size, quantity, and layout of urban green space and the physiological characteristics and spatial arrangement of urban vegetation significantly influence their cooling effect. Additionally, two other research gaps were identified. First, more research needs to be done in southern hemisphere cities experiencing rapid urbanization and severe impacts of extreme weather. Second, a comprehensive method for quantifying interactions and cumulative effects of natural and artificial factors in the urban environment is required. Future study needs a holistic understanding of the interactive effects of vegetation spatial distribution on urban environment and climate for a more accurate analysis of optimal cooling greening layouts in large urban areas at multi-scales.

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* Corresponding author.
E-mail address: jiawei.fu@my.jcu.edu.au (J. Fu).
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Contents

1. Introduction

Cities are facing challenges from climate change (Gouldson et al., 2016; Iturriza et al., 2020). Today, there are more than 3.4 billion people (50% of the world's population) living in urban areas, and it is expected to increase to 5 billion (60% of the world's population) by 2030 (Karakounos et al., 2018). By the end of the 21st century, global mean temperature is predicted to increase by up to 5.5 °C (IPCC, 2018). Continuing temperature rise increases the probability of extreme climate events (such as heatwaves, floods, and intense tropical cyclones) which put urban residents in a more vulnerable position (Aleksandrowicz et al., 2017). The Fifth Assessment Report (FAR) of the United Nations, Intergovernmental Panel on Climate Change (IPCC, 2014) projected that global warming will lead to high risks of severe, widespread, and irreversible impacts without effective mitigation measures by the end of the 21st century.

Under global warming, the frequency and duration of heatwaves have increased (Mazdiyasni et al., 2017). In the city, urban heat island (UHI) aggravates the effect of heatwaves (Rizvi et al., 2019). Higher urban temperature significantly increases energy consumption for cooling, heat-related mortality and morbidity, generation of air pollutants and indoor and outdoor thermal discomfort (Akbari et al., 2016; Soltani and Sharifi, 2017). For instance, the death toll from fatal heatwaves in Chicago in 1995 and Paris in 2003 was calculated at 514 and 4867, respectively (Dousset et al., 2011; Whitman et al., 1997). It is estimated that almost 50% of the world's population may be affected by deadly heatwaves on at least 20 days every year by 2100 (Mora et al., 2017). Within this context, it is then significant to seek an effective and sustainable way to mitigate UHI.

Vegetation is a nature-based solution for cooling urban areas. As one of the most vital parts of the urban ecosystem, it can help mitigate the UHI by providing thermal comfort, adjusting microclimate, weakening greenhouse gas (GHG) effect, and reducing energy usage (Coccolo et al., 2018; Velasco et al., 2016; Xu et al., 2017). In general, more greening has a stronger cooling effect in the city (Li and Zhou, 2019; Morakinyo and Lam, 2016; Teshnehdel et al., 2020). In practice, however, the area of vegetation is limited due to the restrictions of urban land resources. Considering the cost involved in planting and maintaining urban vegetation and the limited resources available to their configuration, it is essential to configure urban vegetation in a way that brings maximum cooling benefit. In view of this, more and more studies have tried to find an optimized greenery configuration to mitigate urban heat in the past decade. These studies are usually conducted at local and microscale levels and evaluate the optimal vegetation arrangement to improve outdoor microclimate and human thermal comfort. For instance, de Abreu-Harbich et al. (2015) and Rahman et al. (2020) compared the effect of different tree species in different sites of the city on human thermal comfort, and Millward et al. (2014) and Wang et al. (2015) investigated the effect of urban vegetation in microclimate. At the urban and regional levels, studies usually cover the area of a city and investigate the role of green space in reducing land surface temperature (LST). For example, Asgarian et al. (2015), Yu et al. (2018b), and Yao et al. (2020) assessed different spatial patterns of green space in reducing and Li and Zhou (2019) investigated optimizing the urban greenspace spatial pattern to mitigate UHI effects at city scale. These studies demonstrate that the appropriate vegetation placement can effectively mitigate urban heat. However, there are not any systematic investigations of the studies on the best urban greenery configuration for reducing UHI or improving thermal comfort at a comprehensive scale level.

Under the context of increasingly extreme heat, optimizing greenery configuration in the limited urban green areas is increasingly important. Assuming the existence of the optimal greening configuration, this paper systematically analyzes studies on the optimal vegetation configuration for reducing UHI or improving thermal comfort. In addition, industry practitioners and academic researchers need basic guidance for selecting appropriate methods to optimize greenery configuration for mitigating the impact of climate change in complex urban environments. To this end, this paper comprehensively assesses the current methods adopted. Particular attention is given to empirical studies of cooling effects generated by different spatial arrangements of urban greenery, including variations of vegetation arrangements, vegetation type, and the size and shape of urban green space. The associated potential research directions in the topic based on the current research gap and the state of the art of the focus area will be discussed. By presenting a more comprehensive and holistic view of this topic, the extensive findings will provide a firm basis for the optimized green strategy to mitigate urban heat. This review is expected to serve as the basis for future collaboration and research, which will benefit a wide range of stakeholders.

2. Methodology

The systematic quantitative literature review enables the analysis of existing scientific literature and produces a structured quantitative summary in a specific research area (Pickering and Byrne, 2014). The advantage of this method includes a narrow focus, comprehensive evidence seeking, evidence selection based on relevant criteria, rigorous evaluation of validity, objective or quantitative summary, and evidence-based reasoning (Collins and Fauser, 2005). Compared with traditional narrative reviews, a systematic quantitative literature review is explicit and reproducible, and can provide an overall assessment of the existing studies and identify the research gaps for further research.

The study carried out a systematic review of the literature on the greenery configuration to mitigate urban heat. Articles written in English and published between 2010 and 2020 were included, and the latest literature search was conducted on March 20, 2021. The articles were searched by using the search query string "("cooling effect" OR "human thermal comfort" OR "heat stress" OR "urban heat" OR microclimate) AND ("planting design" OR "landscape design" OR "urban vegetation" OR "green infrastructure")" in three electronic databases: Science Direct, Scopus, and Web of Science. The search resulted in 3221 articles, with 1327 articles remaining after duplicates were removed. To guarantee precision and scientific quality, 1080 peer-reviewed articles published in academic journals written in English were then retrieved. Only the papers describing the optimal greenery configuration for reducing urban heat or improving human thermal comfort were included. If the article mentioned the cooling effect of urban greenery without investigating its most effective configuration for urban heat mitigation, it was then excluded. During the screening process, the abstracts of the collected papers were assessed, and 168 papers were selected for further review. Afterwards, the full text of the selected papers was read to identify whether the study was qualified for further analysis. Finally, 85 eligible peer-reviewed papers were included for reviewing (Fig. 1).

Each selected paper was systematically reviewed, assessing (1) time of research and publication, (2) geographic distribution of the research, (3) research focus and discipline, (4) research methods adopted, (6) whether the research addressed the relationship between urban greenery arrangement and urban heat mitigation or thermal comfort improvement, (7) the finding in the optimized greenery configuration to reduce urban heat. From these articles, 11 items of information were recorded in a Microsoft Excel spreadsheet (Appendix A): (1) author(s), (2) title, (3) journal, (4) year of publication, (5) research location (research area, city, country, and climatic zone), (6) data acquisition period (year, month, time), (7) parameters used in the research (meteorological parameters, human thermal indices, vegetation physiological characteristics, and geometry conditions of built spaces), (8) methodology (research method, scale and software adopted), (9) optimal greenery strategy (size and shape of green space, greenery spatial arrangement, vegetation physiological characteristics, vegetation type or species, planting location, time or period), (10) annotated bibliography, (11) any other relevant information for reference.

3. Overview of the reviewed literature

3.1. Overview of the reviewed literature

The reviewed articles were retained from 27 journals in six different disciplines and published between 2010 and 2020 (Table 1). The three journals that most frequently publish in the focus area are *Urban Forestry & Urban Greening* (17 papers, 20.0%), *Building and Environment* (12 papers, 14.1%), and *Sustainable Cities and Society* (10 papers, 11.8%), which are consistent with two major disciplines: Environment and Ecology (39 papers, 45.9%) and Arboriculture and Forestry (20 papers, 23.5%). Other disciplines include Urban Planning/Landscape (10 papers, 11.8%), Climatology (7 papers, 8.2%), Energy (3 papers, 3.5%), and others (6 papers, 7.1%). The three most discussed topics are UHI, human thermal comfort, and heat mitigation (Fig. 2). Studies also concentrate on the cooling effect of urban greenery, planting design, and urban planning/urban design, while few papers investigate insolation mitigation and energy consumption.

Concerning the development of the study on greenery configuration to mitigate urban heat over the studied decade (Fig. 3a), findings show that overall little attention was paid to the topic before 2014, with only one paper published per year from 2011 to 2013. The number of

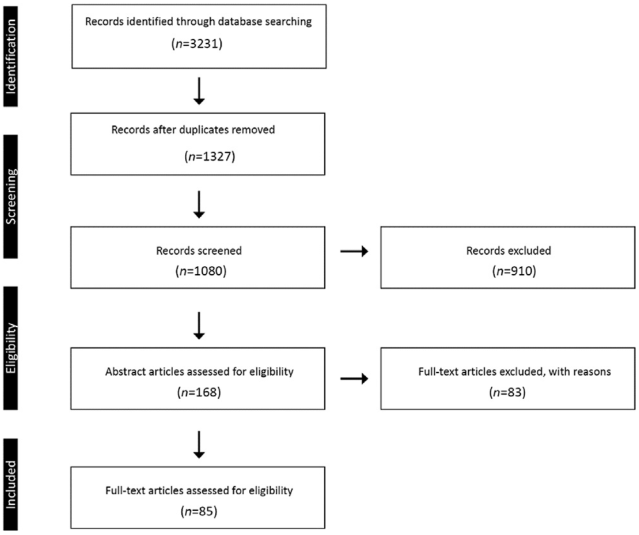


Fig. 1 PRISMA flow diagram adapted from Moher et al. (2009).

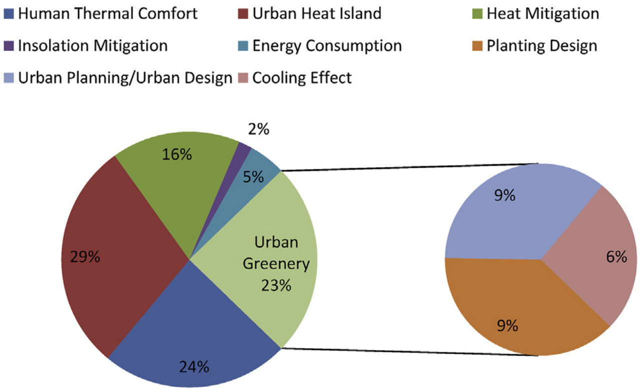


Fig. 2 Topics discussed in the reviewed literature.

articles quadrupled from 2 in 2014 to 8 in 2015 and stayed the same in 2016. The subsequent three years from 2016 to 2018 witnessed a steady increase, while slightly dropped by 5 in 2019. The increasing engagement with the topic has reached a peak in 2020 with 26 articles published. The growing interest in the topic can be attributed to the continually rising urban temperature and increasing awareness of the influence of greenery configuration on urban heat mitigation (Mazdiyasni et al., 2017; Sodoudi et al., 2018).

Geographically, 78 studies (91.8%) are located in the northern hemisphere with Asia (46 studies, 61.5%)

Table 1 Journals and disciplines list for the 85 reviewed articles on optimized vegetation configuration.

