Journal of Thermal Biology 110 (2022) 103340

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

A clustering review of vegetation-indicating parameters in urban thermal environment studies towards various factors

Jian Zhang [a,c,*], Maryam Khoshbakht [c], Jianlin Liu [b], Zhonghua Gou [d], Jie Xiong [a], Maoting Jiang [e]

[a] School of Civil Engineering and Architecture, Southwest University of Science and Technology, Mianyang, China
[b] College of Environmental Science and Engineering, Donghua University, Shanghai, 201620, China
[c] School of Engineering and the Built Environment, Griffith University, Southport, QLD, 4222, Australia
[d] School of Urban Design, Wuhan University, Wuhan, 430072, China
[e] School of Economics and Management, Southwest University of Science and Technology, Mianyang, China

ARTICLE INFO

Keywords:
Outdoor thermal environment/comfort
Urban heat island
Remote sensing
Simulation
Field measurement
Meteorological station observation

ABSTRACT

People in outdoor areas suffer from more heat stress than indoors during warm seasons due to the lack of shelters or cooling facilities. This problem is pressing with urban heat island and continuous global warming. Researchers have explored various strategies for ameliorating thermal stress, coining the term 'outdoor thermal environment (OTE)' for this area of study. It has been found that the OTE is affected by vegetation and other factors (i.e., geometry) of a location. There have been many studies on vegetation, with these conducted at various levels and using different methods. Several parameters have been used to characterise vegetation and have been found to statistically correlate with many thermal indices (i.e., physiologically equivalent temperature, PET; universal thermal climate index, UTCI etc.). This article reports on a review of journal papers that investigated the climatic regulations of vegetation. In this study vegetation-indicating parameters were clustered according to the methods, scope, and thermal indices. Studies involving large scales preferred general indicators (e.g., NDVI, vegetation cover etc.) whereas specific, detailed parameters (e.g., crown sizes) were more frequently used in studies of micro levels. Outdoor thermal environment studies involving vegetation were mostly conducted in regions with high heat stress levels. Also, remote sensing and meteorological station observation were more frequently used in large-scale studies, while small-scale studies preferred simulation and field measurements. Their findings were expressed by the statistical correlation between vegetation parameters and thermal indices. For instance, *NDVI, LAI*, and crown size were negatively correlating with temperatures. The findings of this study help inform directions for future vegetation studies regarding outdoor thermal environment designs. Researchers would be clearer on selection methods and thermal indices regarding their targets and supporting tools.

1. Introduction

Outdoor environments in urban areas are very important for the quality of life. Their importance can be expressed as an increase in city vitality and health improvement for residents (Lai et al., 2019). However, not many people can actively stay outdoors for long time especially in hot days due to the considerably higher temperatures in outdoor spaces compared to indoor spaces (Morakinyo et al., 2016) when there is a of lack shelters or cooling facilities (i.e., air conditioners). More time indoors means higher building energy loads (Lai et al., 2014) since air conditioners are unneeded for people outside (Niu et al., 2015). This seasonal change in building energy loads is particularly a big issue in tropical and subtropical regions with seasonal hot weather. Additionally, some climatic phenomena (including global warming, UHI, heatwave, drought etc. (He et al., 2022)) due to modern human activities are exacerbating this problem. The world has experienced a significant temperature increase since the end of last century, which is called global warming (Meteorological Service, 2020). In addition, city centres are warmer than their surrounding suburban areas due to urban heat island effect (UHI) (Oke, 1973). The UHI phenomenon negatively impacts city living quality particularly in hot and temperate climates during hot seasons. There is an urgent need to explore ways to mitigate heat stress, for current and future generations. Additionally, the global urban

---

* Corresponding author. School of Civil Engineering and Architecture, Southwest University of Science and Technology, Mianyang, China.
E-mail address: jianzhang1020@sina.com (J. Zhang).

https://doi.org/10.1016/j.jtherbio.2022.103340
Received 4 April 2022; Received in revised form 30 July 2022; Accepted 15 September 2022

Abbreviations:

OTE	outdoor thermal environment
OTC	outdoor thermal comfort
UHI	urban heat island
NDVI	normalised difference vegetation index
RMS	remote sensing
MSO	meteorological station observation
SIMU	simulation
FDM	field measurement
PET	physiological equivalent temperature
SET	standard effective temperature
MRT	mean radiant temperature
T_a	air temperature
UTCI	universal thermal climate index
LST	land surface temperature
SUHII	surface urban heat island intensity
LSE	land surface emissivity
UTFVI	urban thermal field variance index
MTHI	remote sensing-based temperature-humidity index
PMV	predicted mean vote
TSV	thermal sensation vote
LAI	leaf area index
LAD	leaf area density
SVF	sky view factor
MLR	multiple linear regression
ANOVA	analysis of variance

population is predicted to rise from 50% in 2014 to 66% in 2050 (United Nations and Division, 2014); which means a higher proportion of the global population will experience urban thermal problems. Previous studies have not used universal and specific protocols to address the topic, and it is necessary to develop more specific research design methods and an analytical model that reflects the three-dimensional elements of the collected data and the physical properties of cities.

Research has been conducted into approaches for adjusting the outdoor thermal environment (OTE). It has been found that the OTE can be affected by the site geometry (Sharmin et al., 2015), water surface ratio (Du et al., 2016), and vegetation cover (Yan et al., 2018). Vegetation and water surfaces are naturally cooling effective. The city geometry (influenced by building morphology density and orientation) affects thermal environment by two aspects, shading and ventilation (He et al., 2020). Vegetation was found to improve human visual (Kent and Schiavon, 2020), psychological (Chiang et al., 2017), and thermal wellbeing (Spangenberg et al., 2008). Indeed, vegetation has been the subject of many studies relating to the OTE. These studies could be divided into various types depending on their scope, from large scale vegetation studies to intermediate, small, and micro scale studies. Additionally, several parameters have been proposed to evaluate vegetation's effects, which also differed depending on scope. Most of the parameters were found being influential (Zeng et al., 2020). For example, the normalised difference vegetation index (NDVI) was used for a whole city (Neinavaz et al., 2020), vegetation coverage for a street (Klemm et al., 2015a), and leaf density for a courtyard (Darvish et al., 2021). Studies also have revealed that vegetation can have different cooling effects, which includes temperature (Teshnehdel et al., 2020), wind (Zhong et al., 2022), and relative humidity (Cheung et al., 2021). Teshnehdel et al. (2020) simulated trees of different species, confirming that the summer air temperature of highly-dense tree sites was 0.29 °C lower than bare ones; He et al. (2019) used Landsat to reveal that the land temperature was reduced by 1.04 °C for every km^2 of vegetation area increase; while Coutts et al. (2015) measured several sites around Melbourne and confirmed that there was a (universal) thermal index increase due to tree cover reduction. These findings provided promising directions for OTE improvement. Furthermore, additional parameters have been proposed and used, which will support future more detailed studies relating to the thermal effects of vegetation.

Numerous thermal indices can be used in thermal environment studies. The thermal environment is a complex system affected by a variety of factors, including temperature, humidity, wind, and radiation, which are also key factors for classifying the climate (Ward, 1914). These are all suitable for evaluating the thermal performance of vegetation. The cooling effects of trees has been investigated by analysing their impacts on temperature (Oke, 2002), wind (Morakinyo et al., 2016), radiation (Charalampopoulos et al., 2012), humidity (Broadbent et al., 2018), and thermal comfort (Zhao et al., 2018). However, due to factor diversity, researchers have proposed many complex indices to comprehensively evaluate thermal environments. Some of these contain various types of methods for evaluating thermal comfort including physiologically equivalent temperature (PET (Puliafito et al., 2013)), standard effective temperature (SET (Xiong et al., 2020)), universal thermal climatic index (UTCI (Taleghani et al., 2016)), mean radiant temperature (MRT (Kong et al., 2017)), and land surface temperature (LST (Tien Nguyen, 2020)). UHI intensity (UHII) is another index evaluating the level of UHI, which refers to the temperature difference between urban and suburban areas, indicated by LST (Onishi et al., 2010) or T_a (Lin et al., 2017). Higher UHIIs cause more heat stress (Lowe, 2016). The different calculation processes for these indices means that they have different focuses. For example, MRT was calculated using an equation (Thorsson et al., 2007) and PET using software (RayMan (Matzarakis et al., 2007)). MRT evaluates heat levels relating to radiation, PET and UTCI relate to people's perceptions of heat.

Vegetation-indicating parameters and thermal indices are both expressed quantitatively. These values can be collected through various techniques, such as remote sensing (Daramola and Balogun, 2019) and field measurements (Meili et al., 2021). The development of computing also means that environmental scenes can now be created virtually; for example, researchers can create any environmental scene to simulate thermal performance relating to their study aims and objectives (Zheng et al., 2016). Some studies also use climatic data from meteorology stations (Siu and Hart, 2013). Using abovementioned methods many researchers have found that vegetation is significant contributor to outdoor thermal comfort.

Many studies encompass the characteristics of vegetation to evaluate thermal environment. However, these characteristics have rarely been summarised and there may be valuable conclusions to be drawn from a comprehensive review of existing literature. Most research articles used one or two methods to collect data. They have few opportunities to compare the properties of different methods. This study aimed to review literatures of OTE involving vegetation; it abstracted quantitative information about that from the literatures using document clustering method. Clustering helps in understanding the natural grouping in literature and partitioning them into groups of logical classes. Document clustering is a fundamental means of knowledge discovery in literature.

Accordingly, this article clustered literature and reviewed the methodologies of published studies investigating the urban thermal environments (mostly involving vegetation) and analysed these regarding their technical characteristics, such as the study scope. It was hypothesised that study methodologies may be linked to certain contextual conditions; for example, certain parameters would suit large-scale studies. The results of this study might provide clear direction for future studies in similar domains.

2. Influencing factors of vegetations for outdoor thermal comfort

2.1. Vegetation-indicating parameters

Many vegetation-indicating parameters were used in the reviewed studies on sites of various scales and types. This study divided them into four types, NDVI, vegetation cover, tree cover/planting pattern (trees in groups), and individual trees. Generally, the four aspects were divided by their indicating scopes, which is explained and approved in the following sections of this article.

2.1.1. NDVI

The normalised difference vegetation index (NDVI) is a dimensionless index that describes the difference between visible and near-infrared reflectance of vegetation cover (Chen et al., 2006). The NDVI measures the difference between near-infrared (NIR) (which the vegetation reflects) and red light (which the vegetation absorbs). NDVI has a range from −1 to +1 and is calculated by Equation (1) (GISGeography, 2021):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red}\ )}{(\mathrm{NIR} + \mathrm{Red})} \tag{1}$$

where Red and NIR stand for the spectral reflectance measurements acquired in the visible red and near-infrared regions, respectively. It is measured by remote sensing through satellite sensors. Nowadays, NDVI was frequently used in urban environment and agriculture studies. NDVI was found significantly correlating with thermal environment. NDVI is available to indicate any type of land cover. Generally, NDVI differed vegetated and unvegetated sites by positive and negative figures (Chen et al., 2006), yet not exactly clear. NDVI was negatively correlated with temperature (LST). This phenomenon was confirmed by RMS studies in Sydney (Zhang et al., 2012), Czech (Neinavaz et al., 2020), and Akure (Daramola and Balogun, 2019).

2.1.2. Vegetation cover

Vegetation cover is a significant important index that has been used by researchers widely across the Globe. In some studies vegetation cover was referred to by different names such as vegetation cover fraction (Zhang et al., 2012), vegetation cover ratio (Zeng et al., 2022), and vegetation coverage (Darvish et al., 2021), all of which measured the percentage/ratio of vegetation cover. In all studies vegetation cover was calculated by the ratio of vegetation area to the whole site area, which could be a district, a street, a park etc. (Hami et al., 2019; Mballo et al., 2021). Vegetation cover could be any type and species of plants such as arbours, shrubs, grasses etc. In studies, vegetation cover, as a parameter indicating land use, was significantly correlated with climatic indices and had negative correlation with thermal stress level. The increase of vegetation cover helped reducing LST (Coutts et al., 2016) as well as PET (Jamei and Rajagopalan, 2017) by 1.2 °C and 5.1 °C, respectively. This property is similar to NDVI.

2.1.3. Trees in groups

2.1.3.1. Tree cover. Tree canopy cover (Ziter et al., 2019) or tree coverage (Jamei and Rajagopalan, 2017) refer to the proportion of the land covered by the vertical projection of the tree crowns. A 35% increase in tree coverage can contribute to decrease SET by 0.5 °C (Xiong et al., 2020). Sites covered by significantly more tree coverages have been found to reduce MRT by 20.04 °C in Tabriz (Teshnehdel et al., 2020). The cooling effect of tree cover varies with the time of the day (Meili et al., 2021) and season (de Abreu-Harbich et al., 2015).

