Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4

Zhixin Liu[a], Wenwen Cheng[b], C.Y.Jim[c], Tobi Eniolu Morakinyo[d], Yuan Shi[a], Edward Ng[a,e]

a. Institute of Future Cities, The Chinese University of Hong Kong, New Territories, Hong Kong
b. College of Architecture, the University of Oklahoma, Oklahoma, USA
c. Department of Social Sciences, The Education University of Hong Kong, New Territories, Hong Kong
d. School of Geography, University College Dublin, Dublin, Ireland
e. School of Architecture, The Chinese University of Hong Kong, New Territories, Hong Kong

Abstract

Urban green and blue infrastructures (GBI) are considered an effective tool for mitigating urban heat stress and improving human thermal comfort. Many studies have investigated the thermal effects of main GBI types, including trees, green roofs, vertical greenings, and water bodies. Their physical characteristics, planting designs, and the surrounding urban-fabric traits may impact the resultant thermal effects. ENVI-met, a holistic three-dimensional modeling software which can simulate the outdoor microclimate in high resolution, has become a principal GBI research tool. Using this tool, the GBI studies follow a three-step research workflow, i.e., modeling, validation, and scenario simulation. For providing a systematic and synoptic evaluation of the extant research workflow, a comprehensive review was conducted on GBI-targeted studies enlisting ENVI-met as the primary tool. The findings of 79 peer-reviewed studies were analyzed and synthesised for their modeling, validation, and scenario simulation process. Special attention was paid to scrutinising their data sources, evaluating indicator selection, examining main analytical approaches, and distilling recommendations to improve the research workflow. This review provides researchers with an overview of the ENVI-met methodology and recommendations to refine research on GBI thermal effects.

Keywords

ENVI-met simulation; vegetation modeling, urban green and blue infrastructure; urban thermal environment; human thermal comfort; planting design

1. Introduction

Many cities suffer from severe heat stress because of the urban heat island (UHI) effect caused jointly by global warming and intensive urbanization, imposing a major environmental challenge [1]. UHI may considerably increase summer temperatures in megacities, with intensified duration and frequency of hot days and extreme heat stress [2, 3]. The menace of accumulated heat may bring multiple negative impacts such as compromised thermal comfort [4, 5], excess heat-related morbidity and mortality [6-8], degraded air quality [9-11], additional cooling energy consumption, and collateral economic and social costs [12, 13].

Climate-sensitive urban design offers a sustainable solution to urban overheating. It involves a combination of innovative choices including urban fabric, urban morphology, and re-integration of urban green and blue infrastructures (GBI) of trees, shrubs, herbs, green-roofs, vertical greenings and water bodies [14]. In particular, urban greenery has been identified as one of the most effective countermeasures due to cooling by shading, guiding airflows, intercepting precipitation, and evapotranspiration [15-24]. Water bodies can cool the overlying and adjoining air through evaporation and convection [25-28]. The direct and spillover cooling effects of urban GBI have been extensively documented in previous reviews [29-40].

Traditionally, assessing the thermal effect of GBI is achieved using field monitoring approaches with relevant meteorological instruments. With significant advancements in computation resources in recent decades, numerical simulation has gradually become one of the principal GBI research approaches [32, 33, 41-44]. EBM(Energy Balance Models)-based models including RayMan, SOLWEIG, green-CTTC, TEB-Veg, and CFD (Computational Fluid Dynamic)-based models including OpenFOAM, FLUENT, STAR-CCM+, PHOENICS, ENVI-met are commonly used numerical simulation applications [45]. Compared to EBM-based models, CFD-based models have two advantages: their explicit coupling simulation capability and high-resolution [46]; and have been applied in more urban GBI-related studies [45]. Among them, different CFD-based models treat urban GBI in different ways: For plant description, PHOENICS and FLUENT use the so-called Ideal canopy model, which only represents a tree by its crown height, trunk height, and basic plant canopy geometry such as the spherical, oval, and conical. OpenFOAM, the FOLIAGE module of PHOENICS, and the Simple Plant module of ENVI-met use the Statistical method, associating LAI with the plant morphology. ENVI-met 3D-Plant module uses the Geometry method, discretizing the tree crown by mesh generation and defining each plant’s own specific shape and spatial position [45]. For plant calculation, plants are considered as porous media for their aerodynamic effects in most CFD-based models, including PHOENICS, FLUENT, OpenFOAM, STAR-CCM+, and ENVI-met. For radiation effects, tree canopies are treated as semi-transparent materials with different light transmittance due to their structural geometry and crown density settings in some CFD-based models such as OpenFOAM, FLUENT, ENVI-met [45, 46].