Discipline[a]	Name of journal	Papers per journal	Discipline total
Arboriculture and Forestry (4)	Urban Forestry & Urban Greening	17	20
	Agricultural and Forest Meteorology	2	
	Forests	1	
Climatology (4)	Urban Climate	2	7
	Atmosphere	3	
	Theoretical and Applied Climatology	1	
	Advances in meteorology	1	
Energy (2)	Energy and Buildings	2	3
	Thermal Science	1	
Environment and Ecology (9)	Building and Environment	12	39
	Sustainable Cities and Society	10	
	Sustainability	8	
	Sustainability (Switzerland)	4	
	Ecological Indicators	1	
	Urban Ecosystems	1	
	Environmental Monitoring and Assessment	1	
	Environmental Management	1	
	Journal of Environmental Engineering and Landscape Management	1	
Urban Planning/Landscape (4)	Landscape and Urban Planning	7	10
	Landscape and Ecological Engineering	1	
	Journal of Urban Planning and Development	1	
	Journal of Architectural and Planning Research	1	
Other (5)	Journal of Cleaner Production	2	6
	International Journal of Applied Earth Observation and Geoinformation	1	
	Landscape Research	1	
	Advances in Space Research	1	
	Cities	1	
Total		85	85

[a] Classification based on Roy et al. (2012).

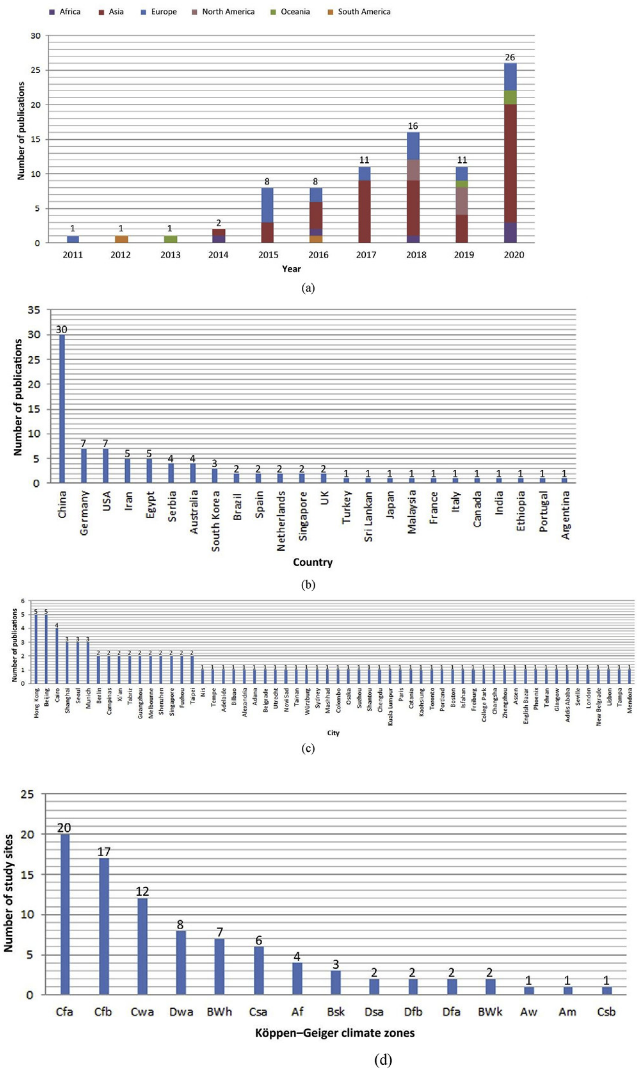


Fig. 3 Geographical distribution of reviewed studies based on research location, year, and climate zones. (a) Number of papers published yearly in different continents. (b) Country distribution of study sites in the reviewed literature. (c) Urban distribution of study sites in the reviewed literature. (d) Distribution of study sites per climate zone in the reviewed literature.

predominantly represented followed by Europe (19 studies, 22.4%) and North America (8 studies, 9.4%). Mainly three countries are investigated: China (30 studies, 35.3%), Germany (7 studies, 8.2%) and USA (7 studies, 8.2%) (Fig. 3a and b). Before 2015, Asia had little interest in the optimal greenery configuration for mitigating urban heat. Research in Asia has shown an overall growth from 2014 to 2017, although declining after 2017, the number of studies increased dramatically to 17 in 2020. Compared with Asia, the annual distribution of the number of studies in Europe was relatively balanced in the studied decade. In Europe, the number of articles published after 2015 was between 2 and 5, although there was only one study in 2011 preceding 2015. In North America, the relevant articles only appeared in 2018 and 2019. In South America, the number of studies (2 studies, 2.4%) is the least. Among all studied cities, Hong Kong and Beijing are the focus with the largest number of studies (5 studies), followed by Cairo (4 studies) (Fig. 3c). Shanghai, Seoul, and Munich are in third place having been investigated three times. According to the Köppen—Geiger climate classification system (Yang and Matzarakis, 2019), the studies are largely in humid subtropical (Cfa), temperate oceanic (Cfb), and warm oceanic climate/humid subtropical (Cwa) climate zones (Fig. 3d). The prevalence of study in the subtropical cities of Asia could be explained by their rapid urbanization leading to population booms and insufficient buildable land resources. In particular the thermal heat stress within the compact subtropical city morphology enables the study on this topic to be foremost in the literature (Ng et al., 2012).

3.2. Research methods adopted

Different research methods have been applied in the reviewed literature to investigate the most effective vegetation arrangement to counterbalance urban heat effects (Appendix B). Numerical simulation (54 studies, 63.5%) and field measurement (52 studies, 61.2%) are most widely adopted followed by remote sensing (30 studies, 35.3%) and questionnaires (5 studies, 5.9%) (Fig. 4). The accuracy of field measurement and remote sensing is limited by monitored time and area, while numerical simulation and statistical analysis are increasingly precise due to recent computational advancements (Aflaki et al., 2017). To better improve accuracy, 47 (55.3%) studies apply multiple methods. The following section explains in more detail the objectives of the three most used research methods.

3.2.1. Numerical simulation

With the advancement of computational techniques, researchers are increasingly applying simulation approaches in studying the relationship between urban vegetation and the UHI phenomenon (Tsoka et al., 2020). These studies are carried out on various platforms, such as ENVI-met, WindPerfect, PHOENICS, RayMan, Solar Long Wave Environmental Irradiance Geometry model (SOLWEIG), Rhinoceros with Grasshopper plug-in, and Weather Research and Forecasting (WRF) (Table 2). The majority of these platforms (53 studies, 98.1%) are Computational Fluid Dynamics (CFD) software or Energy Balance Model (EBM) software.

CFD software is the most popular (39 studies, 72.2%) and is a numerical simulation of fluid motion and heat transfer and is widely used for investigating the impact of urban greenery on wind and thermal comfort. Three pieces of CFD software are used in the reviewed literature: ENVI-met (37 studies), WindPerfect (1 study), and PHOENICS (1 study). WindPerfect and PHOENICS are respectively employed to investigate the effect of tree allocation on human thermal comfort (Hsieh et al., 2016) and microclimate (Li et al., 2019a). ENVI-met is one of the most widely used CFD software systems in urban microclimate. It is a three-dimensional microclimate modeling software for assessing and quantifying outdoor thermal comfort through simulating computational fluid dynamics, thermodynamics, and radiation balance. Concerning urban greenery, ENVI-met is applied for investigating the effect of vegetation arrangement on urban thermal comfort (Abdi et al., 2020; Atwa

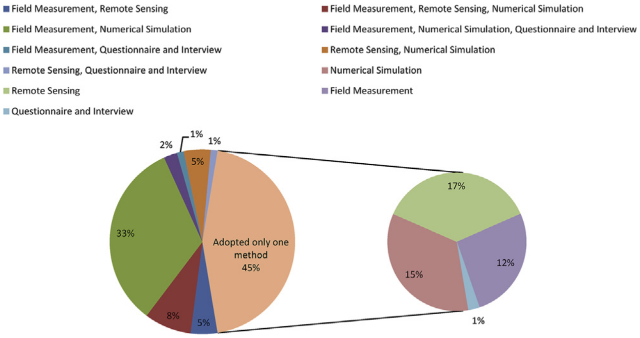


Fig. 4 Methods adopted in the reviewed literature.

et al., 2020; Tan et al., 2016, 2017), evaluating the cooling effect of urban vegetation (Jiang et al., 2018; Ng et al., 2012), and assessing the effect of tree species on thermal comfort (Morakinyo et al., 2017, 2020). However, the calculation of radiation flux in the ENVI-met model is not precise. Thus its accuracy is often validated by comparing ENVI-met output data with the data from field measurement (Morakinyo et al., 2017; Tan et al., 2016, 2017).

EBM software is used to simulate the energy and water exchange between city and atmosphere. In the reviewed literature, EBM based models are simulated in three pieces of software: RayMan (11 studies), SOLWEIG (2 study), and SURFEX (1 study). RayMan, as the second most used software in the reviewed literature, is employed for evaluating the human thermal comfort in urban green spaces (de Abreu-Harbich et al., 2015; Morakinyo et al., 2017). SOLWEIG is a model for analyzing radiation fluxes in a complex urban environment. Two studies adopt SOLWEIG for calculating mean radiant temperature (T_{mrt}) reduction of different tree species (Kong et al., 2017) and for quantifying the influence of increasing street trees (Thom et al., 2016). de Munck et al. (2018) build the EBM based model in SURFEX to investigate the impact of different green schemes on thermal comfort, and energy and water consumption.

Other software (Rhinoceros with Grasshopper plug-in and WRF) is applied in four studies. Grasshopper is a plug-in of the Rhinoceros platform which provides automated processes, generating geometric figures by mathematical functions, and rapidly changing complex models. Three studies adopt Rhinoceros with the Grasshopper plug-in to investigate the influence of changing tree locations on insolation mitigation (Stojakovic et al., 2020), thermal comfort (Milošević et al., 2017), and shade benefit (Langenheim et al., 2020) integrating with Ecotect, Ladybug, and PedestrianCatch respectively. Stojakovic et al. (2020) use an evolutionary algorithm in Grasshopper, which is an optimization problem-solving method based on natural selection, to find the optimized tree location for insolation mitigation. WRF is only applied once. As a next-generation mesoscale numerical weather prediction system, WRF is often used for analyzing urban meteorology. It has been coupled with the Single Layer Urban Canopy Model (SLUCM) to assess the effectiveness of different green scenarios on UHI and thermal comfort levels in Tehran (Arghavani et al., 2020).

In addition to the use of the aforementioned simulation approaches, Park et al. (2018) introduce the multilayer mean radiant temperature (MMRT) model. The MMRT model simulates radiation transfer of different urban elements. This model is applicable to streets with differing building and tree heights in the city (Park et al., 2018). Park et al. (2019) apply the MMRT model to evaluate the influence of various spacing and sizes of trees on pedestrian T_{mrt}.

3.2.2. Field measurement

In the research of urban microclimate, field measurement traditionally dominates (Tsoka et al., 2020), and has been applied since 1818, when it was first used by Luke Howard for studying UHI in London (Aflaki et al., 2017). The meteorological parameters (air temperature, wind speed, and relative humidity) and the vegetation physiological information (tree height, leaf area index, and tree crown width) are frequently measured to examine the effect of vegetation on urban microclimate (Abdi et al., 2020; Liu et al., 2020; Morakinyo et al., 2017). During the studied decade, field measurement was the second-most used method behind the numerical simulation.

Field measurements are generally divided into fixed-type observations and mobile-type observations. The measurement of vegetation physiological information adopts fixed type observation. As a common meteorological observation method, fixed-type observations are conducted in the majority of studies (40 studies). These studies adopt various instruments including temperature and humidity measuring instrument, weather station, and anemometer, etc. Temperature and humidity measuring instrument, such as TESTO data logger, iButton, Easy Log EL-USB-1/2, Elitech RC-4HC mini temperature and humidity data logger, Omegascope handheld infrared thermometer, AR847 humidity temperature meter, HOBO temperature/relative humidity data logger, and Campbell CS215 logger, is used most frequently (33 studies). The meteorological data from weather station is applied in 19 studies by using Watchdog weather station, Hobo U30 USB weather station, Graphtec data logger (GL240), and Davis Temp Station. Besides, anemometer (Testo anemometer, Davis anemometer, and RM Young Ultrasonic anemometer) and solarimeter (TSL tube solarimeter) are used in combination with temperature and humidity measuring instrument. Mobile-type observation is possible to obtain accurate data when the number of measuring equipment is limited and measurement points are close. In the reviewed literature, 12 studies conduct mobile traverse observation by using mobile measuring unit in the vehicle or bicycle. It is notable that 1 study combines fixed-type observation and mobile-type observation to receive more precise in site data.