2.1.3.2. Tree planting pattern. Trees planted in small pieces of lands should be planned to maximise their thermal effect. Planting patterns could be evaluated by form plans (Rahman et al., 2020a), orientation (Sodoudi et al., 2018), horizontal distance (Srivanit and Jareemit, 2020), enclosure area (Guo et al., 2020) etc. Planning correlates with thermal environment due to its effect on natural ventilation, shading, and relative humidity. The MRT was decreased by 5 °C when the enclosure area changed from 100 to 10 m^2 (Guo et al., 2020). Trees when planted more densely had better cooling performances, yet planting trees too close to each other can negatively affect growth (Rahman et al., 2020a). Evergreen trees rectangularly planted in the outer rows caused higher PET reduction (Abdi et al., 2020).

2.1.4. Individual trees

2.1.4.1. Canopy extension. Crown diameter (Lin and Tsai, 2017), width (Morakinyo et al., 2018), or length (Teshnehdel et al., 2020) indicated the horizontal crown size, which could be all defined as *crown diameter*. This defined the extent of a canopying (i.e., its shade area), which is thermally relevant. Increasing the crown radius from 1 m to 7 m can reduce PET by more than 15 °C (Wang et al., 2021a).

2.1.4.2. Vertical sizes. Vertical dimensions included tree height (Morakinyo et al., 2017), trunk height (Morakinyo and Lam, 2016), and crown height (Morakinyo et al., 2018). One study used the branching point height (Zhang and Gou, 2021), similar to trunk height and evaluated the vertical size of trees and vertical positions of crowns. Taller trees have better cooling intensities than shorter ones (Yang et al., 2018). Trunk height negatively correlates with cooling effects, where trees with shorter trunks have a more efficient cooling effect (Kong et al., 2017). The advantages of short trunks were discussed by Kong et al. (2017), Morakinyo et al. (2017), and Morakinyo and Lam (2016).

2.1.4.3. Leaf properties. Leaf parameters were usually used in thermal studies, with the LAI (Shahidan et al., 2010) and LAD (Chan and Chau, 2021) being most frequently used. In a study de Abreu-Harbich et al. (2015) used the plant area index (PAI) to evaluate the visible ratio of plants in the hemispheric image at any site; its meaning was the same as the tree view factor (TVF) used by Yang (2009). These parameters could partly evaluate leaf quantity and density. Increasing LAI by one point reduced MRT by more than 5 °C (Guo et al., 2020).

2.1.4.4. Biological properties. There are several parameters indicating biological properties of trees. Transpiration (Mballo et al., 2021) and evaporation (Rahman et al., 2020a)) were analysed as these may affect air humidity, which is thermally effective. Different species also show different cooling effects due to the rates of transpiration and evaporation (Gupta et al., 2018). For example, *Tilia cordata* Mill has better cooling effects than *Robinia pseudoacacia* L. (Rahman et al., 2020a). Schima superba has better cooling effects than Eucalyptus citriodora and Acacia auriculaeformis due to favourable biological properties (Chen et al., 2019). *Pyrus calleryana* and *Crataegus laevigata* show higher cooling efficiencies than *Prunus* 'Umineko', due to their wider canopies, denser leaves, and higher stomatal conductance (Rahman et al., 2014). Leaf habit (deciduous or evergreen) was considered by a few studies (Abdi et al., 2020) to distinguish variations in the canopy condition of trees (caused by leaf quantity change) in various seasons.

2.1.5. Others

Thermal effect of trees are also influenced by physical properties of sites. Trees planted in urban canyons had a more efficient cooling effect than in open spaces (Kong et al., 2017). The MRT was decreased by more than 20 °C due to street trees in urban canyons (Spangenberg et al., 2008). In terms of land cover, trees next to asphalt result in higher cooling intensities than in lawns (Rahman et al., 2019). This might result from thermal effect of openness (Hien and Jusuf, 2009) and albedo (Akbari and Matthews, 2012). Green roofs showed more excellent cooling effects compared with other materials (Zhang et al., 2021). Yet cooling effect of them was affected by vegetation species and water supply (Zhang et al., 2020a). Therefore, certain OTE studies of vegetation considered them. Openness (Lin and Tsai, 2017), orientation (Morakinyo et al., 2017), albedo (Yang et al., 2011), and land use (Yang et al., 2018) were frequently involved.

2.2 Current popular research methods.

There are four methods frequently used in urban thermal and environmental data collection. They are remote sensing (Tien Nguyen, 2020), simulation (Teshnehdel et al., 2020), field measurement (de Abreu-Harbich et al., 2015), and meteorological station observation (Gaffin et al., 2008). Each method has its own benefits and disadvantages.

Remote sensing (RMS) is a method of surface data collection using sensors installed on satellites or aircrafts. They are hard to distinguish the surface in detail due to being far from the land. It collects geographical information in a certain area or object by photographing, which would be a large area (above 100 km^2). Hence RMS was often used in the study of a whole city, including the information of vegetation, building, albedo etc. (Feng et al., 2020; Mijani et al., 2020; Sharma et al., 2021). It involves land changes spanning several years. Most studies used it to explore long-term city development and climate change (Li et al., 2009; Sharma et al., 2021; Tien Nguyen, 2020).

Field measurement (FDM) is a traditional method of data acquisition. It utilises certain professional tools to acquire data of samples. Instruments of FDM are placed at its sample sites, which differs it from RMS. FDM and RMS both acquire physical (i.e., site openness (Daramola and Balogun, 2019) and albedo (Erell et al., 2014)) and meteorological data (air temperature, wind etc. (Coutts et al., 2015)) in OTE studies. FDM collects absolute real data that are highly reliable. de Abreu-Harbich et al. (2015) compared a wide spectrum of tree species and found the PET within their shades were reduced differently. However, the instruments are available for sites where they are installed. And they are functional when being installed only. As a compensation, some studies acquired comprehensive data through simulation (SIMU). SIMU is a method in computing that creates virtual physical scenes for small pieces of lands to output data (Taleghani et al., 2016). It is supported by various digital tools, including CFD, SOLWEIG, and ENVI-met (Kong et al., 2017; Rinchumphu et al., 2021; Taleghani et al., 2016). Researchers usually created them following practical templates (such as building sizes, types, and orientations), details (i.e., vegetation covers) were created to distinguish their different thermal effects (Zölch et al., 2019). Large trees provided significantly more cooling than shrubs in simulation scenes (Rinchumphu et al., 2021).

Meteorology stations are also huge data resources as they provided very accurate and real data of their locations. Weather stations normally belong to one administrative area (a city, a town, a county etc.) with several kilometers distance from each other; hence, meteorology of each station would be affected by its surrounding environment, i.e., vegetation cover (Lee et al., 2016). As a result, studies using station data involved quite large lands and regions, at least one whole city (Lee and Baik, 2010). Meteorology station observation (MSO) is usually utilised in long-term meteorology investigations (Siu and Hart, 2013) similar to RMS.

2.2. Meteorological and thermal comfort/environment indices

There is a wide spectrum of indices used in OTE studies. This study clustered them as meteorological and thermal comfort/environment indices. In fact, any meteorology index would be influential for thermal perceptions. For simplifying, this study defined unity indices as meteorological indices, while composite ones as OTE/OTC indices.

2.2.1. Meteorological indices

A meteorological index can usually be acquired by an instrument directly. Temperature, wind, humidity, and radiation use to be used. These are also significant classifying factors for regional climate zones (Ward, 1914). Air temperature (T_a) (Klemm et al., 2015a) was relatively frequently used. Land surface temperature (LST) (Nichol, 2005) is an index usually used indicating regional meteorology in some recent studies. LST is often processed by RMS while T_a can be acquired from FDM or SIMU.

2.2.2. Outdoor thermal comfort/environment indices

Thermal comfort/environment is a complex phenomenon influenced by a variety of meteorological parameters. There were diverse complex indices considering several meteorological parameters proposed in OTE/OTC studies. Temperature was the most popular index, with many types of temperatures indicating complex thermal conditions. Physiological equivalent temperature (PET) (Puliafito et al., 2013), mean radiant temperature (MRT) (Lin and Tsai, 2017), and universal thermal climate index (UTCI) were relatively frequently used. The indices have various processing methods. PET, SET, and MRT are complex indices containing several simple parameters. For instance, MRT contains T_a, radiation, and wind; PET and SET consider subjective factors (e.g., clothing isolation and workload) in addition to meteorology. Changes of them were used as well. ΔPET (Morakinyo et al., 2018) refers to PET reduction caused by vegetation. It is insignificantly different from PET. There are also other indices, such as Urban Thermal Field Variance Index (UTFVI) (Singh et al., 2017) and land surface emissivity (LSE). A few studies used subjective indices. PMV (Kim et al., 2016) and TSV (Zhang and Gou, 2021) have been utilised. Each study could select one or more index regarding its con study aims.

2.3. Findings of vegetation studies

Findings in vegetation studies include various thermal indices relating to vegetation parameters (Chan and Chau, 2021) and time of the day that the data was collected and simulated in Meili et al. (2021). These findings were expressed by either diagrams (de Abreu-Harbich et al., 2015) or statistical models and equations (Neinavaz et al., 2020).

2.4. Climate, geometry, and timespan

Reviewed studies were conducted in various climatic zones with different degrees of thermal stress. Regional climate classification is determined by several geographical factors (latitude, altitude, surface albedo etc.) (Geography, 2021). Studies were clustered into three climatic groups based on their geographical locations and temporal scopes, which is defined by geographical scope and timespan; e.g., macroclimate are those above 100 km for geographical scope and half a day to 1 week of timespan (NIWA, 2021). Geographical scope and timespan were also used to define and cluster reviewed studies.

2.4.1. Köppen climate classification

Climate is a complex phenomenon affected by diverse geographical factors. Latitude, altitude, and distance from the sea are all influential. For exact indication, Köppen has divided the world into 29 climate zones (Arnfield et al., 2016) against regional permanent meteorology. Temperature, humidity, dryness, wind, rainfall etc. were all considered. The 29 climate zones were roughly separated into five types (Peel et al., 2007), including Zone A (Tropical; i.e., Aw), B (Arid; i.e., BWh), C (Temperate; i.e., Csa), D (Cold; i.e., Dwc), and E (Polar; i.e., ET). Latitude is relatively essential, which divides the world into tropical (0–23.5°), temperate (23.5–66.5°), and cold (66.5–90°), hence it is significant on thermal perceptions (Acerecho, 2020; Zhang et al., 2022a, 2022b). Reviewed studies might be conducted in different climate zones.

2.4.2. Geographical scope

The geographical scope was one key approach to cluster urban thermal studies in this review. Depending on the scale of the project to be a whole city (Sharma et al., 2021), a district (Teshnehdel et al., 2020), a street (Yang et al., 2018), or a small land (Guo et al., 2020), each study provided a site map indicating its geographical location. This review used the effective width of scaled map as the parameter of geographical scope. For example, as shown in Fig. 1, the distance between A and B is the geographical scope of the study by Lee et al. (2016).

2.4.3. Timespan

The duration of studies varied considerably among studies, ranging from one day to several decades. Studies that were conducted over a few days of one month was defined as one month or 0.1 years. In larger scale studies, some researchers investigated land use/cover changes over more than a decade (i.e. 1993-2006 (Zhang et al., 2012)) but only used a total of two years' data. However, as the land-use changes occurred during the whole period, the timespan was defined as all the spanned years (13 years). Diagrams illustrating the timespans of studies employed units of one year with a minimum value of 0.1. Studies that operated less than one year were defined similarly; for example, a study which spanned from January to March (Zhang et al., 2019), was categorised as three months (0.3 years) although the data was collected in only eighteen days.

2.5. Research gaps and questions

This chapter has reviewed previous thermal environment studies regarding indicating parameters, methods, and thermal indices. Each of these types of studies has certain characteristics with various scales. These studies were clustered regarding these characteristics. This clustering method and comparative analysis was rarely investigated by previous studies which mainly focused on certain case studies and sample sites. However, there was a large volume of studies in this field conducted in different cities. There were studies that included one whole city or a park and use RMS or FDM. There were, admittedly, a vast of reviews concluding these studies. Koc et al. (2016) concluded several kinds of vegetation indicators and contrasted some of their physical properties. Lai et al. (2019) concluded various thermal adjusting factors and compared their cooling intensities. Lam et al. (2021) focused on simulation studies and discussed their techniques in detail. Previous reviewing papers are directive for future studies; however, they rarely comprehensively compared the whole properties of studies. This article complexly reviewed OTE/OTC studies involving vegetation about their properties. Studies of different properties were clustered regarding their characteristics in this review paper. Extracting data from published papers is an available approach of clustering.