Among the above-mentioned CFD-based models, the ENVI-met, a holistic three-dimensional microclimate CFD model developed by Michael Bruse in 1998 [47-49], has been used by more than half of the vegetation thermal effect simulations [45]. Based on the principles of fluid mechanics, thermodynamics, and atmospheric physics laws, ENVI-met can simulate the surface-plant-air interactions in an urban environment. A unique feature of ENVI-met is the detailed vegetation model [50], in which plants are not only symbolized as a porous media to solar insolation and wind flow, but could actually interact with the surrounding environment by evapotranspiration [22]. With a high spatial resolution, the physiological vegetation processes can be evaluated and vegetation can be represented in a very detailed manner, enabling multiple scenario comparisons that are otherwise impossible in the real world [32].

With the continual advancements of ENVI-met, the modeling and calculation of the vegetation model have experienced notable improvements. In V3, plants are modeled as vegetation columns and are unable to characterize the tree shape[51, 52]. With several minor patch versions, ENVI-met V4.0 was released in 2014, and it allows vegetation modeling in two ways: *simple plants* and *3D-plants*. The former is similar to the 1D vegetation models in V3, and the latter has the ability to digitize complex tree crown and tree root by clusters of cells with a LAD (leaf area density) and RAD (root area density) [50] . The new function, the plant-as-object model in V4, allows aggregating all calculation processes of trees as a whole, making the *3D-plant* a complete organism [50, 52].

For the application of ENVI-met vegetation models, Tsoka et al. [33] reviewed ENVI-met and the thermal performance of urban greenery. They performed a meta-analysis of the ENVI-met evaluation and simulation results, assessing model accuracy and indicating the cooling potential of urban greenery. However, this review focused on the reported data and excluded research methods such as the critical vegetation modeling process.

From the research process perspective, most ENVI-met-based GBI research in recent years usually follows a three-step research workflow, i.e., modeling, validation, and scenario simulation, which is universal in numerical-simulation-related research. These systematic procedures influence the accuracy of simulation results and the validity of the simulation-based design recommendations. Although the related intensive studies have followed the three-step research approach, the following issues have remained outstanding:

(1) Modeling

A holistic technique of vegetation modeling is lacking. With the ENVI-met updates, the differences in vegetation modeling among the versions has become apparent. Due to the complexity and diversity of modeling input data, the GBI-related researchers face a time-consuming task in gleaning and processing the required data. The data acquisition for vegetation modeling input needs to be rationalized and standardized.

(2) Validation

It has been a consensus to conduct validation before scenario simulation. For studies focusing on GBI thermal effects, the validation should encompass the integrated thermal environment, as well as the ENVI-met simulation performance of GBI itself. A detailed GBI-targeted validation analysis is needed. Moreover, for some validation setting details, the selection of microclimate parameters needs to be scrutinized because inappropriate selections of variables and statistical metrics may bias the validation results.

(3) Scenario simulation

Concerning the analysis of scenario simulation results, the main analytical aspects of previous studies need to be expressed in-depth to enhance understanding of the research field. Furthermore, to improve comparisons with related studies, the most frequently used analytical approaches, evaluation indicators, and selection criteria can be explained. However, this essential step is often lacking.