The majority of studies that adopted field measurement (42 studies) use multiple approaches (Fig. 4). The data obtained from field measurements are used as the raw data to support the case study. For example, de Abreu-Harbich et al. (2015) input parameters (air temperature, relative humidity, wind speed, and global radiation) obtained from field measurement in RayMan model to quantify the effect of the physiological characters and arrangement of trees on human thermal comfort. Without the data measured from the field, it would be difficult to accurately calculate Physiologically Equivalent Temperature (PET) in this study. In addition, field measurement is used for the validation of numerical simulation to improve the precision of the

Table 2 Platforms adopted for numerical simulation in the reviewed literature.

Platform	Number of times adopted	Scale[a]	Parameters considered	Topic[b]	Research Focus[c]
ENVI-met	37	Microscale, Localscale, Localscale/Microscale, Mesoscale/Microscale	Air Temperature (T_a) Relative Humidity Wind Speed Inflow Direction Solar Radiation Geographical Location Roughness Length Initial Temperature Atmosphere Vegetation Information Surface Information Gender Age Clothing	UHI, HM, IM, EC, HTC, CE, PU, PD	Pa, GI, UGS, TC, VT, VT-GR, TC-VT, UGS-VT, GI-TC-GR, GI-VT
RayMan	11	Microscale, Localscale/Microscale, Mesoscale	Air Temperature (T_a) Globe Temperature Relative Humidity Wind Speed Geographical Location Albedo Vegetation and Building Information Gender Age Clothing Activity	HTC, UHI, PD, HM, PU, EC	UGS, GI, TC, GI-VT
Rhinoceros with Grasshopper plug-in	3	Microscale, Localscale/Microscale	3-Dimensional Site Model Trees Locations Insolation Values Pedestrian Shading	HTC, PD, IM	TC
SOLWEIG	2	Microscale, Localscale/Microscale	Air Temperature (T_a) Solar Radiation (global, direct and diffuse radiation) Relative Humidity Wind Speed Digital Surface Model (DSM) Geographical Location Albedo and Emissivity (walls and ground) Transmissivity (wall) Absorption Coefficient (short wave radiation) Emissivity (human body)	UHI, HTC, PD	TC
WindPerfect	1	Localscale/Microscale	Air Temperature (T_a) Wind Speed Inflow Direction Geographical Location	UHI, HTC, PD	TC
PHOENICS	1	Microscale	Air Temperature (T_a) Relative Humidity Wind Speed Inflow Direction Solar radiation Long-wave Radiation Direct and Diffuse Radiation Vegetation Information Surface Information	UHI, PD	TC

Table 2 (*continued*)

Platform	Number of times adopted	Scale[a]	Parameters considered	Topic[b]	Research Focus[c]
SURFEX	1	Mesoscale	Air Temperature (T_a) Wind components Surface Radiative Temperature Land Cover Information Surface Flux Albedo and Emissivity Heat Capacity Thermal Conductivity	UHI, HTC, EC	GI
WRF	1	Mesoscale	Land Surface Model (LSM) Planetary Boundary Layer (PBL) Cumulus Parameterization Shortwave and Longwave Radiation Microphysics (MP) Air Temperature (T_a) Relative Humidity Solar Radiation Gender Age Clothing Temperature Humidity Index (THI) Effective Temperature Index (ETI) Activity	UHI, HTC, EC	VF-GR

[a] Mesoscale (10 km—200 km), Localscale (100 m—50 km), Microscale (1 cm—1 km) based on Erell et al. (2010).

[b] CE cooling effect, EC energy consumption, HM heat mitigation, HTC human thermal comfort, IM insolation mitigation, PD planting design, PU urban planning/urban design, UHI urban heat island.

[c] GI green infrastructure, GR green roof, Pa park, TC tree canopy, UGS urban green space, VF vegetation fraction, VT vegetation type.

comprehensive computational spatial and data analysis (Abdi et al., 2020; Aboelata and Sodoudi, 2019; Morakinyo et al., 2017).

3.2.3. Remote sensing

Along with the development of satellites, remote sensing technology is widely used by researchers. Remote sensing data has increasingly been employed in evaluating the relationship between vegetation arrangement and urban thermal conditions (Morakinyo and Lam, 2016; Tan et al., 2017). On mesoscale and localscale levels, remote sensing approach has been applied for assessing the change of vegetation land cover effect on the LST. For example, Bartesaghi-Koc et al. (2020) apply a GIS-based approach to assess the influence of morphological and spatial properties of various green infrastructure (GI) types on their cooling effect from VHR airborne remote sensing data. Yu et al. (2018a) employ Light Detection and Range (LiDAR) data to investigate the relationship between vegetation height and LST. Shih (2017) evaluates the green space cooling effect by analyzing Landsat 8 satellite imagery in Quantum GIS (QGIS). On the microscale level, remote sensing approach is integrated with numerical simulation to evaluate the impact of vegetation arrangement on urban thermal environments. In many studies, remote sensing technology is combined with ENVI-met. For instance, Makido et al. (2019) evaluate the use of GI treatments by applying an ENVI-met model based on remote sensing digital files and field measurements to investigate changes in ambient temperatures of different land uses in Portland. Sk and Swades (2020) examine the UHI mitigation effect of different greening scenarios by comparing the ENVI-met models in different local climatic zones (LCZ) based on the Lansat TM and OLI images. In addition, SOLWEIG model with the data from the digital surface model (DSM) is employed to quantify the influence of street trees on thermal comfort in the research conducted by Thom et al. (2016). The impact of greenery spatial distribution on urban thermal environments can be observed from various scales through remote sensing technology by employing a combination approach, which enables studies using remote sensing to make the best use of its advantages and bypass its disadvantages (Table 3).

Among the methods adopted in the reviewed literature, numerical simulation is most widely adopted in the studied decade, although field measurements have previously been predominant. In pace with the development of

Table 3 The three most widely used methods in the reviewed literature.

	Numerical simulation	Field measurement	Remote Sensing
Pros	Comprehensive analysis of the data Simulation is not restricted by time and space Cost and time effective	Accurate first hand and detailed data The method is adaptable and flexible Widely used observation methods	The advantages of spatial data management, spatial analysis and visualization Accurate analysis makes better predictions
Cons	Accuracy is affected by simplifying the boundary conditions and material properties High reliance on computer technology Complicated operation and strong specialization	Limited by field conditions such as time and space. Needs more manpower and time	Unsteadiness of the data Costly GIS software Complicated operation and strong specialization

computational and remote sensing technology, numerical simulation and remote sensing are growing in use. In search of accuracy, a majority of scholars apply combined approaches. The most common combined method adopted is field measurement integrating with numerical simulation (28 studies, 32.9%). This combination may be attributed to obtaining more precise results through processing field measurement data in the numerical model (Table 3). The combined research method helps to achieve accurate results that contribute to arranging vegetation in the city for urban heat mitigation in practice.

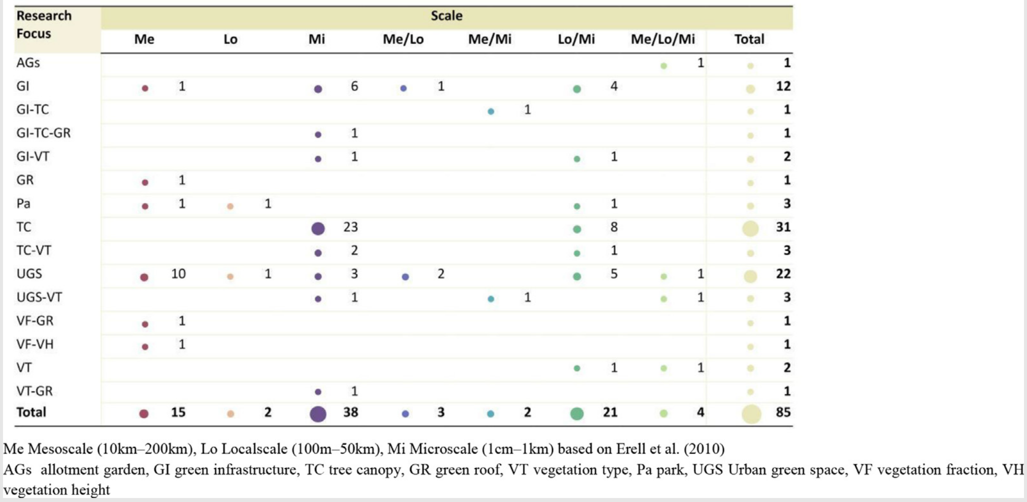
4. Findings about optimized greenery configuration to mitigate urban heat

The influence of urban greenery on temperature reduction is scale-dependent (Kong et al., 2014; Liu and Weng, 2009). Thus, studies on the effect of urban greenery on urban heat are usually conducted at a specific scale level. According to the classification of different scales for climate study suggested by Oke in 1987, the studies in this review are conducted on three different scale levels: Mesoscale, Localscale, and Microscale (Erell et al., 2010). Most of the reviewed literature studies the optimized vegetation configuration for urban heat mitigation at microscale (38 studies, 44.7%) (Table 4). Hence, the following section presents in more detail the findings of the optimized greenery configuration at two different scale levels: 1. Localscale and Mesoscale, 2. Microscale.

4.1. Optimized greenery configuration at local and meso scale

Some scholars find that green coverage has a negative linear relationship with air temperature (Chen et al., 2020; Middel et al., 2015), while the optimized green coverage ratio (GCR) differs in various studies. For example, in Glasgow Clyde Valley Region, UK, an increase of 20% of the existing GCR could reduce by at least one-third the UHI effect expected by 2050 (Emmanuel and Loconsole, 2015), but Yao et al.

Table 4 Analysis of research focus and scale in the reviewed literature.



Research Focus	Scale							
	Me	Lo	Mi	Me/Lo	Me/Mi	Lo/Mi	Me/Lo/Mi	Total
AGs							1	**1**
GI	1		6	1		4		**12**
GI-TC					1			**1**
GI-TC-GR			1					**1**
GI-VT			1			1		**2**
GR	1							**1**
Pa	1	1				1		**3**
TC			23			8		**31**
TC-VT			2			1		**3**
UGS	10	1	3	2		5	1	**22**
UGS-VT			1		1		1	**3**
VF-GR	1							**1**
VF-VH	1							**1**
VT						1	1	**2**
VT-GR			1					**1**
Total	**15**	**2**	**38**	**3**	**2**	**21**	**4**	**85**

Me Mesoscale (10km–200km), Lo Localscale (100m–50km), Mi Microscale (1cm–1km) based on Erell et al. (2010)
AGs allotment garden, GI green infrastructure, TC tree canopy, GR green roof, VT vegetation type, Pa park, UGS Urban green space, VF vegetation fraction, VH vegetation height

(2020) reveal that optimizing green space arrangement is more effective than increasing the GCR when GCR is more than 30% in Beijing, China. Zhao et al. (2020b) find that LST greatly reduces with increasing vegetation aggregation when green coverage is lower than 40%. In Shenzhen, China, Yan et al. (2020) indicate that the thermal environment of residents is relatively stable when the vegetation coverage exceeds 55%. In Cairo, Egypt, 50% tree coverage in the built-up area is the best scheme to reduce urban heat and improve thermal comfort (Aboelata, 2020), especially in the high-density area (Aboelata and Sodoudi, 2020) during the daytime (Aboelata and Sodoudi, 2019). In Campinas, Brazil, and Mendoza, Argentina, a GCR of 60% combined with high albedo pavements and roofs is an effective cooling method (Alchapar et al., 2016). In Tampa, USA, the maximum cooling effect of vegetation can be reached when vegetation coverage is more than 93.33% (Yu et al., 2018a). Huang and Chen (2020) find that increasing the GCR of streets to 60%, parks to 80%, and public building roofs to 100% can effectively reduce the UHI effect in Kaohsiung, Taiwan, China. These different findings are probably due to the difference in vegetation arrangement, plant species, surrounding urban structure, and climate background.