This study aims to conduct a comprehensive clustering of thermal environment investigations. Studies in different methods were clustered by diverse variables. The whole work was conducted through the following steps.

- Finding studies of urban thermal environment via various methods (RMS, SIMU, FDM, & MSO).
- Extracting variables defining characteristics of reviewed studies (scopes, timespans, thermal indices etc.).
- Statistically associating one characteristic variable with methods and with other variables for more comprehensive technical clustering.

Findings of this study would be available for future studies about their methodologies.

3. Methodology

This study implemented a technical clustering approach to published research articles about the thermal effects of vegetation; article searches were conducted through inputting keywords into various scholarly websites, including Google Scholar and Web of Science.

Many keywords were utilised to search for relevant publications, such as outdoor thermal environment/comfort; vegetation (cover/size/area); tree (cover/planting pattern/characteristic); urban heat island; thermal/heat stress (mitigation); cooling (effect), and various thermal indices (PET, MRT, air temperature etc.). Thermal/heat environment/comfort/stress was included in every search and with at least one vegetation parameter. Vegetation parameters were key to this review. There were a variety of vegetation indices involved, such as the NDVI, vegetation cover ratio, and some specific for trees. Other vegetation indices were excluded as they were rarely used in thermal studies. The whole process of literature inclusion, hypothesis, and paper clustering are illustrated in Fig. 2. The analysis was roughly divided into four steps, 1) vegetation parameters were abstracted from various articles and listed; 2) the large number of parameters was clustered into a few parameter types according to their indicative scope, from macro to micro; 3) all parameter types were clustered according to the properties of each study, including its method, site size, thermal indices etc; 4) finally, the parameters were summarised in terms of their characteristics and utilisation scopes.

In total, this study reviewed 80 peer-reviewed articles reporting on urban climate/thermal environment studies involving vegetation published in recent 3 decades. Studies involving vegetation were characterised by various factors, including indicative parameters, methods, thermal indices, and other properties. The reviewed articles were functionally clustered according to their common features. Sections 2.1 to 2.5 explain and define all aspects of the methodology employed.

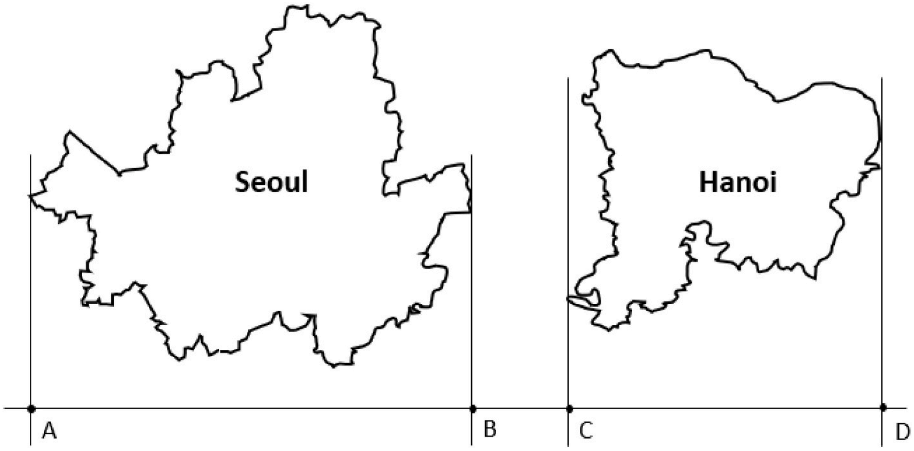

Fig. 1. Geographical scope definition, with the distance between A and B and between C and D referring to the scopes of Lee et al. (2016) and Tien Nguyen (2020), respectively.

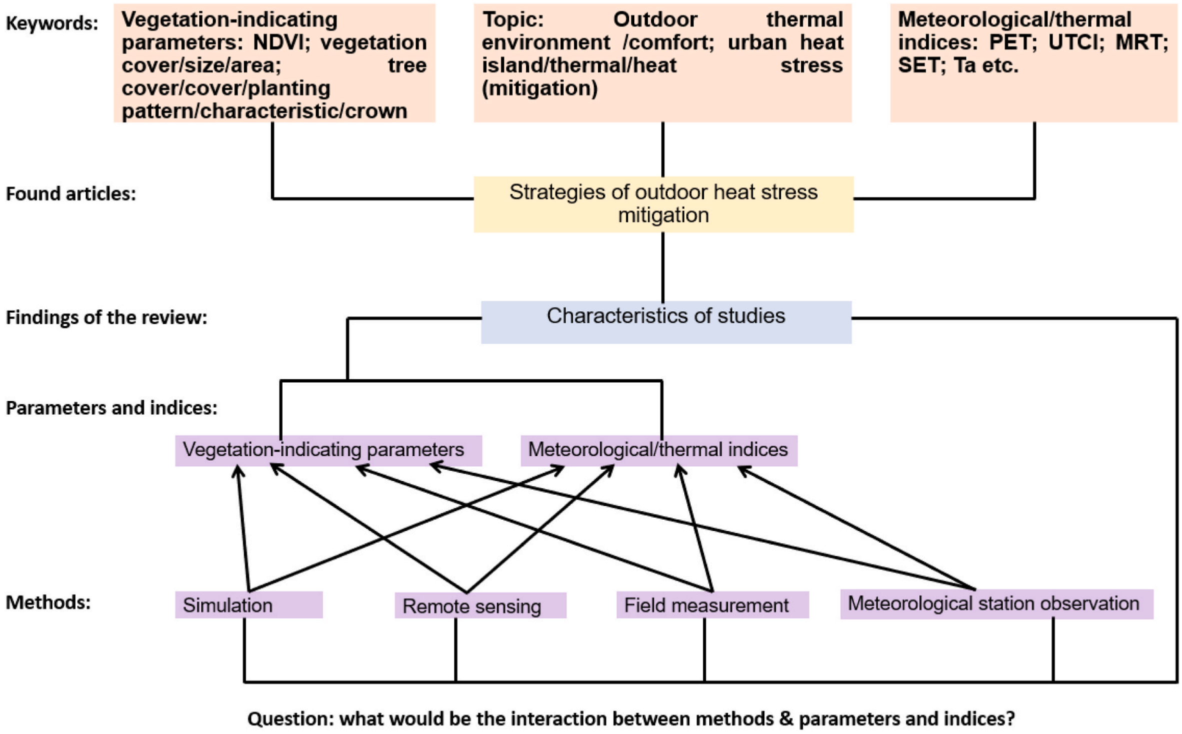

Fig. 2. The process of paper selection and data clustering.

3.1. Source of articles

Reviewed articles were from scientific journals issued by mainstream publishers, such as Elsevier, Springer, Taylors, and the SAGE. A large proportion of papers were from *Landscape and Urban Planning*, *Building and Environment*, *Urban Climate*, *Urban Forestry & Urban Greening*, *Sustainable Cities and Society* etc. The quantity of papers provided by certain journals is shown in Fig. 3. Most papers were published in *Sustainable Cities and Society* (9) and *Building and Environment* (9) followed by *Ecological Indicators* (5) and *Urban Forestry & Urban Greening* (5). Six journals offered three papers, e.g., *Remote Sensing Applications: Society and Environment*, *Science of Total Environment*, and *Landscape and Urban Planning*. Journals providing less than three papers were defined as *others* and included 30 papers.

3.2. Clustering factors from the reviewed studies

Last chapter has concluded that there were several properties found in OTE/OTC studies. One property might be interactive with others. This study clustered properties of all studies through their quantities. For instance, there would be a large number of RMS studies using LST as their meteorology index; yet it should be infrequently used by SIMU. This could differ studies of different methods in other aspects.

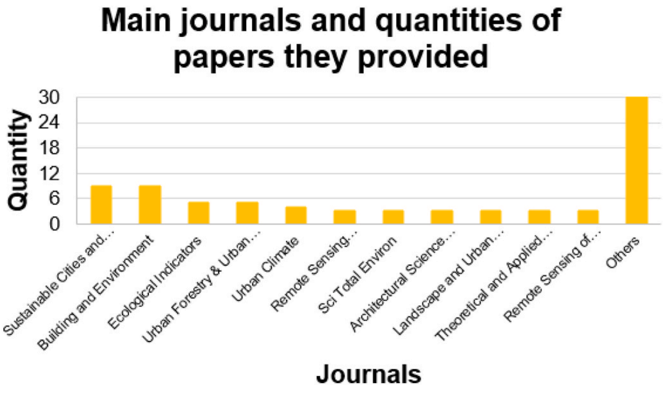

Fig. 3. Main journals and quantity of papers.

4. Results

4.1. General information expression of reviewed studies

Tables 1–4 list general information of reviewed papers regarding their methods. Studies using a same method had some common properties. As to studies using RMS (Table 1), NDVI was a popular vegetation parameter, which is used by nearly all studies. They also consider the types of land uses (Peres et al., 2018). LST was the most frequently used meteorological index(Daramola and Balogun, 2019). Indices of emissivity (Neinavaz et al., 2020) and thermal perception (Mijani et al., 2020) were also used by a few studies. Most studies of RMS were large-scaled, which is expressed in both space and time. Their geographical scopes spanned tens of kilometers, such as Zhang et al. (2012) andAhmed (2018). They spanned very long time as well, usually longer than one decade (Adeyeri et al., 2017). Some similar properties can be found in studies of MSO (Table 4). They often utilised LST as the index. Large spans in geography and time were key features of them. They spanned tens of kilometers, even nearly 1000 km (Ren et al., 2007). They also studied the meteorology of very long term.VEZ et al. (2000)used the data of nearly one century.

Studies using SIMU and FDM had different properties (Tables 2 and 3) compared with RMS and MSO. They have diverse vegetation parameters, such as LAI (Rahman et al., 2020a) and crow (Morakinyo et al., 2018). These were rarely used by RMS and MSO studies. Their thermal indices were differed from those. PET (Lehnert et al., 2020) and MRT (Kong et al., 2017) were most popular ones. They had smaller timespans and geography scopes. They usually investigated sites of small pieces; most of them studied the small site by a short period, such as Guo et al. (2020)measuring trees in the park by one week only.

All reviewed studies were conducted in different cities. Each one has its own climate. Hence, there were diverse climatic zones involved, such

Table 1
Key data of reviewed studies using RMS.

Reference	City (Climate)	Vegetation parameter	Geographical scope (km)	Timespan (year)	Thermal/meteorological index
Daramola and Balogun (2019)	Akure (Aw)	Vegetation cover, NDVI	11	Dec. 2014	LST, surface heat flux
Neinavaz et al. (2020)	Czech (Cfb)	Vegetation cover, NDVI	26	Aug. 2015	LST, land surface emissivity (LSE)
Zhang et al. (2012)	Sydney (Cfa)	Vegetation cover, NDVI	60	1993–2006	LST
Sharma et al. (2021)	Noida (Cwa)	NDVI	20	Apr. 2011 & 2019	LST, UTFVI
Mijani et al. (2020)	Tehran (Csa)	Environmental and surface biophysical parameters	45	2013–2018	Discomfort index
Feng et al. (2020)	Nanjing (Cfa)	Landscape Division Index & Aggregation Index, NDVI	60	1994, 2000, 2010 & 2013	LST, MTHI
Tien Nguyen (2020)	Vietnam (Aw)	NDVI	20	1996–2006	LST
Peres et al. (2018)	Rio de Janeiro (Aw)	Land use mapping	150	1984–2015	LST/UHII
Shirani-bidabadi et al. (2019)	Isfahan (Bwk)	Vegetation cover, NDVI	25	Jun. 1999, Jun. 2006, Jun. 2013, May 2016	LST/URI
Zhou et al. (2018)	YRDUA	Land use	300	2013–2016	SUHII
Singh et al. (2017)	Lucknow (Csa)	NDVI	30	2002 & 2014	LST, UTFVI
Ahmed (2018)	Suez (Cfa)	NDVI	65	1988–2014	LST, UTFVI, LSE
Chen et al. (2006)	Pearl River Delta (Cfa)	NDVI	300	1990–2000	LST
Li et al. (2009)	Shanghai (Cfa)	Land use	120	1997 & 2004	SUHII
Nichol (2005)	Hong Kong (Cwa)	Landform	20	Sept. – Otc. 2002	LST
Rogan et al. (2013)	Worcester (Cfa)	Tree canopy cover loss	25	2008–2010	ΔLST
Coutts et al. (2016)	Port Phillip (Cfa)	NDVI, Vegetation cover	8	Feb. 2012	LST, T_a
Adeyeri et al. (2017)	Abuja (Aw)	MSAV, NDVI	80	November 2016	SUHII
Du et al. (2016)	Shanghai (Cfa)	Green land, grass land	30	August 29th, 2013	LST, ΔTa
Wu et al. (2018)	Pearl River Delta (Cfa)	NDVI	5	July 4th, 2015	LST
Chibuike et al. (2018)	Abuja (Aw)	NDVI	15	Nov. 2017	LST
Imhoff et al. (2010)	4 cities in the US	NDVI		2003–2005	LST
Morabito et al. (2021)	The whole country of Italy (Csa)	NDVI, Tree cover density, Surface landscape		2016–2018	LST

as Aw (Daramola and Balogun, 2019), BWk (Shirani-bidabadi et al., 2019), and Cfa (Feng et al., 2020).