This study conducts a comprehensive review to synthesize the three research steps of ENVI-met GBI studies and analyze the overall state of the research to resolve the critical issues mentioned above. This review aims to provide researchers with an overview of methodological aspects to refine future research concerning modeling, targeted validation, and systematic simulation analysis. Considering ENVI-met V4 has been released for about six years (since 2014) with significant updates for its vegetation modeling and calculation methods, this review concentrates on ENVI-met V4 and above. Due to the different modeling settings of individual studies, this review will not focus too much on the absolute values of validation and scenario simulation results. Instead, more attention is given to their analytical approaches.

2. Methods

This study employed five major bibliographic databases to extract the relevant papers, including JSTOR, ProQuest, Web of Science, PubMed, and Scopus. Combinations of relevant keywords (such as ‘ENVI-met’, ‘green*’, ‘tree*’, ’vegetation*’, ‘plant*’, ‘water*’, ‘blue*’) were used to search the references. The inclusion criteria used in the search were: 1) the research objects were urban green or blue infrastructures; 2) the research approaches were mainly ENVI-met simulation using V4 and above; and 3) the research goal was to improve the outdoor thermal environment or human thermal comfort. Furthermore, all included papers were peer-reviewed journal articles written in English.

Three rounds of literature search were conducted to pinpoint the target papers: title review, abstract review, and full-text review (Fig. 1). In total, 635 non-repetitive articles were initially identified, from which 79 articles were chosen. Four strands of information were extracted from the selected articles: the basic bibliographic profile, vegetation modeling, validation, and scenario simulation (Appendix A).

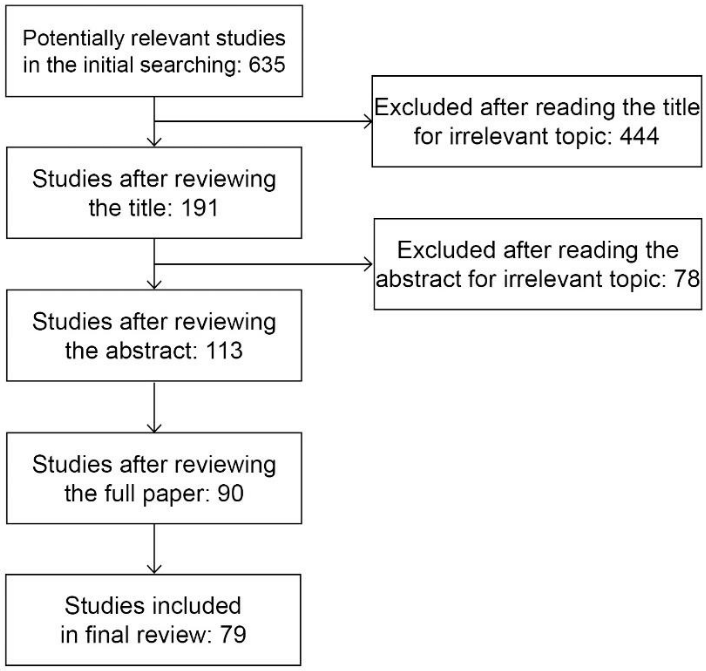

Fig. 1. The literature selection process.

3. Results

3.1. Basic bibliometric profile

Some basic statistics were extracted from the papers. These included the year of publication, journal name, geographical distribution of study area, climate zone, and GBI type. Fig.2 shows the yearly distribution of the studies. There was a continual increase from 2015 to 2020 with most articles (32, 40.51%) published in 2020. The top five journals were *Building and Environment* (11), *Sustainable Cities and Society* (10), *Urban Forestry & Urban Greening* (9), *Sustainability* (6), and *Energy and Buildings* (5).