The cooling effect of urban green space is strongly correlated with the size, shape, and spatial pattern of green space (Feyisa et al., 2014; Kong et al., 2014). Some studies reveal that a large area of green space can improve the cooling ability effectively (Feyisa et al., 2014; Jiang et al., 2018; Rost et al., 2020; Shih, 2017; Xiao et al., 2018). For example, in Suzhou, China, increasing green area with a greater leaf area index (LAI) average and average canopy density of green space enhances the cooling capacity of green space (Xiao et al., 2018). Shih (2017) finds that LST in Taipei tends to be lower in a large green area with more vegetation and water content. In Shanghai, China, increasing large green space is beneficial to the cooling effect of residential quarters in summer (Jiang et al., 2018). In Berlin, Germany, the cooling effect of the allotment garden is positively related to its size and distance to the city center (Rost et al., 2020). In Addis Ababa, Ethiopia, the park cooling ability is positively correlated with Normalized Difference Vegetation Index (NDVI) and the size of the park (Feyisa et al., 2014). In Beijing, China, the cooling effect of the park is greater with a larger size (Qiu and Jia, 2020). Lin and Lin (2016) also indicate that larger park areas, more parks and park diversity results in more significant cooling effects in Taipei. It is worth noting that Cheng et al. (2015) find that LST of the park decreases logarithmically with the increase of park size, while eventually reaching an asymptote in Shanghai, China. In Fuzhou, China, Yu et al. (2017) find that larger green areas provide higher cooling, while the cooling effect becomes stable at a certain point, which is the threshold value of efficiency (TVoE). They calculate the TVoE is 4.55 ± 0.5 ha, which is the optimal area of green space for mitigating UHI in Fuzhou (Yu et al., 2018b). Du et al. (2017) also indicate that a larger green space area under the threshold (40 ha) can reduce LST in Shanghai effectively. In Lisbon, Portugal, Reis and Lopes (2019) suggest the minimum area of green space is 50 m^2 as 50 m^2 of vegetation decreases air temperature by 1 °C. In a highly urbanized area, however, connected small green space might be a more realistic and effective way to reduce urban heat. Kim et al. (2016) indicate that small green infrastructure is an effective way to improve urban micro thermal conditions in high-density urban areas after measuring the temperature at different height levels and simulating a microscale climate model in Seoul, Republic of Korea.

In terms of the shape of green space, some studies have shown that the green space with a more complex shape offers more cooling benefits (Asgarian et al., 2015; Cheng et al., 2015; Du et al., 2017). For instance, in Beijing, China, Yao et al. (2020) indicate that raising the complexity of forest patch edges may be a more practical path to mitigate UHI effect in the limited ecological space of built-up areas by improving the landscape structure of green space. In Isfahan, Iran, Asgarian et al. (2015) proposed to allocate as many irregular-shaped green patches with large perimeter-to-area ratios as possible in urban areas to better reduce the LST. In Shanghai, China, Cheng et al. (2015) reveal that the impact of urban man-made land use on thermal environments can be mitigated by increasing the complexity of landscape shapes, and Du et al. (2017) find a more complex green space shape can efficiently decrease LST. In Phoenix, USA, Yan et al. (2019) indicate that increasing edge density and shape complexity of green spaces can cool the surrounding landscape while may warm individual vegetation patches. They further point out that heat transfer from the surrounding environment to green space is accelerated with more edge areas. Li and Zhou (2019) find that the surface UHI intensity in Illinois, Indiana, Ohio of USA is negatively related to mean patch shape of green patches while positively related to the edge density of urban green patches. At the same time, Shih (2017) reveals that a green space with a compact and simple shape effectively mitigates LST in Taipei. In Suzhou, China, Xiao et al. (2018) find that a green space with a large area while having less perimeter has a better cooling capacity. Interestingly, Feyisa et al. (2014) indicate irregular and elongated parks have lower cooling intensity and larger cooling distance compared with regular and compact parks in Addis Ababa, Ethiopia. For the specific shape, elongated (Jiang et al., 2018; Sodoudi et al., 2018), circle, and square (Yu et al., 2017) green spaces are suggested for mitigating urban heat.

Regarding the spatial distribution of green space, some studies show that evenly allocating green spaces reduces urban heat effectively (Asgarian et al., 2015; Lin and Lin, 2016; Liu et al., 2020). It is because the even distribution of green spaces improves the thermal environment by decreasing solar irradiation (Liu et al., 2020) and LST (Asgarian et al., 2015), and increases the synergistic cooling ability by connecting individual green spaces (Lin and Lin, 2016). On the other hand, Zhao et al. (2020b) indicate that a clustered distribution strengthens the aggregation cooling of green spaces in Beijing. Li and Zhou (2019) find that the more patch density of vegetation the less surface UHI intensity. During the studied decade, scholars in Europe tried to find the optimal density of urban green space. In London, UK, Monteiro et al. (2016) advise an interval of 100—150 m spreading with 3—5 ha of green space to achieve continuous cooling in the whole city during warm nights. In Munich, Germany, Alavipanah et al. (2015) find the LST is significantly reduced when vegetation coverage is 70%—79% per km^2.

4.2. Optimized greenery configuration at micro scale

During the studied decade, trees have been the most studied (23 studies, 60.5%) at microscale level (Table 4). Trees are an extremely important vegetation type for mitigating UHI effect through transpiration and shading (Dekić et al., 2018; Yoshida et al., 2015). On the pedestrian level, trees can effectively improve thermal comfort, especially during hot periods (Srivanit and Hokao, 2013; Tan et al., 2017). Therefore, the optimized greenery configuration at microscale is described by dividing it into the optimized configuration of tree and different kinds of vegetation in the following section.

4.2.1. Optimized tree configuration

An appropriate increase of trees positively affects the urban thermal environment (Milošević et al., 2017; Teshnehdel et al., 2020; Wu and Chen, 2017). In Changsha, China, increasing the number of trees by 60% resulted in reducing the temperature at pedestrian level in mid-rise and low-rise building areas (Chen et al., 2020). In Assen, Netherlands, Wang et al. (2015) find that high density tree groves provide a strong cooling effect. However, in order to improve thermal comfort, the distance between trees should not be too close for preserving wind corridors (Hsieh et al., 2016). Zheng et al. (2018) indicate that the space of two trees with a distance of mature canopy diameter is found to be the most effective way to mitigate urban heat in Shantou, China. In Seoul, Republic of Korea, Park et al. (2019) find that an interval of 3—10 m of small trees effectively decreases T_{mrt}, while the effect of big tree spacing on tree cooling is not significant.

Trees with different physiological characteristics adjust to wind speed, humidity and solar radiation differently. In Novi Sad, Serbia, Milošević et al. (2017) find that the cooling ability of trees with cylinder-shaped tree crowns is better than those with sphere-shaped and cone-shaped tree crowns. Some studies suggest applying deciduous trees in the city to better adjust microclimate (Afshar et al., 2018; Mahmoud, 2011; Zhao et al., 2020a). In the city, the selection of trees depends on people's activities and the climate conditions of the area where the trees are located. For example, Altunkasa and Uslu (2020) suggest planting deciduous trees in courtyards and pedestrian areas for providing shade during summer and transmitting sunlight during winter, while using evergreen trees at the north of the building for blocking wind during winter in Adana, Turkey. In general, tall mature trees with a large and dense canopy, which contribute to ventilating and shading, can better improve thermal comfort (Langenheim et al., 2020; Liu et al., 2020; Park et al., 2019; Yang et al., 2018a; Zaki et al., 2020). In the urban environment, however, the cooling effect of trees is often affected by the spatial morphology of the city (Lobaccaro and Acero, 2015; Morakinyo et al., 2017; Yao et al., 2020). In Hong Kong, for instance, Kong et al. (2017) suggest using dense canopy tree species in high-density area with high buildings and trees with a short trunk base in the narrow street for providing adequate shade to the ground, while Morakinyo et al. (2017) advise planting trees with less canopy density and higher trunk in a deeper street canyon and vice versa. In Changsha, China, Chen et al. (2020) also find that the cooling effect of increasing trees by 30% or 60% in high-rise building areas is worse than that in mid-rise and low-rise building areas. It is because the space between tall buildings is better shaded during daytime which leads to increasing trees being less efficient (Chen et al., 2020). However, in Cairo, Egypt, Aboelata and Sodoudi (2020) reveal that trees are effective in reducing air temperature and energy consumption in high-density building areas, but not in low-density areas. It is due to more than 50% trees needing to be planted in low-density areas to achieve cooling and shading, which is difficult to implement in arid Cairo (Aboelata and Sodoudi, 2020).

Previous studies demonstrated the effect of tree layout on the urban thermal environment (Altunkasa and Uslu, 2020; de Abreu-Harbich et al., 2015; Rahman et al., 2020). During the reviewed decade, studies have indicated that planting trees in a position to maximize canopy shading and minimum wind disturbance is an effective way to lower urban heat and improve the thermal environment. For instance, Tan et al. (2016) advise distributing trees in the wind corridors as the cooling effect of trees in the areal wind paths is twice those in the leeward areas in Hong Kong. Some studies demonstrate that clustered planting (Bartesaghi-Koc et al., 2020; de Abreu-Harbich et al., 2015; Millward et al., 2014; Rahman et al., 2020; Thom et al., 2016; Zhao et al., 2020a), rectangular planting (Abdi et al., 2020; Liu et al., 2020) and double-rows of trees (Atwa et al., 2020; Klemm et al., 2015; Li et al., 2019b; Zhao et al., 2018) provide greatest thermal comfort. For example, de Abreu-Harbich et al. (2015) and Thom et al. (2016) indicate that clustered trees greatly reduce high temperatures as they significantly increase shaded areas improving outdoor thermal comfort. In Tabriz, Iran, the optimal planting scheme for improving thermal comfort is rectangular planting of trees perpendicularly to the prevailing wind, with evergreen trees surrounding intermediate deciduous trees (Abdi et al., 2020). In Utrecht, Netherlands, T_{mrt} of the street with double-row trees is lower than that of the street without greenery and streets with trees combined with both sides front gardens (Klemm et al., 2015). Atwa et al. (2020) and Zhao et al. (2018) reveal that the isometric arrangement of double trees provides the best human thermal comfort benefits by providing adequate shade in a mid-latitude desert city (Alexandria, Egypt, and Tempe, USA).

4.2.2. Optimized vegetation configuration

Various vegetation types and configurations influence the urban thermal environment differently. Some studies show that the cooling capacity of vegetation is related to time, season, and research topic (Aboelata, 2020; Aboelata and Sodoudi, 2019; Zhang et al., 2020). For instance, in Cairo, Egypt, Aboelata and Sodoudi (2019) find that 50% trees achieve better thermal comfort than 30% trees and 70% grass do during daytime, and the opposite is true at night, because trees provide shade during daytime and a large area of grass increase evaporation and heat dissipation during night-time.

In the street with height-to-width ratio (H/W) 1:1 of Cairo, Aboelata (2020) finds that 70% of grass planting on the street shows better in reducing energy demand and air temperature compared with 20% and 50% of tree planting schemes, while trees perform better in enhancing thermal comfort. In Chengdu, China, Zhang et al. (2020) find that the thermal comfort in groves is better than that on the lawn during summer, while the opposite is true in winter. In Seoul, Republic of Korea, the temperature at different high levels (ground surface, 0.1 m, and 1.5 m) in the forest is lower than that in the grass area both in summer and winter (Kim et al., 2016). These findings, to a certain extent, provide a research basis for developing the optimal planting configuration to reduce the UHI effect.