The four tables showed that studies in various methods were different in some properties. There might be some similarities of reviewed studies clustered regarding their properties, which is expressed in the following sections of this chapter. Each property was clustered by its quantity of paper.

4.2. *Clustering of reviewed studies via various approaches*

4.2.1. *Clustering by climate zone*

Reviewed studies were from various climatic zones. Many climatic zones were covered, including Aw in Akure (Daramola and Balogun, 2019) and Rio de Janeiro (Peres et al., 2018), BSk in Isfahan Tabriz, Bwh in Suez (Ahmed, 2018), Cfb in Port Phillip (Coutts et al., 2016), and Cfa in the Pearl River Delta (Chen et al., 2006). Quantities of studies conducted in different climate zones are illustrated in Fig. 5. Generally, it can be seen that reviewed studies were around the areas with a latitude below 40°. There were a large number of studies carried out in China, including Cfa (Guo et al., 2021) and Cwa (Cheung et al., 2021), especially SIMU. The Europe (Azcarate et al., 2021) and west Asia (Mijani et al., 2020) were less frequently studied, they were more implemented in C zones. The America, both the North and Latin, were studied in a few states. Africa was very infrequently studied, only in the Am zone. It can be seen from the image, climate types of C were most preferred. The type of A was considered. The types of B and D were involved by fewer studies.

4.2.2. *Clustering by geographical scopes*

The four methods used for urban climate/thermal environment studies (RMS, SIMU, FDM, and MSO) were clustered according to their geographical or temporal scope. Geographically, RMS and MSO usually investigated large scales such as whole cities. RMS studies investigating Sydney (Zhang et al., 2012), Tehran (Mijani et al., 2020), Nanjing (Feng et al., 2020), and Lucknow (Singh et al., 2017) had the geographical scopes of 60 km, 45 km, 60 km, and 30 km, respectively, while MSO, such as Seoul (Lee et al., 2016), New York (Gaffin et al., 2008), and Singapore (Chow and Roth, 2006) had geographical scopes of 35 km, 100 km, and 50 km, respectively. In contrast, SIMU and FDM studies had smaller scopes with a maximum in Peking of 9 km (Sun et al., 2017) and Gold Coast of 16 km (Zhang et al., 2019)). Quantities of studies with various geographical scopes performed by different methods are shown in Fig. 6. Geographical scopes were divided into a colour of different darkness for distinction. This was also used in some following sections. A darker colour means a larger geographical scope. Fig. 6 shows that bars of RMS and MSO were obviously darker than SIMU and FDM. That is to say, RMS and MSO were more suitable for macro-level studies, SIMU and FDM suit micro-level ones.

4.2.3. *Clustering by timespans*

All studies also varied in duration. RMS and MSO were suitable for the acquisition of long-term data as they were used in studies over longer periods. Studies at Noida (Sharma et al., 2021), Vietnam (Tien Nguyen, 2020), and Shanghai (Li et al., 2009) spanned nearly one decade, at 8 years, 10 years, and 7 years, respectively; while Seoul (Lee and Baik, 2010) and Singapore (Chow and Roth, 2006) were studied for nearly half a decade. SIMU and FDM were used for shorter duration of mostly less than one year, such as one in Kowloon that spanned several months (Morakinyo et al., 2017). A few studies were even implemented in only a day, such as that by Kong et al. (2017). Quantities of studies with various timespans performed by different methods are shown in Fig. 7. The bars of RMS and MSO were obviously darker than SIMU and FDM, which is similar with geographical scopes. RMS and MSO were more suitable for long-term studies.

4.2.4. *Clustering by thermal indices*

A variety of meteorological/thermal indices were used. Each index had its own physical characteristics, which influenced its usage scopes in terms of the data acquisition methods. Fig. 8 shows the distributions of various indices according to their associated methods. T_a and LST were the most preferred meteorological indices, utilised by 19 and 22 papers, respectively. PET was used the most frequent OTE/OTC index (30

Table 2
Key data of reviewed studies using SIMU.

Reference	City	Vegetation parameter	Geographical scope (km)	Timespan (year)	Thermal index
Morakinyo et al. (2017)	Kowloon (Cwa)	Species and morphological properties, canyons, leaf area index, tree height and trunk height	0.07	Aug.–Oct. 2016	△PET
Lobaccaro and Acero (2015)	Bilbao (Csa)	Tree and grass	0.4	Aug. 2010	PET
Teshnehdel et al. (2020)	Tabriz (Bwh)	Tree cover & species; height, crown length, diameter, LAI	1.5	Jun. & Dec. 2917	T_a, RH, MRT, & PET
Sun et al. (2017)	Peking (Dwa)	Grass, tree height	9	Aug. 2016	△PET
Abdi et al. (2020)	Tabriz (Bwh)	Trees leaf habit (deciduous & evergreen)	0.12	Oct. 2018	PMV & PET
Srivanit and Jareemit (2020)	Bangkok (Aw)	Tree planting pattern (distance)	6	Apr. 2016	PET
Chan and Chau (2021)	Hong Kong (Cwa)	LAD, tree cover	0.4	Aug. 2017 & Jan. 2018	PET
Jamei and Rajagopalan (2017)	Melbourne (Cfa)	Tree canopy coverage	0.15	Jan. 2015	MRT, PET
Morakinyo and Lam (2016)	Hong Kong (Cwa)	LAI, LAD, tree cover area, trunk height, tree planting pattern	0.1	Aug. 2015	△PET
Yang et al. (2011)	Shanghai (Cfa)	Greenery (tree) cover	2		PET
Zhao et al. (2018)	Tempe (Bwh)	Clustered tree arrangement	0.4	Jun. 2017	PET
Xiong et al. (2020)	Suzhou (Cfa)	Tree cover	0.1	Jan. & Jul. 2016	SET
Chen and Ng (2013)	Hong Kong (Cwa)	Tree & grass cover	0.4	Jun. 2008	PET
Sodoudi et al. (2018)	Berlin (Cfb)	Tree canopy sizes, hedges and shrubs, grass (sizes/length)	5	Jun. 2014	PET
Zölch et al. (2019)	Munich (Cfa)	Novel greening design	0.06	Summer 2015	PET
Azcarate et al. (2021)	Bilbao (Csa)	Tree configuration & species	0.1	Aug. 2019	PET
Taleghani et al. (2016)	California (Csb)	Type of infrastructure, Green roof, street tree	0.25	Jul. 2014	UTCI, MRT, PET
Kong et al. (2017)	Hong Kong (Cwa)	Tree height, trunk height, crown height & diameter, LAI, planting density, transpiration, species	0.5		MRT, solar radiation, wind
Rinchumphu et al. (2021)	Chiang Mai (Aw)	Large tree, shrubs	0.1	Apr.	PET, T_a, RH, Wind, MRT
Guo et al. (2021)	Shanghai (Cfa)	Vertical greening system LAI, tree	0.24		PET, ΔT_a
Darvish et al. (2021)	Qazvin	vegetation coverage, leaf habit, tree height, LAD	5	Jun. & Dec. 2018	PET
Spangenberg et al. (2008)	São Paulo (Cfa)	LAI, LAD, tree	0.7		PET, T_a, RH, wind MRT
Yang et al. (2018)	Xi'an	LAI, tree layout (planting pattern), tree height	0.47	Jul. & Aug. 2017	PET
Hong and Lin (2015)	Peking (Dwa)	Tree planting arrangement	0.08	Jul.	Wind, SET
Morakinyo et al. (2018)	Kowloon (Cwa)	Tree species, tree height, trunk height, crown height, crown width, LAI, transmissivity	0.1	Aug. & Oct. 2016	ΔPET, ΔT_a, ΔMRT
Altunkasa and Uslu (2020)	Adana (Csa)	Tree height, trunk height, crown length/width, leaf habit, transmissivity, species	0.25	Feb.–Aug. 2017	PMV

papers). Of the acquisition methods, RMS (22) supported the collection of LST while SIMU (22) and FDM (8) were used to acquire PET. Also, each index had its suiting method. T_a was the only index that could be acquired by all four methods. RMS was suitable for LST while SIMU and FDM were useable for PET. OTE/OTC indices were usually collected through SIMU and FDM.

4.3. Clustering by vegetation parameters

4.3.1. Clustering of vegetation parameters against methods

Vegetation parameters were clustered into four types regarding their indicative ranges. These were also studied using various methods. NDVI, vegetation cover, trees in groups, and individual trees were investigated by different methods (see Fig. 9). Proportionally, NDVI was only studied by RMS (15); vegetation cover was mainly studied by RMS (5) and FDM (4); tree studies preferred SIMU (28) and FDM (15), especially when investigating individual trees (15 and 6). RMS was the only method used by all four indicative parameters.

4.3.2. Clustering of vegetation parameters against scopes

Fig. 10 compares the quantities of papers utilising the four vegetation parameters regarding their geographical scopes (left) and time (right). In each of them, the bars were getting lighter from the left to the right. NDVI was the darkest among all in both two images, which means, studies using NDVI usually involved large scales. Most of them involved tens of kilometres and several years, even above 100 km. It was followed by vegetation cover. Parameters about trees were preferred by studies involving thermal environment/comfort of micro scopes in short terms.

4.3.3. Clustering of vegetation parameters against meteorological/thermal indices

Vegetation parameters were also clustered by indices (Fig. 11). PET was preferred by tree studies, especially individual trees (25), more than group trees (14). T_a had better adaptability, for it was used by all four parameters. LST was more frequently used by studies exploring NDVI (16) and vegetation cover (6). MRT was selected by tree studies for several times and only once for vegetation cover. Other indices were rarely used. The right image illustrates that OTE/OTC indices were more available for micro vegetation parameters.

4.4. Others

4.4.1. Statistical models

A wide range of analysis methods was suitable and was used, depending on the preferences of researchers and the data characteristics. Multiple linear regression (MLR), Pearson's correlation, and analysis of variance (ANOVA) were most frequently used. These showed that vegetation parameters were statistically significantly correlated with the thermal environment (indices), which demonstrated the significance of the parameters. A few studies were conducted without data analyses and produced illustrative results (de Abreu-Harbich et al., 2015).

4.4.2. Physical site factors in addition to vegetation

Vegetation was examined in various contextual environments to

Table 3
Key data of reviewed studies using FDM.

Resource	City	Vegetation parameter	Geographical scope (km)	Timespan (year)	Thermal index
de Abreu-Harbich et al. (2015)	Campinas (Cfa)	Tree species (differing by geometry, height, permeability, evergreen or deciduous, leaf shape & type), plant	1.3	2007–2010	PET, solar radiation
Klemm et al. (2015b)	Utrecht (Cfb)	Tree canopy cover	1.5	Jul. & Aug. 2012	MRT
Coutts et al. (2015)	Melbourne	Tree canopy cover	3	Feb. 2012	UTCI, solar radiation
Rahman et al. (2020a)	Würzburg (Cfb)	Tree species, tree planting design, LAI, canopy, evaporation, crown volume	2	2017 & 2018	ΔT_a, ΔRH, PET
Meili et al. (2021)	Singapore (Af)	Tree cover within canyon, vegetated ground fraction within canyon, tree LAI, ground vegetation LAI, leaf dimension, tree light extinction coefficient,	1.5	Jul.–Nov. 2019	UTCI
Klemm et al. (2015a)	Utrecht (Cfb)	Tree canopy/vegetation cover	6	Summer 2011–2012	PET, MRT, T_a
Puliafito et al. (2013)	Mendoza (Bwk)	Trees	11	Dec. 2004 & Jan. 2005	PET
Lehnert et al. (2020)	Czech (Cfb/Dfb)	Tree shade	0.5	Summers 2018 & 2019	PET
Lin and Tsai (2017)	Chiayi (Cwa)	Crown diameter, species	1	July–October 2014	PET, MRT
Mballo et al. (2021)	Angers (Cfb)	Crown dimension, ground vegetation cover, LAD, LAI, tree transpiration	0.05	Jun.–Sept. 2020	UTCI, wall fluxes & temperature
Cheung et al. (2021)	Hong Kong (Cwa)	Shrub cover, tree cover	3	Jun.–Aug. 2018	ΔT_a, ΔRH
Zhang et al. (2019)	Gold Coast (Cfa)	Tree cover	16	Jan.–Mar. 2018	ΔT_a
Zhang et al. (2020b)	Gold Coast (Cfa)	Crown diameter, trunk height, LAI, TVF	1	Dec. 2019–Jan. 2020	MRT
Zhang and Gou (2021)	Deyang (Cwa)	Crown diameter, height, leaf gap ratio, LAI	1	Jul. 2019	MRT, TSV
Guo et al. (2020)	Xindu (Cwa)	Planting pattern & LAI	0.1	Aug. 2019	MRT, solar radiation, wind, T_a
Wang et al. (2021a)	Xindu (Cwa)	Crown radius, trunk height, LAI	0.1	Aug. 2019	PET
Ziter et al. (2019)	Wisconsin (Dfb)	Tree canopy cover	2.5	Summer 2016	T_a
Shahidan et al. (2010)	Malaysia (Af)	Tree species, LAI, transmissivity, shade area amount	0.05	Feb. 2006	Thermal radiation filtration
Xu et al. (2019)	Xi'an (Cfb)	Leaf habit	0.5	Jan. & Jul. 2018	UTCI, TSV
Zheng et al. (2018)	Guangzhou (Cfa)	LAI, LAD, species, transpiration	1	Jul. 2017	PET, MRT, radiation, GST, T_a, humidity, wind, LST
Yan et al. (2018)	Peking (Dwa)	Vegetation cover	6	Aug. 2010	T_a
Yan and Dong (2015)	Peking (Dwa)	Tree cover, lawn cover	1.3	Jul. 2010	T_a

Table 4
Key data of reviewed studies using MSO.