For geographical distribution, most studies were conducted in Asia and Europe (46, 58.23% and 18, 22.78%, respectively), followed by Africa (9, 11.39%), North America (4, 5.06%), and South America (1, 1.27%) (Fig.3). Research in Asia was generated largely in China (29, 36.71%) with some in Iran (5, 6.33%), the former including 29.11% (23) from mainland China and 7.59% (6) from Hong Kong SAR, China. European studies were mainly conducted in Germany and Italy (6, 7.59% and 4, 5.06%, respectively). Four studies covered more than one city, of which three focused on cities in one continent [20, 53, 54], and one on megacities from different continents [16]. The single-city-based studies concentrated on large cities such as Hong Kong (6), Nanjing (6), and Cairo (5).

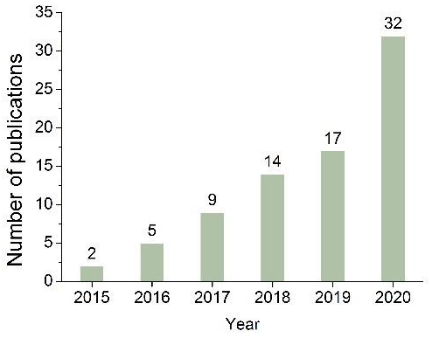

Fig. 2. Yearly distribution of the studies.

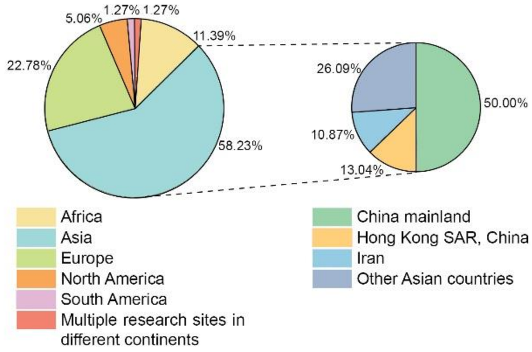

Fig. 3. Geographical distribution of the study areas.

By the Köppen-Geiger climate classification [55], most studies were conducted in the temperate zone (48, 60.76%), followed by the arid zone (14, 17.72%), the cold zone (7, 8.86%), and the tropical zone (6, 7.59%) (Fig.4). In the temperate zone (C), Cfa, Cfb, and Cwa were the most frequently studied locations (27.85%, 13.92%, and 10.13%, respectively), mostly contributed by China mainland and Hong Kong SAR, China. Some studies covered multiple research sites (4, 5.06%) by comparing cities in different climate zones [16, 20, 53, 54].

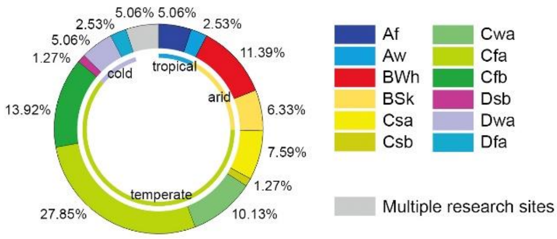

Fig. 4. Distribution of the reviewed studies by Köppen-Geiger climate zones.

3.2. Main types of GBI

Fig. 5 shows the main GBI types investigated by the studies (other landscape elements such as buildings and pavements were not counted here). Approximately two-thirds of the studies focused on only one GBI type. The studies were strongly biased toward trees (27, 34.18%), followed by green roofs (12, 15.19%), vertical greenings (6, 7.59%), and water bodies (4, 5.06%). Grass and shrubs were not investigated as an independent element but usually combined with other GBI types. About one-third of the studies focused on the thermal effects of a combination of different GBI types. Trees with grass (8, 10.13%), trees with green roofs and vertical greenings (5, 6.33%), trees with grass and shrubs (5, 6.33%) were the top combinations. Consequently, trees as the most frequently used GBI type was considered by 69.72% (55) of the studies. The concentration on trees is understandable for their prominent biomass, visual impacts, and effective regulation of the outdoor thermal environment.