Concerning the optimal configuration of different vegetation types for heat mitigation, some studies show that combining trees with other surface vegetation, such as trees-grass structures (de Munck et al., 2018; Dekić et al., 2018; Li et al., 2019b; Lobaccaro and Acero, 2015; Makido et al., 2019; Yan et al., 2019; Yang et al., 2018a), provides distinct cooling benefits. For example, in Bilbao, Spain, combining trees and grass provides the maximum PET reduction of streets, thus improving pedestrian thermal comfort (Lobaccaro and Acero, 2015). Makido et al. (2019) indicate that adding trees in a large open area with soils or grass is perhaps a simple and effective way to lower temperature in Portland, Oregon. On the other hand, Jiang et al. (2018) and Li et al. (2020) suggest using a tree-shrub-grass planting configuration for cooling subtropical cities (Shanghai and Zhengzhou, China). Bartesaghi-Koc et al. (2020) also find that rows or clusters of trees planted on irrigated shrubs and grasses constantly decreases LST in Sydney, Australia. However, some studies indicate that groves provide the most effective cooling benefit (DR et al., 2020; Kim et al., 2016; Stojakovic et al., 2020; Xu et al., 2017). For example, in Singapore, the secondary forest shows the largest cooling capability (-1.7 °C), followed by tree-shrub (-0.9 °C) and tree-grass (-0.9 °C) (DR et al., 2020). In Shenzhen, China, increasing 10% grove cover most effectively reduces the maximum air temperature among three proposed urban green infrastructures (increasing 10% greenway, increasing 10% grove, and increasing 10% green roof) (Wang et al., 2019).

To compensate for the limitation of an isolated cooling method of surface vegetation, the implementation of combined cooling factors, such as cool pavement (Alchapar et al., 2016; Yuan et al., 2017), shading devices (Stojakovic et al., 2020; Xu et al., 2017), green roofs (Arghavani et al., 2020; Chen et al., 2020), green walls (Herath et al., 2018; Zölch et al., 2016), and water bodies (Cheng et al., 2015; Du et al., 2017; Jiang et al., 2018; Mahmoud, 2011; Yu et al., 2017), synergistically promote temperature reduction. For example, in Shanghai, China, green improvement (increase in street trees and riparian green areas, adoption of green roofs, and use of tree-shrub-herb structures instead of tree-herb structures in green nodes) integrated with water bodies have a synergistic cooling effect (Jiang et al., 2018). In Colombo, Sri Lanka, a combination of trees on curbsides, 50% green roofs and 50% green walls most effectively reduces temperature (Herath et al., 2018). In Changsha, China, the temperature reduces greatly when adopting increasing trees by 60% coupled with cool pavement material in open residential areas (Chen et al., 2020). This illustrates that multiple methods can be combined to cool the complex urban environment by using vegetation.

5. Discussion

The studies retrieved in this review are predominantly conducted in cities from northern latitudes focusing on Asian and European cities with subtropical and temperate climates. The factors that affected this geographical distribution are (1) limitations of the approach of the systematic literature review, such as the limited accessibility of information from selected databases, and language limitations, as consulted databases are all in English language only. (2) national variation in the number of researchers and funding. (3) differences in research needs and interests across regions. For example, the cities severely affected by urban heat (Hong Kong and Beijing) tend to be more investigated regarding the cooling effect of vegetation configuration. Research on such topics is not found in high latitude cities with low solar radiation or extremely cold or arid areas with little vegetation because of the unfavorable environment for growth. Little work has been done on the topic in the cities of developing countries in the southern hemisphere. Special focus should be put on cities experiencing rapid urbanization with large population growth and severe impacts of extreme weather. With the increasing cases of high-temperature weather in cities around the world due to the increasingly severe impact of climate change, more research needs to be done in different regions of the world. More generalized conclusions can then be reached in future work in order to provide sufficient information about the optimized vegetation configuration on urban mitigation in different regions.

A systematic literature review has its inherent limitations (Petticrew and Roberts, 2006), and this study is no exception. In this review, only peer-reviewed articles published in academic journals written in English were retrieved. Future studies, including valuable literature in other languages and grey literature, may shed more light on this topic. Furthermore, the reviewed articles were collected from Science Direct, Scopus, and Web of Science by using the keywords "("cooling effect" OR "human thermal comfort" OR "heat stress" OR "urban heat" OR microclimate) AND ("planting design" OR "landscape design" OR "urban vegetation" OR "green infrastructure")". The purpose of the retrieval process is to achieve a precisely replicable search and to keep search terms simple and consistent. Even so, some articles that did not include matching words or were not in these three databases were unintentionally excluded. It is suggested to scrupulously conduct future systematic literature reviews to strike a balance between better comprehensiveness and accurate replication. In spite of this limitation, this study demonstrates a holistic view of the current studies on the optimal vegetation configuration for urban heat mitigation and the methods adopted. This view will form a firm basis for the optimized green strategy to mitigate urban heat and serve as the basis for future collaboration and research.

In the studied decade, studies are overwhelmingly conducted in summer and daytime, rarely in cold seasons, all year round and night-time (Fig. 5). It may be attributed to the influence and variation of outdoor thermal stress that are more significant in warm weather and daytime exposure to solar radiation. More of the literature has studied the optimized vegetation configuration for urban heat mitigation at a microscale in the urban public space, such as streets, parks, and public squares, than in private space (Fig. 6). Because public space is an important place for urban residents to carry out social and living activities, it is more feasible to optimize public space through planning and design than private space. As a complex climatic phenomenon, urban heat influences people at different scales, dimensions, times, and spaces in the city. Therefore, future research should conduct a more comprehensive analysis on how to optimize urban greening to improve urban microclimates both in the hot and cold seasons at multi-scale levels through combining with multi-disciplines. In addition, studies have indicated the cooling effectiveness of optimizing green coverage ratios and green space patterns, while the optimal GCR differs in various studies (Alavipanah et al., 2015; Emmanuel and Loconsole, 2015; Xiao et al., 2018). There is no unified answer for the best specific shape (Jiang et al., 2018; Shih, 2017; Sodoudi et al., 2018) and density (Alavipanah et al., 2015; Monteiro et al., 2016) of green space to mitigate urban heat. Therefore, more studies should pay attention to the specific optimized size, shape, configuration, quantity and layout of urban green space for heat mitigation and thermal comfort improvement. Furthermore, assessing the temporal heterogeneity and connectivity of spatial vegetation at a multi-spatial level is necessary. A holistic understanding of how vegetation affects urban climate at different scales is needed.

The research methods adopted, depending on research objectives, topics, and spatial scale, largely apply numerical simulation, field measurement and remote sensing. Numerical simulation is dominantly used in the studied decade due to the development of computer technology. With the development of science and technology, future studies will simulate urban climate in more technological approaches, such as machine learning, to model more complex environments with more variables, such as human activity and plant growth (Stojakovic et al., 2020). Research at the mesoscale usually adopts remote sensing to investigate the role of green space in reducing LST in areas of a city (Alavipanah et al., 2015; Du et al., 2017; Li and Zhou, 2019; Yu et al., 2018b). The adoption of low-altitude infrared remote sensing on the topic needs to develop. Little work on the optimized greenery configuration for urban heat mitigation has been conducted at multi-scale levels (Privitera and Rosa, 2018). In order to carry out the research more fully, scholars need to adopt a combination of methods. In the future, research should combine multidisciplinary methods to study the cooling effect of urban vegetation at a multi-scale level. A comprehensive method for quantifying interactions and cumulative effects of natural and artificial factors in the urban environment is required.

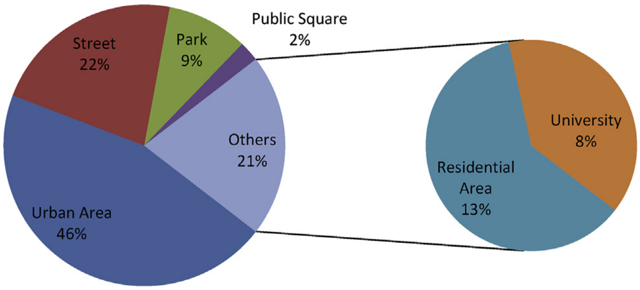


Fig. 6 Study location of the studies in the reviewed literature.

5.1. The effect of physiological characteristics of vegetation

The physiological characteristics of vegetation directly impact its cooling. Trees, which have substantial effects on the amount of sunlight penetrating through to the amount of shadow cast on the ground (Mastura et al., 2016), have been predominantly investigated during the researched

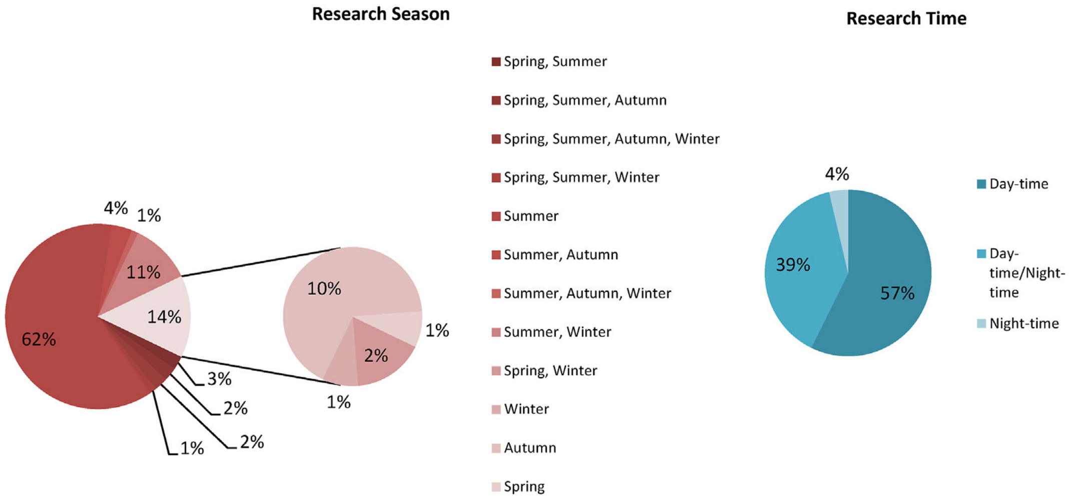


Fig. 5 Research season and time of the studies in reviewed literature.

decade. The cooling potential of vegetation is influenced by different factors in various degrees in different locations. More research is needed to compare the effect of the Plant Area Index (PAI), tree height, branching height, and tree crown on the microclimatic and human thermal benefits (Morakinyo et al., 2017). In addition, studies demonstrate vegetation in good irrigation conditions provides better cooling benefits (Bartesaghi-Koc et al., 2020; Reis and Lopes, 2019; Rost et al., 2020). In Sydney, Australia, Bartesaghi-Koc et al. (2020) indicate arranging trees on well-irrigated shrubs and grasses can reduce LST considerably. However, there is little knowledge on the interactive effect between trees and other vegetation on urban climate under different growth and irrigation conditions. Research on the optimal physiological characteristics of vegetation other than trees (shrub, grass, climbers and aquatic vegetation) for cooling the city is still lacking. Filling this research gap will promote optimized vegetation configuration for urban heat mitigation by providing evidence for the cooling effect of different plant combinations.