Resource	City	Vegetation parameter	Geographical scope (km)	Timespan (year)	Thermal index
Milošević et al. (2017)	Novi Sad (Cfa)	Tree planting pattern	10	Jul. 2015	UTCI
Lee et al. (2016)	Seoul (Dwa)	Vegetation area	35	Whole 2012	T_a, wind, humidity
Gaffin et al. (2008)	New York (Cfa)	Land use	100	1900–2002	T_a, energy load
Lee and Baik (2010)	Seoul (Dwa)		30	1999–2002	LST
Li et al. (2020)				2003–2013	LST
Siu and Hart (2013)			9	1990–2008	
VEZ et al. (2000)	Granada (Csa)		7	90 years before 2000	
Ren et al. (2007)			900	1960–2000	T_a
Chow and Roth (2006)			50		

evaluate cooling effects. However, in addition to vegetation, there were other factors that either directly or indirectly affect thermal evaluation, such as site openness or sky view factor (SVF) (Coutts et al., 2015), orientation (Sodoudi et al., 2018), and land use which affected albedo (Yang et al., 2011). It was found that trees had the highest cooling effect in impervious sites (Rahman et al., 2020b). Therefore, in coastal cities for example, effectiveness of vegetation in cooling the thermal environments varied periodically depending on the perviousness of the site (Zhang et al., 2019).

4.5. Results of reviewed studies

There were 80 papers reviewed in this study. Each of them had its own findings. Accordingly, instead of indicating findings from each individual paper in detail, this research presents a general overview of the whole. Nevertheless, some commonalities (similarities) between their findings could be drawn out, such as the relationship between thermal indices and vegetation indicators; that is, a larger amount of vegetation resulted in cooler environments. This study focused on vegetation parameters. A large quantity of them were negatively correlated with temperatures while others showed positive correlation.

NDVI, vegetation cover, tree cover, tree crown sizes, and LAI were negatively related to temperatures. This was found by both RMS and FDM. This means that increasing either of them can reduce temperatures. The increases of NDVI by 0.1 (Daramola and Balogun, 2019), vegetation cover by 10% (Yan et al., 2018), and tree cover by 10% (Cheung et al., 2021) reduced LST by 0.089 °C, T_a by 0.17 °C, and T_a by 0.04 °C, respectively. Their effects also varied for based on the time on

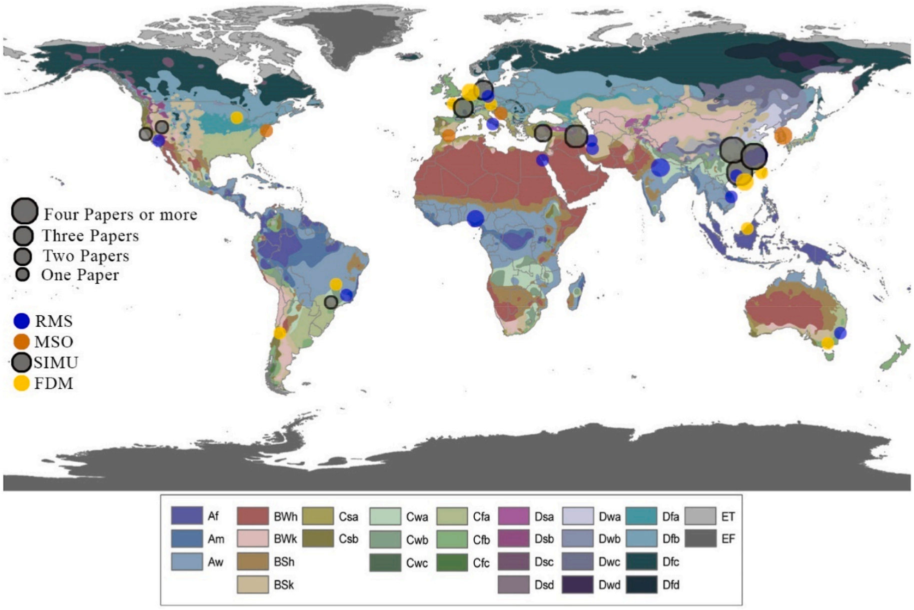

Fig. 5. Climatic zone distribution of studies using the four methods (Peel et al., 2007).

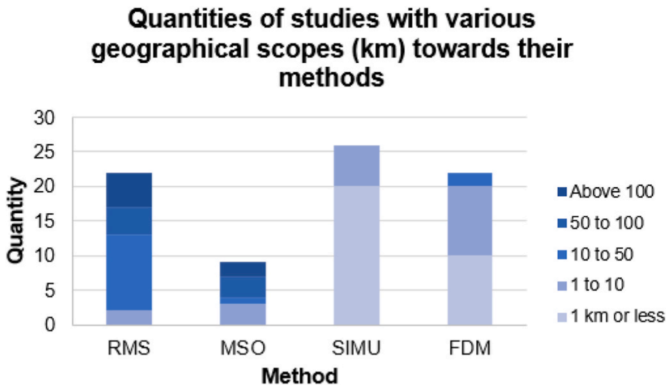

Fig. 6. Quantities of studies differed by geographical scopes using the four methods.

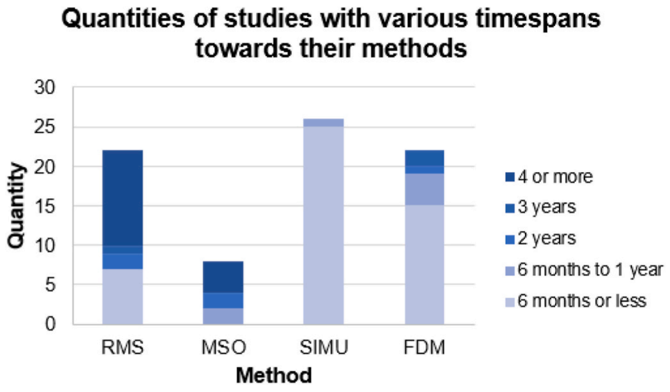

Fig. 7. Quantities of studies differed by timespans using the four methods.

the day (Yan et al., 2018). Increasing crown diameter caused MRT and PET reductions by 30 °C and 20 °C in maximum (Lin and Tsai, 2017). PET decrease of 3 °C can be reached by rising LAI from 1 to 6 (Morakinyo and Lam, 2016).

Some parameters were positively correlated with temperatures, such as openness (SVF), enclosure area (planting distance), and trunk height. Rising SVF by 0.1 resulted in LST increase of 0.06 °C (Daramola and Balogun, 2019). Trees being planted farther (with larger enclosure areas) caused warmer environments, expressed by MRT (Guo et al., 2020) and PET (Rahman et al., 2020a), despite of some negative effects on growing. Trees with shorter trunks were more cooling effective (Morakinyo et al., 2018). Their effects were expressed by stronger thermal effect of the parameter involving both crown sizes and trunk heights (Wang et al., 2021b). These findings were most acquired through FDM and SIMU.

Cooling effects of vegetation also varied for extra factors. Zhang et al. (2019) and Yan et al. (2018) found that plants were relatively cooling significant in the evening. Trees' cooling performances were affected by site geometry (Rahman et al., 2020a) and land cover (Rahman et al., 2019).

These studies all found a correlation between the thermal environment and certain vegetation parameters. Their findings were often expressed by cooling intensity and/or correlation significance. Linear regression was preferred by most studies as it quantitatively expressed both the degree of cooling and the significance.

5. Discussion

This study clustered articles on studies that investigated urban thermal environment based on vegetation parameters and other properties. It was found that the research methodology of studies on the thermal environments were significantly linked with their study target and scope. This link was due to several reasons.

5.1. Studied climate region

Thermal environment studies involving vegetation were mostly conducted in regions with high heat stress levels, such as tropical or subtropical zones (i.e., Aw and Cfa), with latitude below 40°. This was naturally because vegetation have cooling effects in hot climates caused by their shading (Zhao et al., 2017), evaporation (Moss et al., 2018), and transpiration (Pearcy et al., 2000). They might not decrease cold stress levels in colder conditions. However, this expresses the investigation potential of this topic, climate zones of B and D could be significantly considered in future studies.

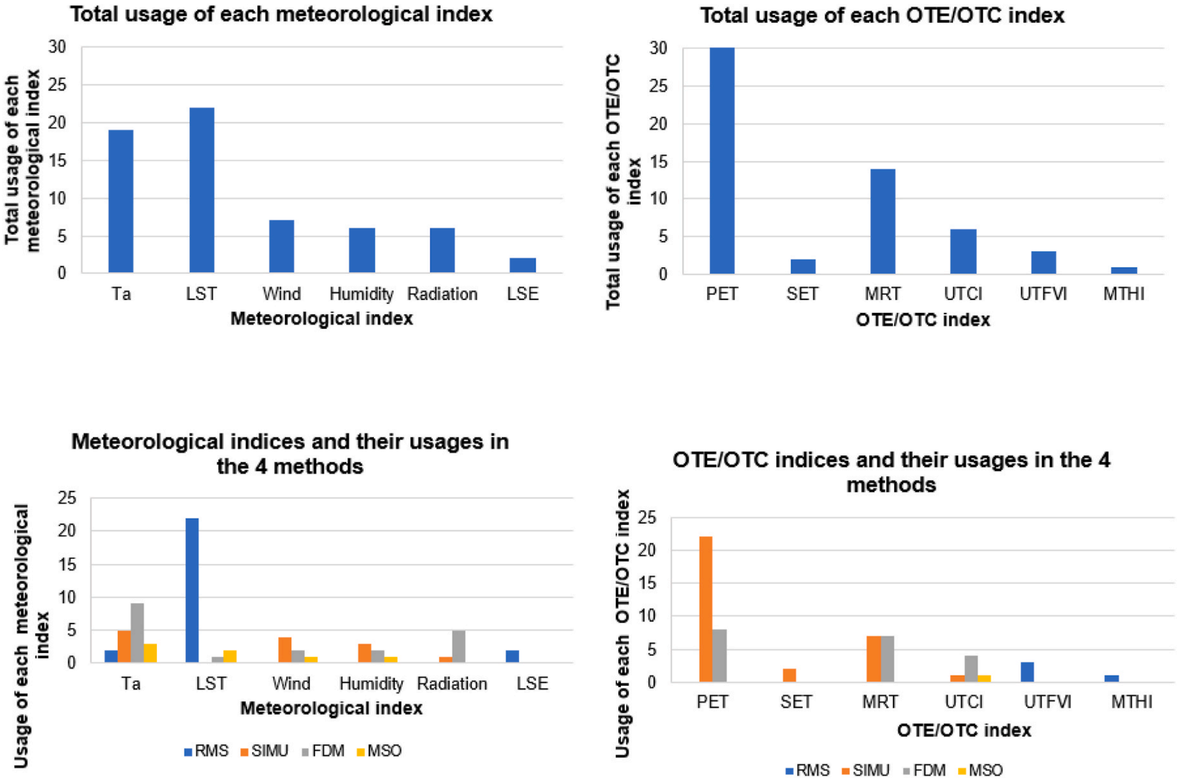

Fig. 8. Meteorological/thermal indices and their use for different acquisition methods.