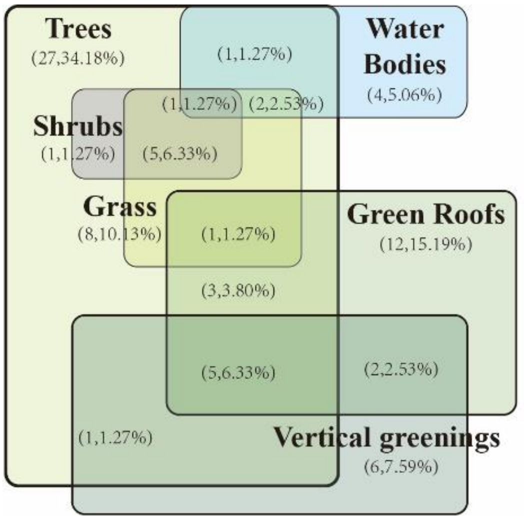

Fig. 5. The GBI research foci of the studies.

3.3. Building models of urban green and blue infrastructures in ENVI-met

3.3.1. Building tree models

ENVI-met V4 allows to build tree models in two ways: *simple plants* and *3D-plants* (Fig. 6 (a)(b)). The former is 1D vegetation model mainly for shrubs and grass, defined by plant height, ten-layers LAD, and ten-layers RAD [51]. It is similar to the vegetation model in V3. For *3D-plants*, a three-dimensional plant editing tool named *Albero* can digitize complex tree models by clusters of cells with a LAD and RAD [50], allowing a plant-as-object simulation such as object-based water access and soil water extraction [50]. Table 1 compares the input parameters of tree modeling between the latest version, V4.4.5 (*3D-plants*), and the previous version V3 (simple vertical structures). Modeling a 3D tree model in ENVI-met V4 and above demands more detailed data on physical traits. Furthermore, in a future version, a new method, Lindenmayer-System, will be implemented in ENVI-met to depict more realistic plants with detailed leaf clusters, branching systems, and plant biomechanics calculations (Fig.6 (c)) [56].

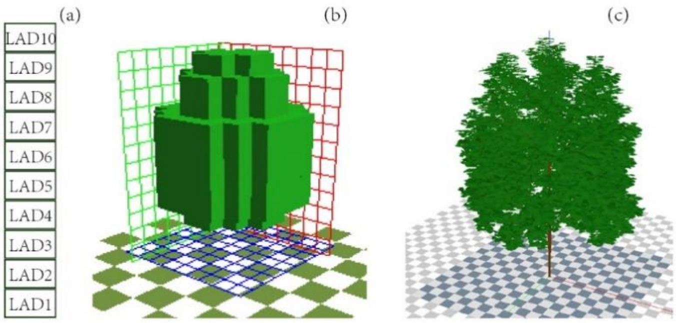

Fig. 6. ENVI-met tree models: (a) *simple plants*; (b) *3D-plants*; and (c) the model using the Lindenmayer-System in a future version [56].

Table 1. The input parameters of tree modeling in ENVI-met V3 and V4.4.5.

Plant parameter	Input variable	V3 [51, 57]	V4.4.5

Tree & crown geometry	Tree height	√	√
	Crown diameter	-	√
Leaf properties	Leaf Area Density (LAD)	√	√
	Leaf type	-	√
	Foliage shortwave albedo	√	√
	Foliage shortwave transmittance	-	√
	Leaf weight	-	√
	Isoprene capacity	-	√
	CO_2 fixation type	√	√
	Tree calendar	-	√
Root geometry	Root Area Density (RAD)	√	√
	Root depth	√	√
	Root diameter	-	√
	Root geometry	-	√