Vegetation with different physiological characteristics, such as tree height, canopy diameter, LAI, and PAI, affects wind speed, humidity and solar radiation variously. Locating the vegetation with the best physiological characteristics for improving the thermal environment at the right place is very important. For instance, deciduous trees effectively improve thermal comfort in cold winters (Afshar et al., 2018). In courtyards, pedestrian nodes and pedestrian roads, deciduous trees are suggested to be planted as they can effectively improve thermal comfort when compared to evergreen trees, by providing shade in hot summer and avoiding excessive shade in cold winter (Altunkasa and Uslu, 2020; Afshar et al., 2018). However, improper vegetation distribution may obstruct wind movement and result in temperature rise (Hsieh et al., 2016). For example, Aboelata (2020) finds that 20% and 50% tree density increases air temperature in streets with H/W 1:1 of Cairo, Egypt. Similarly, increasing groves by 10% reduces the maximum temperature in Shenzhen, China, while the grove site is the hottest and most uncomfortable place during hot periods in Guangzhou, China. It is due to the higher relative humidity and lower wind speed caused by a large number of trees (Wang et al., 2018). Studies show an increase of trees with appropriate density positively affects the urban thermal environment, while the conflicting findings of the best tree density and arrangement to mitigate urban heat (Aboelata and Sodoudi, 2019) leave some questions unanswered. It is suggested to arrange trees to produce a synergistic cooling effect and maximize shading, such as a clustered planting arrangement or rectangular planting arrangement, considering the shading of trees can influence human thermal comfort greatly (de Abreu-Harbich et al., 2015). However, the research reviewed does not elaborate on how to maintain the optimal density of trees when they are growing. The cooling effects of vegetation on urban heat are caused by the complexity of greenery arrangement, built environment, and local climate, which need to be further studied. In addition, future studies need to explore the effect of different types of plants, vegetation physiological characteristics, and planting arrangement on urban microclimate, especially in terms of irrigation, evapotranspiration and shading. More studies should be conducted on the interactive effect between trees and other vegetation on urban climate under different growth and irrigation conditions.

5.2. The effect of spatial morphology of the city

The spatial morphology of the city significantly affects the cooling ability of urban vegetation. The optimal planting configuration for urban heat reduction varies with the change of building form and density, sky view factor (SVF), H/W and orientation of the street, which are proven to directly impact the cooling effect of urban vegetation (Tan et al., 2017). For example, some studies indicate that the cooling effect of trees has a negative correlation with urban density and the height of the buildings (Lobaccaro and Acero, 2015; Morakinyo et al., 2017). In Hong Kong, Tan et al. (2016) find that the cooling ability of trees in the city is closely linked to SVF. They reveal that air temperature decreases most distinctly in the area with high SVF, while the radiation shading is more significant in the medium-low SVF area. Some studies reveal that the cooling effect of the same vegetation scenario differs in the streets with various H/W and orientations (Lee et al., 2020; Ng et al., 2012). In Freiburg, Germany, averaged T_{mrt} reduction of increasing canopy coverage is more significant in shallow street canyons ($H/W = 0.5$) than that in the deep street canyons ($H/W = 2.0$) (Lee et al., 2020). In Cairo, Egypt 50% tree density, which is proven to be the best urban heat reduction scheme by Aboelata and Sodoudi (2019), raises air temperature in an NW-SE 330° street with H/W 1:1. The applicability of the research findings in different urban morphology contexts has no uniform standards in different climate zones. In future work, the influence of urban morphological factors, such as building form and density, SVF, H/W and orientation of the street, on urban microclimate need to be further studied to provide sufficient information for obtaining the most effective vegetation allocation to mitigate urban heat.

In the southern hemisphere, Langenheim et al. (2020) find that when the temperature and ultraviolet radiation are the highest in summer, E-W streets need wider canopy trees while N–S streets require higher trees with close distance to provide greater shading. In Melbourne, Australia, Berry et al. (2013) indicate that placing trees close to the building (1.1 m) efficiently lowers air temperature and building walls' surface temperature. In the cities of the northern hemisphere, some studies indicate planting trees in the E-W street can better improve thermal comfort (Lee et al., 2020; Zaki et al., 2020). For example, trees on the S-facing sidewalk significantly enhance pedestrian thermal comfort in E-W streets in Freiburg, Germany (Lee et al., 2020). In Catania, Italy, allocating trees in the western-southern-eastern or western-eastern sides of the buildings effectively reduces energy consumption (Privitera and Rosa, 2018). In Toronto, Canada, arranging large mature trees 5–10 m from the west of the building distinctly reduces temperature during the afternoon in summer (Millward et al., 2014). Trees are proposed to be arranged on both sides of the street (Jiang et al., 2018; Wang et al., 2018). For instance, in Xi'an, China, street trees are suggested to be arranged in the middle of the N—S street while close to the buildings of the E-W street for improving thermal comfort (Yang et al., 2018b). Different results may be attributed to different tree species, climate background, weather conditions, and urban spatial structures of the cities.

Different results of the optimal greenery arrangement for urban heat mitigation reveal that the cooling potential of vegetation is influenced by multiple factors. These factors have different degrees of influence on the cooling effect of urban vegetation. Weather conditions are vital for the vegetation to regulate the microclimate during summer (Tsoka et al., 2017). In Hong Kong, under cloudy conditions, the influence of building form and SVF is more obvious than that under sunny conditions (Tan et al., 2017). Wind is one of the most significant elements to consider when planning vegetation arrangements to reduce urban heat. It is suggested to allocate vegetation in the windward corridor (Tan et al., 2016) and arrange a green belt parallel to the wind direction (Sodoudi et al., 2018; Wang et al., 2019) for providing the highest cooling benefit. Other factors, such as human activities, ecological benefits, aesthetics and psychology (Lusk et al., 2018; Klemm et al., 2015), should be taken into account when deciding where to arrange vegetation in the city. Thus, more comprehensive conclusions can be reached in future work in order to provide sufficient information for obtaining the most effective vegetation configuration to reduce urban heat and improve thermal comfort.

5.3. The integrated greening cooling approach

In the complex urban environment, vegetation is inevitably interwoven with other elements of the city. To achieve a more synergistic and effective cooling benefit, the combination of vegetation with other cooling elements is suggested to be adopted in the urban area. With continuous urbanization, the investigation of cooling effects of green walls and roofs are increasingly important (Herrera-Gomez et al., 2017; Herath et al., 2018; Zölch et al., 2016). In densely urbanized areas, roof and wall greening is an effective strategy to increase vegetation coverage in areas with limited green areas, thereby providing better cooling benefits. Green roofs have the least adverse effects at night and are a more efficient method than increasing surface vegetation in high-density areas of Tehran metropolitan city (Arghavani et al., 2020). As roof greening is a fruitful strategy to increase vegetation in an urban area with limited green space, in West Bengal, India, it has been advised to apply 100% green roofs and walls in the open mid-rise and compact low-rise area, and planting in suitable areas with 50% green roofs and walls in the open low-rise area (Sk and Swades, 2020). In Seville, Spain, Herrera-Gomez et al. (2017) suggest planting vegetation on 40.6% of the existing buildings for effectively reducing LST. However, not all studies confirm the cooling capacity of green roofs (Ng et al., 2012). For example, in Bilbao, Spain, the cooling efficiency of green roofs is lower than street trees on the street (Lobaccaro and Acero, 2015). In Munich, Germany, a green roof is not effective in reducing PET (Zölch et al., 2016). The findings leave a research gap in the current studies on the evaluation system of roof greening for urban environmental cooling.

Current studies have not explored in-depth the effect of the spatial arrangement of greening roofs and walls on its cooling efficacy. Thus, future studies should investigate the interactive effect between the spatial distribution of green roofs and walls and different meteorological parameters in urban areas based on considering the challenges imposed by continuous rising temperatures. The combination of three-dimensional methods with multi-disciplinary approaches will accelerate the development of future studies through interacting horizontal and vertical space at different temporal and spatial scales. Considering the challenges to the city posed by future increasing temperatures, the optimal greening cooling scheme may be developed by applying advanced computational technologies simulating the environment and climate of future cities. Moreover, studies are necessary to integrate with the assessment of the effect of roof and wall greening on urban heat mitigation at the high-density urban area by simulation. A holistic understanding of the interactive effects of vegetation spatial distribution on urban environment and climate is required for a more accurate analysis of optimal cooling greening layouts in large urban areas at multi-scales. In the future, it is necessary to take a holistic and comprehensive analysis of the optimal vegetation configuration for urban heat mitigation through the organic integration of different cooling elements from different spatial and temporal dimensions. Further study is expected to provide more precise evidence on the optimal vegetation configuration to mitigate urban heat and improve thermal comfort for professionals involved at the phase of decision-making.

6. Conclusions

This review systematically analyzes 85 peer-reviewed papers on the optimal vegetation configuration for urban heat mitigation and comprehensively assesses the current methods adopted. The findings confirm the significant influence of greenery configuration on urban heat mitigation. The main results are summarized as follows. First, numerical simulation and field measurement are the most commonly used methods and are often combined in one research study. Second, most reviewed literature studied the optimized vegetation configuration for urban heat mitigation at microscale, with a strong bias on the arrangement of trees, while research at the mesoscale usually covers an area of a city. Third, large green spaces generally improve the cooling ability effectively. In the high-density urban area, however, multiple small green spaces distributed evenly can effectively mitigate urban heat. Moreover, increasing the complexity of green space may lead to more cooling benefits. Fourth, tall mature deciduous trees with large and dense canopy distinctly enhance the thermal benefits of trees in the city, while less effectively reducing nocturnal temperature and energy demand. Also, an increase of trees with appropriate density positively affects the urban thermal environment. Arranging trees to maximize canopy shading and minimum wind disturbance (e.g., clustered planting, rectangular planting or double tree-row) in the windward corridor, is an effective way to lower urban heat and improve thermal environment. Fifth, it is recommended to combine trees with other vegetation elements (e.g., grass areas or green roofs) for achieving the ideal cooling effect and energy savings in the city. For example, tree-grass, tree-shrub-grass, or tree planting structures can provide effective cooling benefits. Finally, to compensate for the limitation of an isolated cooling method of surface vegetation, the implementation of combined cooling methods (e.g. cool pavement, shading devices, green walls, green roofs, and water bodies) synergistically promote temperature reduction.

This review indicates some research gaps and trends in the topic, which need more attention in the future. First, developing countries with large populations need to receive more attention as little is known about optimal vegetation allocation for urban heat mitigation in these regions. Special focus should be put on cities experiencing rapid urbanization with large population growth and severe impacts of extreme weather. With the increasing cases of high-temperature weather in cities around the world due to the increasing impact of climate change, more research needs to be done in different regions of the world. More generalized conclusions can then be reached in future work in order to provide sufficient information about the optimized vegetation configuration on urban mitigation in different regions. Second, further studies should specifically investigate the optimized size, shape, configuration, quantity, and layout of urban green space for heat mitigation and thermal comfort improvement at mesoscales. In addition, more research needs to pay attention to the temporal heterogeneity and connectivity of spatial vegetation at multi-spatial levels. Third, a comprehensive method for quantifying interactions and cumulative effects of natural and artificial factors in the urban environment is required. Future studies will simulate urban climate through more technological approaches, such as machine learning, to model a complex environment with more variables, such as human activity and plant growth. The combination of three-dimensional methods from multi-disciplines will promote future study through integrating horizontal and vertical space at different temporal and spatial scales. Fourth, future studies need to explore the effect of different types of plants, vegetation physiological characteristics, and planting arrangement on urban microclimate, especially in terms of irrigation, evapotranspiration and shading. More studies should be conducted on the interactive effect between trees and other vegetation on urban climate under different growth and irrigation conditions. Fifth, future studies should consider the challenges to the city posed by future increasing temperatures. The optimal greening cooling scheme may be developed by applying advanced computational technologies simulating the environment and climate of future cities. Moreover, studies are necessary to integrate with assessing the effects of roof and wall greening on urban heat mitigation in high-density urban areas by simulation. Finally, a holistic understanding of the interactive effects of vegetation spatial distribution on urban environment and climate is required for a more accurate analysis of optimal cooling greening layouts in large urban areas at multi-scales. Further study is expected to provide more precise evidence on the optimal vegetation configuration to mitigate urban heat and improve thermal comfort for professionals and urban planners in decision-making.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix A

Table A Summary of the extracted information from 85 reviewed studies.