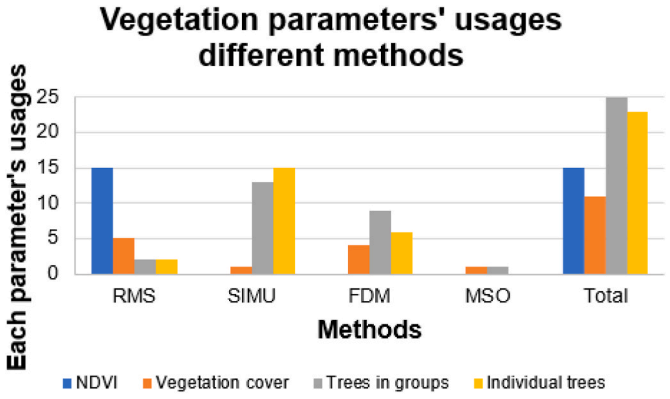

Fig. 9. Number of studies investigating vegetation parameters using the four methods.

5.2. Methods in relation to scope

The methods that were employed by studies varied by geographical and temporal scopes. RMS and MSO supported large-scaled climate studies. Satellites provided overall physical and climatic data for regions with imaging resolutions of more than 30 m (Chen et al., 2006), failed to provide detailed information. Meteorological stations are usually distributed around administrative areas (whole city) and cover tens of kilometres, resulting in large geographical scopes (e.g., Seoul (Lee et al., 2016)). Therefore, these methods are well suited to large-scale climate studies. Additionally, satellites and stations are working all the time and provide data throughout their service periods. Such abundant data resources supported more comprehensive climatic variation investigations, such as its changes resulting from long-term land-use changes (Singh et al., 2017).

5.3. Thermal indices in relation to methods and vegetation parameters

Many thermal indices were used to evaluate the climatic effects of vegetation. These were distributed across different studies, with every

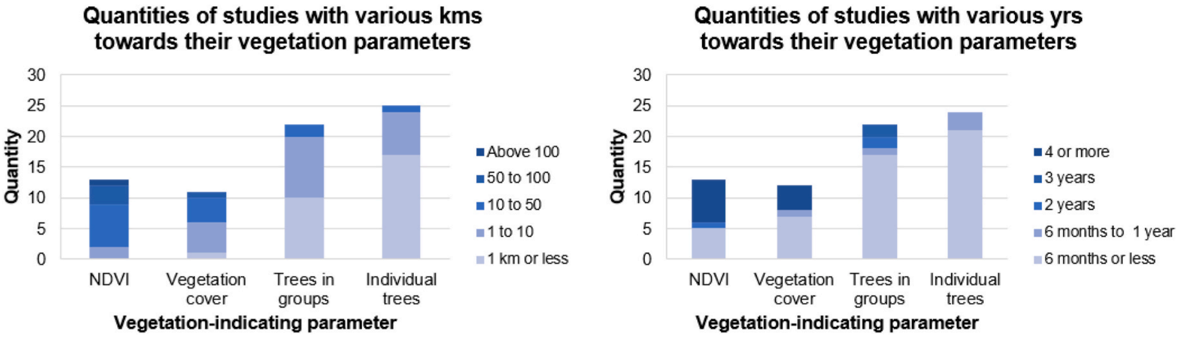

Fig. 10. Quantities of reviewed studies differed by geographical scopes and timespans against the four vegetation parameters.

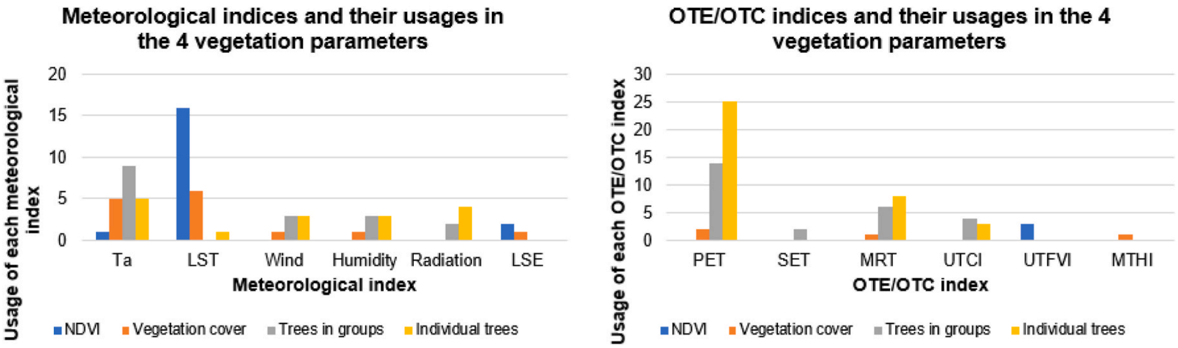

Fig. 11. Meteorological/thermal indices and their use for different vegetation parameters.

study using one or more. PET was the most frequently used thermal index in small-scale studies. This finding was also confirmed by Binarti et al. (2020) and Li and Liu (2020). Smaller-scale sites are sensitive to microclimatic factors, so slight changes in any weather parameters such as wind, humidity, and radiation have a significant effect on thermal conditions. As PET can be affected by nearly all objective thermal factors and some subjective factors, it was frequently used in most reviewed papers to evaluate thermal conditions. LST which can be captured by satellite was the most popular index in macro studies. T_a was the only index studied by all methods including RMS (Du et al., 2016), FDM (Klemm et al., 2015a), SIMU (Rinchumphu et al., 2021) and MSO (Gaffin et al., 2008). T_a is an easily measurable climatic/thermal index, which can be utilised in most sites with different scale of small (Zhang et al., 2019) to large (Ren et al., 2007).

5.4. Vegetation parameters in relation to methods and scope

The four vegetation indicating parameters used in different studies were analysed according to the methods. Vegetation indicating parameters were found to differ by geographical scopes, timespans, methods, and relevant thermal indices. The clustering was directly affected by these properties. NDVI was used for studies with broad geographical (Zhang et al., 2012) and/or temporal (Feng et al., 2020) scope. In macroscopic studies, detailed information were not presented. Therefore, NDVI—a parameter that can differ according to land use—could meet the needs of large-scale studies such as studying climate changes resulting from long-term land-use alteration. Additionally, NDVI is a parameter developed from remote sensing techniques, which is more suitable for large-scale studies.

In contrast, vegetation cover only indicates the density or number of plants in a certain area. As it only differentiates lands with or without plants, vegetation cover's scope is smaller than that of NDVI. However, as vegetation types and vertical layers are not considered by vegetation cover, it has a larger range than parameters involving specific vegetation types, such as trees. Also, the coverage of both vegetation (Yan et al., 2018) and trees (Zhang et al., 2019) are usually captured from satellite maps from which it is difficult to derive detailed data about individual trees.

Individual trees involved the most detailed factors, which even vary for sites a few meters apart. Therefore, its influential range is smaller than parameters involving more than one tree (trees in groups). Explorations of this parameter used methods that were conductive to capture detailed data. For example, FDM instruments harvested data from very small areas, both climatic (e.g., using the Testo 480 radius of 1.5 m) and physical (e.g., WinSCANOPY for one point (WinSCANOPY, 2017)). SIMU usually established characterised scenes based on practical environments. They could create sites with certain building heights (Chan and Chau, 2021), street widths (Morakinyo and Lam, 2016), land cover (Rinchumphu et al., 2021), orientation (Guo et al., 2021) etc. Researchers often set various vegetation conditions as the contexts for comparing their thermal performances. Each site exported scene varying for vegetation but with similar other physical contexts. This helped comparing various thermal performances of sites differing for vegetation only.

5.5. Limitations

This review clustered studies on the thermal environments relating to vegetation in terms of their methodologies. However, some limitations remain unaddressed. The biological effects of vegetation such as transpiration and evaporation, which are key to climatic adjustments, are not dwelled on this review, since only a few reviewed papers involved them. Also, there were some other types of vegetation uninvolved, such as green roof (Wang et al., 2022) and living wall (Meng et al., 2022). They were ignored since rarely being indicated by parameters quantitatively. These issues would be addressed in future studies.

5.6. Practical implications and future outlook

This study would be practically implicative for future urban heat studies:

- Findings of this study are directive for further investigations in similar fields; scholars could select suitable methods, indices, and parameters regarding their research targets.
- Previous studies were mostly conducted in climate zones of A and C. Populated Zones B and D are bare areas of thermal environment studies. These regions could be considered by future studies.
- There were a couple of types of vegetation uninvolved in this study. They are green roofs and living walls. These were rarely indicated by parameters. Most studies just confirmed the fact that green roofs were cooler and more thermal comfortable than bare ones instead of expressing the statistical correlations between the parameters and the indices. Future studies could propose certain parameters quantitatively indicating them. Vegetation on roofs, for instance, could be evaluated by coverage or LAI_G (ground leaf area index (Meili et al., 2021)).

6. Conclusion

This study reviewed journal articles about various aspects of the urban thermal environment. It was found that these studies varied in terms of the vegetation indicating parameters, methods, and thermal indices that were used with variation mainly resulting from their scopes. The results of this study provide clearer directions for future investigations on this topic. Additional findings were as follows:

- Thermal environment studies were mostly conducted in tropical/subtropical regions (latitude <40°) where there was much permanent/seasonal heat stress.
- RMS and MSO were more used for large-scale studies while SIMU and FDM were frequently used in micro-scale studies; here, 'scale' refers to both geographical or temporal.
- Four typical vegetation parameters were used. NDVI and vegetation cover were used in large-scale studies investigating RMS or MSO (indicated by LST). Tree parameters were more common in smaller-scale studies examining FDM and SIMU, which were usually indicated by PET.
- Vegetation parameters were measured by different methods depending on the study scope, with macro-levels parameters obtained by RMS (e.g., for NDVI) and detailed parameters through SIMU and FDM.
- Further studies about vegetation cooling should consider Köppen Climate Zones B and D, which is rarely tried by previous studies.
- Researchers should propose some parameters indicating vegetation other aspects, such as green roofs and living walls; they could be quantitatively defined in design/planning works.

This review will inform future investigations of the thermal environment relating to vegetation regarding the relationship between methodology, research aims, and their contexts.

Funding

There is no funding source available for this work.

Contribution of author

Jian Zhang wrote the manuscript; Maryam and Jianlin Liu edited the manuscript; Zhonghua Gou supervised the whole project; the rest authors conducted data collection and analyses.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdi, B., Hami, A., Zarehaghi, D., 2020. Impact of Small-Scale Tree Planting Patterns on Outdoor Cooling and Thermal Comfort, 56. Sustainable Cities and Society.

Acerecho, E., 2020. What Are the 3 General Zones of Latitude? Addison-Wesley, Reading, MA. Accessed at 12 March 2021. https://findanyanswer.com/what-are-the-3-general-zones-of-latitude.

Adeyeri, O.E., Akinsanola, A.A., Ishola, K.A., 2017. Investigating surface urban heat island characteristics over Abuja, Nigeria: relationship between land surface temperature and multiple vegetation indices. Remote Sens. Appl.: Society and Environment 7, 57–68.

Ahmed, S., 2018. Assessment of urban heat islands and impact of climate change on socioeconomic over Suez Governorate using remote sensing and GIS techniques. Egyptian J. Rem. Sens. Space Sci. 21, 15–25.

Akbari, H., Matthews, H.D., 2012. Global cooling updates: reflective roofs and pavements. Energy Build. 55, 2–6.

Altunkasa, C., Uslu, C., 2020. Use of Outdoor Microclimate Simulation Maps for a Planting Design to Improve Thermal Comfort, 57. Sustainable Cities and Society.

Arnfield, A.J., Rafferty, J.P., Pallardy, R., 2016. Climate Classification, Britannia available from: https://www.britannica.com/topic/classification-1703397. accessed at 25 Mar 2021.

Azcarate, I., Acero, J.Á., Garmendia, L., Rojí, E., 2021. Tree Layout Methodology for Shading Pedestrian Zones: Thermal Comfort Study in Bilbao (Northern Iberian Peninsula). Sustainable Cities and Society.

Binarti, F., Koerniawan, M.D., Triyadi, S., Utami, S.S., Matzarakis, A., 2020. A review of outdoor thermal comfort indices and neutral ranges for hot-humid regions. Urban Clim. 31.

Broadbent, A.M., Coutts, A.M., Tapper, N.J., Demuzere, M., 2018. The cooling effect of irrigation on urban microclimate during heatwave conditions. Urban Clim. 23, 309–329.

Chan, S.Y., Chau, C.K., 2021. On the Study of the Effects of Microclimate and Park and Surrounding Building Configuration on Thermal Comfort in Urban Parks, 64. Sustainable Cities and Society.

Charalampopoulos, I., Tsiros, I., Chronopoulou-Sereli, A., Matzarakis, A., 2012. Analysis of thermal bioclimate in various urban configurations in Athens, Greece. Urban Ecosyst. 16, 217–233.

Chen, L., Ng, E., 2013. Simulation of the effect of downtown greenery on thermal comfort in subtropical climate using PET index: a case study in Hong Kong. Architect. Sci. Rev. 56, 297–305.

Chen, X.-L., Zhao, H.-M., Li, P.-X., Yin, Z.-Y., 2006. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. Rem. Sens. Environ. 104, 133–146.

Chen, X., Zhao, P., Hu, Y., Ouyang, L., Zhu, L., Ni, G., 2019. Canopy Transpiration and its Cooling Effect of Three Urban Tree Species in a Subtropical City- Guangzhou, China, 43. Urban Forestry & Urban Greening.

Cheung, P.K., Jim, C.Y., Siu, C.T., 2021. Effects of Urban Park Design Features on Summer Air Temperature and Humidity in Compact-City Milieu, 129. Applied Geography.

Chiang, Y.-C., Li, D., Jane, H.-A., 2017. Wild or tended nature? The effects of landscape location and vegetation density on physiological and psychological responses. Landsc. Urban Plann. 167, 72–83.

Chibuike, E.M., Ibukun, A.O., Abbas, A., Kunda, J.J., 2018. Assessment of green parks cooling effect on Abuja urban microclimate using geospatial techniques. Remote Sens. Appl.: Society and Environment 11, 11–21.

Chow, W.T.L., Roth, M., 2006. Temporal dynamics of the urban heat island of Singapore. Int. J. Climatol. 26, 2243–2260.

Coutts, A.M., White, E.C., Tapper, N.J., Beringer, J., Livesley, S.J., 2015. Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. Theor. Appl. Climatol. 124, 55–68.

Coutts, A.M., Harris, R.J., Phan, T., Livesley, S.J., Williams, N.S.G., Tapper, N.J., 2016. Thermal infrared remote sensing of urban heat: hotspots, vegetation, and an assessment of techniques for use in urban planning. Rem. Sens. Environ. 186, 637–651.

Daramola, M.T., Balogun, I.A., 2019. Analysis of the Urban Surface Thermal Condition Based on Sky-View Factor and Vegetation Cover. Remote Sensing Applications, 15. Society and Environment.

Darvish, A., Eghbali, G., Eghbali, S.R., 2021. Tree-configuration and species effects on the indoor and outdoor thermal condition and energy performance of courtyard buildings. Urban Clim. 37.

de Abreu-Harbich, L.V., Labaki, L.C., Matzarakis, A., 2015. Effect of tree planting design and tree species on human thermal comfort in the tropics. Landsc. Urban Plann. 138, 99–109.

Du, H., Song, X., Jiang, H., Kan, Z., Wang, Z., Cai, Y., 2016. Research on the cooling island effects of water body: a case study of Shanghai, China. Ecol. Indicat. 67, 31–38.

Erell, E., Pearlmutter, D., Boneh, D., Kutiel, P.B., 2014. Effect of high-albedo materials on pedestrian heat stress in urban street canyons. Urban Clim. 10, 367–386.

Feng, L., Zhao, M., Zhou, Y., Zhu, L., Tian, H., 2020. The seasonal and annual impacts of landscape patterns on the urban thermal comfort using Landsat. Ecol. Indicat. 110.

Gaffin, S.R., Rosenzweig, C., Khanbilvardi, R., Parshall, L., Mahani, S., Glickman, H., Goldberg, R., Blake, R., Slosberg, R.B., Hillel, D., 2008. Variations in New York city's urban heat island strength over time and space. Theor. Appl. Climatol. 94, 1–11.

Geography, Internet, 2021. What factors affect climate? Available from. https://www.internetgeography.net/topics/what-factors-affect-climate/. Accessed 10 April 2021.

GISGeography, 2021. What is NDVI (Normalized difference vegetation index)? Available from. https://gisgeography.com/ndvi-normalized-difference-vegetation-index/. Accessed at 26 Dec. 2021.

Guo, W., Cheng, B., Wang, C., Tang, X., 2020. Tree Planting Indices and Their Effects on Summer Park Thermal Environment: A Case Study of a Subtropical Satellite City. Indoor and Built Environment, China.

Guo, S., Yang, F., Jiang, Z., 2021. Thermal environmental effects of vertical greening and building layout in open residential neighbourhood design: a case study in Shanghai. Architect. Sci. Rev. 1–17.

Gupta, S.K., Ram, J., Singh, H., 2018. Comparative study of transpiration in cooling effect of tree species in the atmosphere. J. Geosci. Environ. Protect. 6, 151–166.

Hami, A., Abdi, B., Zarehaghi, D., Maulan, S.B., 2019. Assessing the Thermal Comfort Effects of Green Spaces: A Systematic Review of Methods, Parameters, and Plants' Attributes, 49. Sustainable Cities and Society.

He, B.-J., Zhao, Z.-Q., Shen, L.-D., Wang, H.-B., Li, L.-G., 2019. An approach to examining performances of cool/hot sources in mitigating/enhancing land surface temperature under different temperature backgrounds based on landsat 8 image. Sustain. Cities Soc. 44, 416–427.

He, B.-J., Ding, L., Prasad, D., 2020. Relationships Among Local-Scale Urban Morphology, Urban Ventilation, Urban Heat Island and Outdoor Thermal Comfort under Sea Breeze Influence, 60. Sustainable Cities and Society.

He, B.-J., Wang, J., Zhu, J., Qi, J., 2022. Beating the urban heat: situation, background, impacts and the way forward in China. Renew. Sustain. Energy Rev. 161.

Hien, W.N., Jusuf, S.K., 2009. Air temperature distribution and the influence of sky view factor in a green Singapore estate. J. Urban Plann. Dev. 136, 261–272.

Hong, B., Lin, B., 2015. Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement. Renew. Energy 73, 18–27.

Imhoff, M.L., Zhang, P., Wolfe, R.E., Bounoua, L., 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. Rem. Sens. Environ. 114, 504–513.

Jamei, E., Rajagopalan, P., 2017. Urban development and pedestrian thermal comfort in Melbourne. Sol. Energy 144, 681–698.

Kent, M., Schiavon, S., 2020. Evaluation of the Effect of Landscape Distance Seen in Window Views on Visual Satisfaction. Building and Environment, p. 183.

Kim, J., Hong, T., Jeong, J., Koo, C., Jeong, K., 2016. An optimization model for selecting the optimal green systems by considering the thermal comfort and energy consumption. Appl. Energy 169, 682–695.

Klemm, W., Heusinkveld, B.G., Lenzholzer, S., Jacobs, M.H., Van Hove, B., 2015a. Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. Build. Environ. 83, 120–128.

Klemm, W., Heusinkveld, B.G., Lenzholzer, S., van Hove, B., 2015b. Street greenery and its physical and psychological impact on thermal comfort. Landsc. Urban Plann. 138, 87–98.

Koc, C.B., Osmond, P., Peters, A., 2016. A green infrastructure typology matrix to support urban microclimate studies. Procedia Eng. 169, 183–190.

Kong, L., Lau, K.K.-L., Yuan, C., Chen, Y., Xu, Y., Ren, C., Ng, E., 2017. Regulation of outdoor thermal comfort by trees in Hong Kong. Sustain. Cities Soc. 31, 12–25.

Lai, D., Guo, D., Hou, Y., Lin, C., Chen, Q., 2014. Studies of outdoor thermal comfort in northern China. Build. Environ. 77, 110–118.

Lai, D., Liu, W., Gan, T., Liu, K., Chen, Q., 2019. A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Sci. Total Environ. 661, 337–353.

Lam, C.K.C., Lee, H., Yang, S.-R., Park, S., 2021. A review on the significance and perspective of the numerical simulations of outdoor thermal environment. Sustain. Cities Soc. 71, 102971.

Lee, S.-H., Baik, J.-J., 2010. Statistical and dynamical characteristics of the urban heat island intensity in Seoul. Theor. Appl. Climatol. 100, 227–237.

Lee, Y.Y., Kim, J.T., Yun, G.Y., 2016. The neural network predictive model for heat island intensity in Seoul. Energy Build. 110, 353–361.

Lehnert, M., Tokar, V., Jurek, M., Geletic, J., 2020. Summer thermal comfort in Czech cities: measured effects of blue and green features in city centres. Int. J. Biometeorol.

Li, J., Liu, N., 2020. The Perception, Optimization Strategies and Prospects of Outdoor Thermal Comfort in China: A Review. Building and Environment, p. 170.

Li, J.-j., Wang, X.-r., Wang, X.-j., Ma, W.-c., Zhang, H., 2009. Remote sensing evaluation of urban heat island and its spatial pattern of the Shanghai metropolitan area, China. Ecol. Complex. 6, 413–420.

Li, L., Zha, Y., Wang, R., 2020. Relationship of surface urban heat island with air temperature and precipitation in global large cities. Ecol. Indicat. 117.

Lin, Y.-H., Tsai, K.-T., 2017. Screening of tree species for improving outdoor human thermal comfort in a Taiwanese city. Sustainability 9.

Lin, P., Lau, S.S.Y., Qin, H., Gou, Z., 2017. Effects of urban planning indicators on urban heat island: a case study of pocket parks in high-rise high-density environment. Landsc. Urban Plann. 168, 48–60.

Lobaccaro, G., Acero, J.A., 2015. Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons. Urban Clim. 14, 251–267.

Lowe, S.A., 2016. An energy and mortality impact assessment of the urban heat island in the US. Environ. Impact Assess. Rev. 56, 139–144.

Matzarakis, A., Rutz, F., Mayer, H., 2007. Modelling radiation fluxes in simple and complex environments—application of the RayMan model. Int. J. Biometeorol. 51, 323–334.

Mballo, S., Herpin, S., Manteau, M., Demotes-Mainard, S., Bournet, P.E., 2021. Impact of well-watered trees on the microclimate inside a canyon street scale model in outdoor environment. Urban Clim. 37.

Meili, N., Acero, J.A., Peleg, N., Manoli, G., Burlando, P., Fatichi, S., 2021. Vegetation Cover and Plant-Trait Effects on Outdoor Thermal Comfort in a Tropical City. Building and Environment, p. 195.

Meng, X., Yan, L., Liu, F., 2022. A New Method to Improve Indoor Environment: Combining the Living Wall with Air-Conditioning. Building and Environment, p. 216.

Meteorological Service, S., 2020. Past Climate Trends, 2020, assessed 17 September 2020. http://www.weather.gov.sg/climate-past-climate-trends/.

Mijani, N., Alavipanah, S.K., Firozjaei, M.K., Arsanjani, J.J., Hamzeh, S., Weng, Q., 2020. Modeling outdoor thermal comfort using satellite imagery: a principle component analysis-based approach. Ecol. Indicat. 117.

Milošević, D.D., Bajšanski, I.V., Savić, S.M., 2017. Influence of changing trees locations on thermal comfort on street parking lot and footways. Urban For. Urban Green. 23, 113–124.

Morabito, M., Crisci, A., Guerri, G., Messeri, A., Congedo, L., Munafo, M., 2021. Surface urban heat islands in Italian metropolitan cities: tree cover and impervious surface influences. Sci. Total Environ. 751, 142334.

Morakinyo, T.E., Lam, Y.F., 2016. Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. Build. Environ. 103, 262–275.

Morakinyo, T.E., Dahanayake, K.W.D.K.C., Adegun, O.B., Balogun, A.A., 2016. Modelling the effect of tree-shading on summer indoor and outdoor thermal condition of two similar buildings in a Nigerian university. Energy Build. 130, 721–732.

Morakinyo, T.E., Kong, L., Lau, K.K.-L., Yuan, C., Ng, E., 2017. A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. Build. Environ. 115, 1–17.

Morakinyo, T.E., Lau, K.K.-L., Ren, C., Ng, E., 2018. Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. Build. Environ. 137, 157–170.

Moss, J.L., Doick, K.J., Smith, S., Shahrestani, M., 2018. Influence of Evaporative Cooling by Urban Forests on Cooling Demand in Cities. Urban Forestry & Urban Greening.

Neinavaz, E., Skidmore, A.K., Darvishzadeh, R., 2020. Effects of prediction accuracy of the proportion of vegetation cover on land surface emissivity and temperature using the NDVI threshold method. Int. J. Appl. Earth Obs. Geoinf. 85.

Nichol, J., 2005. Remote sensing of urban heat islands by day and night. Photogramm. Eng. Rem. Sens. 71, 613–621.