Author (year)	Location (Country/ Region)	Climate[a]	Season[b]	Time[c]	Research Methods[d]	Scale[e]	Topic[f]	Research Focus[g]	Optimal Greenery Arrangement[h]
Abdi et al. (2020)	Tabriz (Iran)	Dsa	Au	DT	FM, NS	Mi	HTC, PD	TC	RP (ET outer, DeT inner), PPW
Aboelata (2020)	Cairo (Egypt)	Bwh	Au	DT, NT	FM, NS	Mi	UHI, HTC, EC, PU	TC-VT	70% grass for EC, 50% T for HTC in H/W 1:1
Aboelata and Sodoudi (2019)	Cairo (Egypt)	Bwh	Au	DT, NT	FM, NS	Mi	UHI, HTC, EC, PU	TC-VT	50% T during DT, 30% T and 70% grass during NT
Aboelata and Sodoudi (2020)	Cairo (Egypt)	Bwh	Au	DT, NT	FM, NS	Lo/Mi	UHI, EC	TC	50% T
Afshar et al. (2018)	Mashhad (Iran)	BSk	Wi	DT	FM, NS	Lo/Mi	HTC, PD	TC-VT	DeT, grass
Alavipanah et al. (2015)	Munich (Germany)	Cfb	Su	DT, NT	RS	Me	UHI	UGS	VC 70-79%/km^2
Alchapar et al. (2016)	Campinas (Brazil), Mendoza (Argentina)	Cwa, BWk	Su	DT, NT	FM, NS	Mi	HM	GI	60% GCR and HAPR
Altunkasa and Uslu (2020)	Adana (Turkey)	Csa	Su, Wi	DT, NT	NS	Mi	UHI, HTC, PU	TC	DeT in Co/St, ET in N of B
Arghavani et al. (2020)	Tehran (Iran)	Csa	Su	DT, NT	RS, NS	Me	UHI, HTC, EC	VF-GR	Add 30% GR in LD, add 20% surface VF and 30% GR in HD
Asgarian et al. (2015)	Isfahan (Iran)	BWk	Sp	DT	RS	Me	UHI, PU	UGS	EnD, more GCR and PAR
Atwa et al. (2020)	Alexandria (Egypt)	BWh	Su	DT	NS	Lo/Mi	UHI, HTC, PU	TC	DTR
Bartesaghi-Koc et al. (2020)	Sydney (Australia)	Cfa	Su, Wi	DT	RS	Me/Lo	HM	GI	TR/CT surrounded by grass/shrub
Berry et al. (2013)	Melbourne (Australia)	Cfb	Su	DT	FM	Mi	IM	TC	T close (1.1 m) to building, combine T with GW
Chen et al. (2020)	Changsha (China)	Cfa	Su	DT, NT	NS	Mi	UHI, CE	GI-TC-GR	Add 60%T in OLR and OMR
Cheng et al. (2015)	Shanghai (China)	Cfa	Su	DT	RS	Me	UHI	Pa	WB
de Abreu-Harbich et al. (2015)	Campinas (Brazil)	Cwa	Su, Wi	DT	FM, NS	Mi	HTC, PD	TC	CT

de Munck et al. (2018)	Paris (France)	Cfb	Su		NS	Me	UHI, HTC, EC	GI	GR for EC, T-G
Dekić et al. (2018)	Nis (Serbia)	Cfa	Su	DT, NT	FM	Mi	UHI, HTC	UGS	T-G
Du et al. (2017)	Shanghai (China)	Cfa	Su		RS	Me	UHI, PU, CE	UGS	WB, LGS under 40 ha, more SI of UGS and less IS
Emmanuel and Loconsole (2015)	Glasgow (UK)	Cfb		DT	RS, NS	Lo/Mi	UHI	GI	increase 20% GCR
Feyisa et al. (2014)	Addis Ababa (Ethiopia)	Cfb	Au	DT	FM, RS	Me	UHI, HM	UGS	large Pa, more NDVI, increase SI of Pa can enhance PCI while reducing PCD, vice versa
Herath et al. (2018)	Colombo (Sri Lanka)	Af	Su	DT	FM, NS	Mi	UHI	GI	T in curbsides and 50% GR and 50% GW
Herrera-Gomez et al. (2017)	Seville (Spain)	Csa	Sp, Su	DT	RS	Me	HM	GR	40.6% GR of the total building covered area
Hsieh et al. (2016)	Tainan (Taiwan, China)	Aw	Su	DT	FM, NS	Lo/Mi	UHI, HTC, PD	TC	T density not too high, T in PWD
Huang and Chen (2020)	Kaohsiung (Taiwan, China)	Am	Su	DT, NT	NS	Lo/Mi	UHI, HM	UGS	60% GRC in St, 80% GRC in Pa, 100% GRC GR
Jiang et al. (2018)	Shanghai (China)	Cfa	Su	DT, NT	NS	Lo/Mi	UHI, PU, CE	UGS	WB, T-S-G, GrC, increase LGS
Kim et al. (2016)	Seoul (Republic of Korea)	Dwa	Su, Wi	DT, NT	FM, RS, NS	Lo/Mi	HTC	UGS	Small GI
Klemm et al. (2015)	Utrecht (Netherlands)	Cfb	Su	DT	FM, QI	Mi	HTC, PD	TC	LCT, enhanced ratio of St greenery in the visual field
Kong et al. (2017)	Hong Kong (China)	Cwa	Su	DT, NT	FM, NS	Lo/Mi	UHI, HTC, PD	TC	T with DC in HD, T with shorter trunk base in narrow St
Langenheim et al. (2020)	Melbourne (Australia)	Cfb	Su	DT	NS	Lo/Mi	HTC, IM, PD	TC	LCT in E-W, high T
Lee et al. (2020)	Freiburg (Germany)	Cfb	Su	DT	NS	Mi	HM	TC	LCT avoid overlap, T in S of B
Li and Zhou (2019)	Illinois, Indiana, Ohio (USA)	Dfa, Dfb, Cfa	Su	DT, NT	RS	Me	UHI, HM	UGS	Low ED, increase VC, patch density and mean patch shape
Li et al. (2019a)	College Park (USA)	Cfa	Su	DT	FM, NS	Mi	UHI, PD	TC	T surrounding Co, multi TR in SW of Co
Li et al. (2019b)	Seoul (Republic of Korea)	Dwa	Su, Wi	DT	FM, RS, NS	Lo/Mi	HTC	GI-VT	DTR, T- loamy soil /T-G
Li et al. (2020)	Zhengzhou (China)	Cwa	Su	DT, NT	FM	Mi	UHI	UGS-VT	T-S-G
Lin and Lin (2016)	Taipei (Taiwan, China)	Cfa	Su	DT, NT	FM, NS	Lo	HM	Pa	LGS, EnD of Pa, more Pa diversity

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Table A (*continued*)

Author (year)	Location (Country/ Region)	Climate[a]	Season[b]	Time[c]	Research Methods[d]	Scale[e]	Topic[f]	Research Focus[g]	Optimal Greenery Arrangement[h]
Liu et al. (2020)	Guangzhou (China)	Cfa	Su	DT, NT	FM, NS	Mi	HTC, PD	TC	RP, EnD of T, high T with DC and low branching height
Lobaccaro and Acero (2015)	Bilbao (Spain)	Cfb	Su	DT, NT	FM, NS	Mi	HTC, PD	VT-GR	T-G
Lusk et al. (2018)	Boston (USA)	Dfa	Su	DT	QI	Mi	PD	TC	T and shrub locate between cycle track and St
Mahmoud (2011)	Cairo (Egypt)	Bwh	Su, Wi	DT	FM, NS, QI	Mi	UHI, HTC	GI-VT	WB, DeT
Makido et al. (2019)	Portland (USA)	Csb	Su	DT	FM, RS, NS	Mi	UHI, HM	GI	Add T in OS or OS with large shrub/grass area
Millward et al. (2014)	Toronto (Canada)	Dfb	Sp, Su, Au	DT, NT	FM	Mi	UHI, HM	TC	CT in W of B
Milošević et al. (2017)	Novi Sad (Serbia)	Cfb	Su	DT	FM, NS	Mi	HTC, PD	TC	cylinder-shaped T crowns
Monteiro et al. (2016)	London (UK)	Cfb	Su, Au	NT	FM, RS	Me/Lo	UHI, HM, CE	UGS	UGS with 3–5 ha, situated 100–150 m apart
Morakinyo et al. (2017)	Hong Kong (China)	Cwa	Su	DT, NT	FM, NS	Mi	HTC, PD	TC	T with less CD and HT in deeper canyon, vice versa
Ng et al. (2012)	Hong Kong (China)	Cwa	Sp, Su	DT	FM, RS, NS	Me/Mi	UHI, HM, PU	UGS-VT	30% T
Park et al. (2019)	Seoul (Republic of Korea)	Dwa	Su	DT	NS	Mi	HTC, IM, PD	TC	large T, small T with an interval of 3-10m
Privitera and Rosa (2018)	Catania (Italy)	Csa	Su		FM, RS, NS	Me/Mi	EC	GI-TC	T in WSE of B and WE of B
Qiu and Jia (2020)	Beijing (China)	Dwa	Su, Au	NT	GIS	Lo/Mi	UHI, HM, CE	Pa	large Pa, more TC, less fragmented TC and IS
Rahman et al. (2020)	Würzburg (Germany)	Cfb	Su, Wi	DT	FM, NS	Mi	HTC	TC	LCT, CT towards center of cities
Reis and Lopes (2019)	Lisbon (Portugal)	Csa	Sp, Su, Wi	DT, NT	FM, RS	Me/Lo	UHI, HM, HTC, CE	UGS	minimal size of UGS is 50m^2
Richards et al. (2020)	Singapore	Af	Su	DT, NT	FM, RS	Me/Lo/Mi	UHI, HTC, PU, CE	VT	SF better than T-S
Rost et al. (2020)	Berlin (Germany)	Cfb	Su	NT	FM	Me/Lo/Mi	UHI, HM, CE	Ags	LGS, close to center of cities
Shih (2017)	Taipei (Taiwan, China)	Cfa	Su	DT	RS	Me	UHI, PU	UGS	WB, LGS with compact/ simple shape, EnD
Sk and Swades (2020)	English Bazar (India)	Cwa	Sp, Wi	DT	RS, NS	Mi	UHI, HM	GI	100% GRW in OmCl,50% GRW in OLR