Niu, J., Liu, J., Lee, T.-c., Lin, Z.J., Mak, C., Tse, K.-T., Tang, B.-s., Kwok, K.C.S., 2015. A new method to assess spatial variations of outdoor thermal comfort: onsite monitoring results and implications for precinct planning. Build. Environ. 91, 263–270.

NIWA, 2021. Macroclimate. A MAF sustainable farming fund project. available from. http://www.pagebloomer.co.nz/wp-content/uploads/2009/09/Macroclimate.pdf.

Oke, T.R., 1973. City size and the urban heat island. Atmos. Environ. 7, 769–779, 1967.

Oke, T.R., 2002. Boundary Layer Climates. Routledge.

Onishi, A., Cao, X., Ito, T., Shi, F., Imura, H., 2010. Evaluating the potential for urban heat-island mitigation by greening parking lots. Urban For. Urban Green. 9, 323–332.

Pearcy, R.W., Schulze, E.-D., Zimmermann, R., 2000. Measurement of transpiration and leaf conductance. In: Plant Physiological Ecology. Springer, pp. 137–160.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.

Peres, L.d.F., Lucena, A.J.d., Rotunno Filho, O.C., França, J.R.d.A., 2018. The urban heat island in Rio de Janeiro, Brazil, in the last 30 years using remote sensing data. Int. J. Appl. Earth Obs. Geoinf. 64, 104–116.

Puliafito, S.E., Bochaca, F.R., Allende, D.G., Fernandez, R., 2013. Green areas and microscale thermal comfort in arid environments: a case study in Mendoza, Argentina. Atmos. Clim. Sci. 3, 372–384.

Rahman, M.A., Armson, D., Ennos, A.R., 2014. A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. Urban Ecosyst. 18, 371–389.

Rahman, M.A., Moser, A., Rötzer, T., Pauleit, S., 2019. Comparing the transpirational and shading effects of two contrasting urban tree species. Urban Ecosyst. 22, 683–697.

Rahman, M.A., Hartmann, C., Moser-Reischl, A., von Strachwitz, M.F., Paeth, H., Pretzsch, H., Pauleit, S., Rötzer, T., 2020a. Tree cooling effects and human thermal comfort under contrasting species and sites. Agric. For. Meteorol. 287.

Rahman, M.A., Stratopoulos, L.M.F., Moser-Reischl, A., Zölch, T., Häberle, K.-H., Rötzer, T., Pretzsch, H., Pauleit, S., 2020b. Traits of Trees for Cooling Urban Heat Islands: A Meta-Analysis. Building and Environment, p. 170.

Ren, G.Y., Chu, Z.Y., Chen, Z.H., Ren, Y.Y., 2007. Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. Geophys. Res. Lett. 34.

Rinchumphu, D., Phichetkunbodee, N., Pomsurin, N., Sundaranaga, C., Tepweerakun, S., Chatchawan, C., 2021. Outdoor thermal comfort improvement of campus public space. Adv. Technol. Innovat.

Rogan, J., Ziemer, M., Martin, D., Ratick, S., Cuba, N., DeLauer, V., 2013. The impact of tree cover loss on land surface temperature: a case study of central Massachusetts using Landsat Thematic Mapper thermal data. Appl. Geogr. 45, 49–57.

Shahidan, M.F., Shariff, M.K., Jones, P., Salleh, E., Abdullah, A.M., 2010. A comparison of Mesua ferrea L. and Hura crepitans L. for shade creation and radiation modification in improving thermal comfort. Landsc. Urban Plann. 97, 168–181.

Sharma, R., Pradhan, L., Kumari, M., Bhattacharya, P., 2021. Assessing urban heat islands and thermal comfort in Noida City using geospatial technology. Urban Clim. 35.

Sharmin, T., Steemers, K., Matzarakis, A., 2015. Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh. Build. Environ. 94, 734–750.

Shirani-bidabadi, N., Nasrabadi, T., Faryadi, S., Larijani, A., Shadman Roodposhti, M., 2019. Evaluating the spatial distribution and the intensity of urban heat island using remote sensing, case study of Isfahan city in Iran. Sustain. Cities Soc. 45, 686–692.

Singh, P., Kikon, N., Verma, P., 2017. Impact of land use change and urbanization on urban heat island in Lucknow city, Central India. A remote sensing based estimate. Sustain. Cities Soc. 32, 100–114.

Siu, L.W., Hart, M.A., 2013. Quantifying urban heat island intensity in Hong Kong SAR, China. Environ. Monit. Assess. 185, 4383–4398.

Sodoudi, S., Zhang, H., Chi, X., Müller, F., Li, H., 2018. The influence of spatial configuration of green areas on microclimate and thermal comfort. Urban For. Urban Green. 34, 85–96.

Spangenberg, J., Shinzato, P., Johansson, E., Duarte, D., 2008. Simulation of the Influence of Vegetation on Microclimate and Thermal Comfort in the City of São Paulo. Revista da Sociedade Brasileira de Arborizacao Urbana.

Srivanit, M., Jareemit, D., 2020. Modeling the influences of layouts of residential townhouses and tree-planting patterns on outdoor thermal comfort in Bangkok suburb. J. Build. Eng. 30.

Sun, S., Xu, X., Lao, Z., Liu, W., Li, Z., Higueras García, E., He, L., Zhu, J., 2017. Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation. Build. Environ. 123, 277–288.

Taleghani, M., Sailor, D., Ban-Weiss, G.A., 2016. Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. Environ. Res. Lett. 11.

Teshnehdel, S., Akbari, H., Di Giuseppe, E., Brown, R.D., 2020. Effect of Tree Cover and Tree Species on Microclimate and Pedestrian Comfort in a Residential District in Iran. Building and Environment, p. 178.

Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. Int. J. Climatol. 27, 1983–1993.

Tien Nguyen, T., 2020. Landsat time-series images-based urban heat island analysis: the effects of changes in vegetation and built-up land on land surface temperature in summer in the hanoi metropolitan area, Vietnam. Environ. Nat. Resour. J. 18, 177–190.

United Nations, D.o.E.a.S.A., Population Division, 2014. World Urbanization Prospects: the 2014 Revision, CD-ROM Edition [Online], Available from. https://esa.un.org/unpd/wup/CD-ROM.

Vez, J.P.M., Guez, A.R., Nez, J.I.J., 2000. A study of the urban heat island of granada. Int. J. Climatol. 20, 899–911.

Wang, J., Guo, W., Wang, C., Yao, Y., Kou, K., Xian, D., Zhang, Y., 2021a. Tree Crown Geometry and its Performances on Human Thermal Comfort Adjustment. Jounral of Urban Management.

Wang, J., Guo, W., Wang, C., Yao, Y., Kou, K., Xian, D., Zhang, Y., 2021b. Tree crown geometry and its performances on human thermalcomfort adjustment. J. Urban Manag. https://doi.org/10.1016/j.jum.2021.02.001.

Wang, X., Li, H., Sodoudi, S., 2022. The Effectiveness of Cool and Green Roofs in Mitigating Urban Heat Island and Improving Human Thermal Comfort. Building and Environment, p. 217.

Ward, R.D., 1914. A NOTE ON THE CLASSIFICATION OF CLIMATES, 46. Bulletin of the American Geographical Society of New *York*.

WinSCANOPY, 2017. WinSCANOPY 2017a for Canopy Analysis. Regent Instrument Inc. [online], Available at: https://regentinstruments.com/.

Wu, D., Wang, Y., Fan, C., Xia, B., 2018. Thermal environment effects and interactions of reservoirs and forests as urban blue-green infrastructures. Ecol. Indicat. 91, 657–663.

Xiong, Y., Zhang, J., Xu, X., Yan, Y., Sun, S., Liu, S., 2020. Strategies for improving the microclimate and thermal comfort of a classical Chinese garden in the hot-summer and cold-winter zone. Energy Build. 215.

Xu, M., Hong, B., Jiang, R., An, L., Zhang, T., 2019. Outdoor thermal comfort of shaded spaces in an urban park in the cold region of China. Build. Environ. 155, 408–420.

Yan, H., Dong, L., 2015. The impacts of land cover types on urban outdoor thermal environment: the case of Beijing, China. J. Environ. Health Sci. Eng. 13, 43.

Yan, H., Wu, F., Dong, L., 2018. Influence of a large urban park on the local urban thermal environment. Sci. Total Environ. 622–623, 882–891.

Yang, F., 2009. The Effect of Urban Design Factors on the Summertime Heat Islands in High-Rise Residential Quarters in Inner-City Shanghai. HKU Theses Online (HKUTO).

Yang, F., Lau, S.S.Y., Qian, F., 2011. Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate. Architect. Sci. Rev. 54, 285–304.

Yang, Y., Zhou, D., Gao, W., Zhang, Z., Chen, W., Peng, W., 2018. Simulation on the impacts of the street tree pattern on built summer thermal comfort in cold region of China. Sustain. Cities Soc. 37, 563–580.

Zeng, F., Lei, C., Liu, J., Niu, J., Gao, N., 2020. CFD simulation of the drag effect of urban trees: source term modification method revisited at the tree scale. Sustain. Cities Soc. 56.

Zeng, P., Sun, F., Liu, Y., Tian, T., Wu, J., Dong, Q., Peng, S., Che, Y., 2022. The Influence of the Landscape Pattern on the Urban Land Surface Temperature Varies with the Ratio of Land Components: Insights from 2D/3D Building/vegetation Metrics, 78. Sustainable Cities and Society.

Zhang, J., Gou, Z., 2021. Tree Crowns and Their Associated Summertime Microclimatic Adjustment and Thermal Comfort Improvement in Urban Parks in a Subtropical City of China, 59. Urban Forestry & Urban Greening.

Zhang, Y., Odeh, I.O.A., Ramadan, E., 2012. Assessment of land surface temperature in relation to landscape metrics and fractional vegetation cover in an urban/peri-urban region using Landsat data. Int. J. Rem. Sens. 34, 168–189.

Zhang, J., Gou, Z., Shutter, L., 2019. Effects of internal and external planning factors on park cooling intensity: field measurement of urban parks in Gold Coast, Australia. AIMS Environ. Sci. 6, 417–434.

Zhang, G., He, B.-J., Dewancker, B.J., 2020a. The Maintenance of Prefabricated Green Roofs for Preserving Cooling Performance: A Field Measurement in the Subtropical City of Hangzhou, China, 61. Sustainable Cities and Society.

Zhang, J., Gou, Z., Zhang, F., Shutter, L., 2020b. A study of tree crown characteristics and their cooling effects in a subtropical city of Australia. Ecol. Eng. 158.

Zhang, G., Wu, Q., He, B.J., 2021. Variation of rooftop thermal environment with roof typology: a field experiment in Kitakyushu, Japan. Environ. Sci. Pollut. Res. Int. 28, 28415–28427.

Zhang, J., Guo, W., Cheng, B., Jiang, L., Xu, S., 2022a. A review of the impacts of climate factors on humans' outdoor thermal perceptions. J. Therm. Biol. 103272.

Zhang, J., Zhang, F., Gou, Z., Liu, J., 2022b. Assessment of macroclimate and microclimate effects on outdoor thermal comfort via artificial neural network models. Urban Clim. 42, 101134.

Zhao, Q., Wentz, E.A., Murray, A.T., 2017. Tree shade coverage optimization in an urban residential environment. Build. Environ. 115, 269–280.

Zhao, Q., Sailor, D.J., Wentz, E.A., 2018. Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. Urban For. Urban Green. 32, 81–91.

Zheng, S., Zhao, L., Li, Q., 2016. Numerical simulation of the impact of different vegetation species on the outdoor thermal environment. Urban For. Urban Green. 18, 138–150.

Zheng, S., Guldmann, J.-M., Liu, Z., Zhao, L., 2018. Influence of trees on the outdoor thermal environment in subtropical areas: an experimental study in Guangzhou, China. Sustain. Cities Soc. 42, 482–497.

Zhong, J., Liu, J., Xu, Y., Liang, G., 2022. Pedestrian-level gust wind flow and comfort around a building array–Influencing assessment on the pocket park. Sustain. Cities Soc. 83 https://doi.org/10.1016/j.scs.2022.103953.

Zhou, D., Bonafoni, S., Zhang, L., Wang, R., 2018. Remote sensing of the urban heat island effect in a highly populated urban agglomeration area in East China. Sci. Total Environ. 628–629, 415–429.

Ziter, C.D., Pedersen, E.J., Kucharik, C.J., Turner, M.G., 2019. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proc. Natl. Acad. Sci. U. S. A. 116, 7575–7580.

Zölch, T., Rahman, M.A., Pfleiderer, E., Wagner, G., Pauleit, S., 2019. Designing public squares with green infrastructure to optimize human thermal comfort. Build. Environ. 149, 640–654.