Sodoudi et al. (2018)	Berlin (Germany)	Cfb	Su	DT, NT	FM, NS	Mi	HTC	UGS	GrC PWD
Stojakovic et al. (2020)	Belgrade (Serbia)	Cfa	Su	DT	NS, EA	Mi	HTC, PD	TC	Sh and T
Stojanovic et al. (2018)	New Belgrade (Serbia)	Cfa	Sp, Su, Au	DT	FM	Mi	UHI, HM	UGS	50% or more broad-leaved T in growing season
Tan et al. (2016)	Hong Kong (China)	Cwa	Au	DT	FM, NS	Mi	UHI, PU	TC	T in PWD
Tan et al. (2017)	Hong Kong (China)	Cwa	Au	DT	FM, NS	Mi	UHI, HTC, PU	TC	T in low SVF and in PWD in HD
Teshnehdel et al. (2020)	Tabriz (Iran)	Dsa	Su, Wi	DT	FM, NS	Lo/Mi	UHI, HTC, PU	TC	Increase more than tripled DeT
Thom et al. (2016)	Adelaide (Australia)	Csa	Su	DT	RS, NS	Mi	HTC	TC	CT
Wang et al. (2015)	Assen (Netherlands)	Cfb	Su	DT, NT	FM, NS	Mi	HTC	GI	grove with high T density
Wang et al. (2019)	Shenzhen (China)	Cwa	Su, Au, Wi	DT	FM, RS, NS	Lo/Mi	HTC, PU	UGS	10% grove, GrC in Su and Wi
Wu and Chen (2017)	Beijing (China)	Dwa	Su	DT, NT	FM, RS, NS	Lo/Mi	UHI, HM	TC	add 10% T
Xiao et al. (2018)	Suzhou (China)	Cfa	Su	DT	FM	Me/Lo/Mi	UHI, HM	UGS	LGS, increase average LAI and average CD of UGS, decrease GAP
Xu et al. (2017)	Beijing (China)	Dwa	Su	DT	FM	Lo/Mi	HM, EC, CE	GI	Sh and T
Yan et al. (2020)	Shenzhen (China)	Cwa	Sp, Su, Au, Wi	DT, NT	FM	Lo	UHI, HM, CE	UGS	55% GCR
Yan et al. (2019)	Phoenix (USA)	BWh	Su, Au	DT	RS, QI	Me/Lo/Mi	HM, EC	UGS-VT	T-G, more edge area of UGS
Yang et al. (2018a)	Singapore	Af	Su	DT, NT	FM, NS	Lo/Mi	HTC	VT	T-G
Yang et al. (2018b)	Xi’an (China)	Bsk	Su	DT	FM, NS	Mi	UHI, HTC, PD	TC	Middle of St in N-S, side of St in E-W
Yao et al. (2020)	Beijing (China)	Dwa	Sp, Su, Au, Wi	DT	RS	Me	UHI, HM	UGS	increase forest ED, consider UGS status when add GCR (GCR < 30%) or improve spatial arrangement of UGS (GCR > 30%)
Yin et al. (2019)	Guangzhou (China)	Cfa	Su	DT	FM, NS	Mi	HTC	TC	33% T covered area in H/W 0.78
Yu et al. (2017)	Fuzhou (China)	Cfa	Su	DT	RS	Me	UHI, PU	UGS	WB, LGS while TVoE is 4.55 ha
Yu et al. (2018a)	Tampa (USA)	Cfa	Sp, Wi		RS	Me	UHI	VF-VH	20 m height T, VF 93.33%
Yu et al. (2018b)	Fuzhou (China)	Cfa	Su	DT	RS	Me	UHI, HM, CE	UGS	WB, LGS, TVoE is 4.55 ± 0.5 ha, circles and squares UGS

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Table A (*continued*)

Author (year)	Location (Country/ Region)	Climate[a]	Season[b]	Time[c]	Research Methods[d]	Scale[e]	Topic[f]	Research Focus[g]	Optimal Greenery Arrangement[h]
Yuan et al. (2017)	Osaka (Japan)	Cfa	Su	DT, NT	FM, NS	Lo/Mi	UHI, PU	UGS	20% GCR and low UA urban albedo
Zaki et al. (2020)	Kuala Lumpur (Malaysia)	Af	Su	DT	FM, NS	Mi	UHI, HTC	TC	high T, T in E—W and NW—SE
Zhang et al. (2020)	Chengdu (China)	Cwa	Su, Wi	DT	FM, NS, QI	Mi	HTC, HM	GI	grove in Su, grass in Wi
Zhao et al. (2018)	Tempe (USA)	BWh	Su	DT	FM, NS	Lo/Mi	UHI, HTC	TC	DTR,
Zhao et al. (2020a)	Xi'an (China)	Bsk	Au	DT	FM	Mi	UHI	TC	CT, DeT
Zhao et al. (2020b)	Beijing (China)	Dwa	Su	DT	RS	Me	UHI, HM	UGS	VF 40%, CGP in low GCR area
Zheng et al. (2018)	Shantou (China)	Cfa	Su	DT, NT	NS	Mi	HTC, HM	TC	dense canopy T, T interval is the mature canopy width
Zölch et al. (2016)	Munich (Germany)	Cfb	Su	DT, NT	NS	Lo/Mi	HTC, HM	GI	34.4% T better than GW and GR
Zölch et al. (2019)	Munich (Germany)	Cfb	Su	DT, NT	NS	Lo/Mi	HTC	GI	T during DT, grass during NT

[a] Based on Köppen-Geiger climate classifications (Peel et al., 2007)

[b] Su Summer, Au Autumn, Wi Winter, Sp Spring. Seasons of simulated periods are roughly defined as spring (autumn) in March to May, summer (winter) in June to August, autumn (spring) in September to November, and winter (summer) in December to February for the northern (southern) Hemisphere, except for the cities in Af climate zone (Singapore, Colombo and Kuala Lumpur) which are considered to have a summer season all-year round.

[c] DT Day-time, NT Night-time

[d] FM field measurement, NS numerical simulation, RS remote sensing, QI questionnaire and interview

[e] Me Mesoscale (10 km—200 km), Lo Localscale (100 m—50 km), Mi Microscale (1 cm—1 km) based on Erell et al. (2010)

[f] UHI urban heat island, HTC human thermal comfort, HM heat mitigation, CE cooling effect, IM insolation mitigation, PD planting design, PU urban planning/urban design, EC energy consumption

[g] AGs allotment garden, GI green infrastructure, TC tree canopy, GR green roof, VT vegetation type, Pa park, UGS urban green space, VF vegetation fraction, VH vegetation height

[h] T trees, T-G tree-grass, T-S tree-shrub, T-S-G tree-shrub-grass, SF secondary forest, GCR green coverage ratio, GR green roof, GW greem wall, GRW green roof and wall, GrC greenway/green corridor, Pa parks, VC vegetation cover, CGP clustering green patches, EnD even distribution, RP rectangular planting, CT clustered trees, TR trees in rows, DTR double tree row, HT higher trunk, LCT large canopy tree, DeT deciduous trees, ET evergreen trees, DC dense canopy, CD canopy density, LGS large area of green space, LAI leave area index, TVoE the threshold value of efficiency of green space, ED edge density, HAPR high albedo in pavements and roofs, GAP green area perimeter, SI shape index, PCI park cooling intensity, PCD park cooling distance, PAR perimeter to area ratio, WB combine with water bodies, Sh combine with shading device, N northern, S southern, W western, E eastern, OS open space, OMR open middle-rise area, OLR open low-rise area, HD high density area with higher buildings, LD low density area with lower buildings, E-W in E-W street, N-S in N-S street, NW—SE in NW—SE street, PPW perpendicular to prevailing wind, PWD parallel to the wind direction, OmCl open mid rise and compact low rise areas, H/W height to width ratio of streets, St streets, Co courtyards, B buildings

Appendix B

Table B Research methods adopted in the reviewed literature.

Research method[a]	Number of studies	Scale[b]	Study area	Climate[c]	Topic[d]	Research Focus[e]	Parameters[f]	Software[g]
FM	10	Mi Lo Lo/Mi Me/Lo/Mi	Urban Area University Park Public Square Street	Cfa, Dfb, Bsk, Cfb, Cwa, Dwa	UHI, HM, IM, EC, HTC, CE	AGs, GI, UGS, TC, UGS-VT	LST, T_a, GCR, T_{mrt}, PET	ANOVA, SPSS, GenStat, Excel, SAS/STAT
FM, RS	4	Me Me/Lo Me/Lo/Mi	Urban Area Park	Af, Csa, Cfb,	UHI, HM, CE, HTC, PU	UGS, VT	LST, T_a, NDVI	R, Arc GIS
FM, RS, NS	7	Mi Me/Mi Lo/Mi	Urban Area Residential Area University Park Street	Cwa, Csa Dwa, Csb	UHI, HM, EC, HTC, PU	GI-VT, TC, UGS-VT, GI, GI-TC, UGS	LST, T_a, T_{mrt}, PET, UTCI	SPSS, ArcGIS, ENVI-met (CFD), TerraScan, TerraModeler
FM, NS	28	Mi Lo Lo/Mi	Park Street Urban Area	Af, Bsk Aw, Cwa Cfb, Cfa, BWh Dsa,	UHI, HM, CE, HTC, PD, EC, PU	GI, UGS, TC, VT, VT-GR, Pa, TC-VT	T_a, T_{mrt}, T_g, PET, UTCI, COMFA, PMV, SET, GCR, LAI	SPSS, R, Ladybug, RayMan (EBM), SOLWEIG (EBM), ENVI-met (CFD), WindPerfect (CFD), PHOENICS (CFD), DesignBuilder, Rhinoceros with Grasshopper plug-in
FM, NS, QI	2	Mi	Park	Bwh Cwa	UHI, HM, HTC	GI, VT	T_{mrt}, PET, UTCI, TSV	RayMan (EBM)
FM, QI	1	Mi	Street	Cfb	HTC, PD	TC	T_{mrt}, PET	ANOVA
RS	14	Me Me/Lo Lo/Mi	Urban Area	Csa, Cfa Dfa, Dfb, Cfb, Dwa Bwk	UHI, HM, PU, CE	GI, UGS, GCR, VF, GR	LST, T_a, NDVI	LiDAR, ArcGIS, ANOVA, FRAGSTATS, MATLAB, Graph Expert Professional, SPSS, ENVI, QGIS,
RS, NS	4	Me Lo/Mi Mi	Urban Area	Csa, Cfb Cwa	UHI, HM, HTC, EC	GI, UGS, GCR, TC, GR	LST, T_{mrt}, PMV, THI, ETI	SOLWEIG (EBM), ENVI-met (CFD), WRF, ArcGIS,
RS, QI	1	Me/Lo/Mi	Residential Area	BWh	HM, EC	UGS, VT	LST	Fragstats, R, AIC, ENVI/IDL, Arc map, ENVI-met (CFD),
NS	13	Me Lo/Mi Mi	University Park Public Square	Am, Csa, Cfa, Cfb, Dwa,	UHI, HM, HTC, PU, CE, PD, IM, EC	GI, UGS, VC, GCR, TC, GR	LST, T_{mrt}, PMV, T_{mrt}, PET, UTCI, SET, T_a, IV	Rhinoceros 3D, SURFEX (EBM), Rhinoceros with

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Table B (*continued*)

Research method[a]	Number of studies	Scale[b]	Study area	Climate[c]	Topic[d]	Research Focus[e]	Parameters[f]	Software[g]
			Street Residential Area Urban Area	BWh				Grasshopper plug-in, 3 ds Max, Ecotect
QI	1	Mi	Street	Dfa	PD	TC		ANOVA
Total	85							

[a] FM field measurement, NS numerical simulation, RS remote sensing, QI questionnaire and interview

[b] Me Mesoscale (10 km—200 km), Lo Localscale (100 m—50 km), Mi Microscale (1 cm—1 km) based on Erell et al. (2010)

[c] Based on Köppen-Geiger climate classifications (Peel et al., 2007)

[d] HTC human thermal comfort, HM heat mitigation, UHI urban heat island, PD planting design, PU urban planning/urban design, EC energy consumption, IM insolation mitigation, CE cooling effect

[e] AGs allotment garden, GI green infrastructure, TC tree canopy, GR green roof, VT vegetation type, Pa park, UGS urban green space, VF vegetation fraction, VH vegetation height, VC vegetation cover

[f] LST Land Surface Temperature, T_a Air Temperature, T_{mrt} Mean Radiant Temperature, T_g Blackglobe Temperature, PET Physiological Equivalent Temperature, NDVI Normalized Difference Vegetation Index, UTCI Universal Thermal Climate Index, PMV Predicted Mean Vote, SET Standard Effective Temperature, COMFA COMfort FormulA, TSV Thermal Sensation Vote, THI Temperature Humidity Index, ETI Effective Temperature Index, IV Insolation Value, GCR Green Cover Ratio, LAI Leaf Area Index

[g] SOLWEIG Solar Long Wave Environmental Irradiance Geometry, WRF Weather Research and Forecasting, CFD Computational Fluid Dynamics, QGIS Quantum GIS, AIC Akaike Information Criterion, EBM Energy Balance model, PHOENICS Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series

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