Modeling a 3D tree in ENVI-met V4 needs detailed data on physical traits to build more accurate tree models that can better denote reality. However, due to limitations of time or instruments, most studies simplified the tree modeling process. Four approaches were commonly adopted to acquire physical tree properties, including citing the literature [18, 23, 58-64], measuring representative trees [20, 22, 24, 53, 65-75], parameterizing according to the physical tree characteristics [3, 76-80], and selecting existing tree models from the *Albero* database [19, 28, 81, 82]. For on-site measurements, leaf albedo was mainly obtained from spectrophotometers [83] or two albedometers (e.g. CMP21 pyranometer, Kipp & Zonen, Delft, the Netherlands) [53, 84]. Leaf Area Index (LAI) was obtained from hemispherical photographs captured by cameras with a fisheye lens [22, 24, 67, 75, 85], scanner [77], or plant canopy analyzer (e.g., LAI-2000 or 2200, LI-COR Biosciences, Lincoln, NE, USA) [53, 71, 75, 84]. The distribution of LAD is difficult to measure precisely [86]; however, the following empirical formula from Lalic and Mihailovic [86] can estimate it from LAI and tree height:

$$LAI = \int_0^h LAD.\Delta z \qquad (1)$$

where h is tree height (m), Δz is vertical grid size (m), LAI is leaf area index, and LAD is leaf area density (m^2/m^3).

Furthermore, some databases of tree morphological characteristics have been generated for ENVI-met modeling. Liu et al. [15] measured 152 common tree species in Guangzhou, China, and developed a regression prediction model for general tree morphological characteristics. Asef et al. [87] developed a method mixing direct and indirect measurements to obtain LAI values to build models of common trees in Cairo. These approaches were based on previous studies confirming the strong correlations among tree morphology parameters [88-90].

Some studies do not select specific tree species but parameterize tree models according to generic physical characteristics (tree height, trunk height, foliage density, and crown diameter) [3, 76-80]. For instance, foliage density and tree height can be sub-classified as “dense foliage, moderate foliage, and sparse foliage” and “tall tree, medium tree, and short tree” [3], respectively. Karimi et al. [21] reported that the combinations of physical parameters and their respective sub-forms could permit a more accurate evaluation of the thermal effects of physical tree characteristics.

Modeling individual trees of different species in a study site is time-consuming. In general, representative trees selected from the literature or field observations were commonly used to represent other trees in a study site. Generally, either several representative trees [18, 21, 23, 58-61, 63, 85, 91-99] or only one [96, 100-111] tree were used, depending on the research purposes. For studies that focused on the combined thermal effects of tree planting strategies (i.e., tree arrangement, number of trees, etc.) and geometries of surrounding urban fabric (urban blocks [101, 107, 109], street canyons [102, 103], residential areas [104, 105, 108, 110], etc.), most studies hypothesized with only one representative tree in the study site.

Notably, although the resolution of tree models is 1m×1m×1m in *Albero*, their 3D representation in the *SPACE* modeling area may look different if their resolutions are different. Albero can visualize the new trees at different resolutions, making it possible to set the data for different horizontal and vertical grid sizes [112].

3.3.2. Building green roof and vertical greening models

ENVI-met V4.4 denotes an important division between an indirect expression of green roof/façade and a new green roof/façade module [68]. The previous ENVI-met version did not have a dedicated vertical greening module. Researchers could only append 1D simple plants on the grid before the wall to emulate indirectly the shading and reduced building emission of longwave radiation [22, 113, 114]. However, the resolution of ENVI-met dictates a minimum 0.5 m distance between two grids [115], which deviates considerably from reality. In contrast, the new green roof/façade module since V4.4 can combine the building, greening, and substrate and consider the heat and vapor exchanges within and between the greenery and substrate layers. The detailed vegetation and substrate type of green roof/façade can be edited in the *Greening* section of the database manager. The main input parameters include LAI, plant thickness, and leaf angle distribution [68]. Notably, even in V4.4 and above, all the plants, including tree models on the green roof, are *simple plants*. The substrate properties include emissivity, albedo, water coefficient of substrate for plants, air gap width between substrate and wall.

Most reviewed studies used the previous ENVI-met versions (before V4.4 but at least V4.0) without the new green roof/facade module. Therefore, the properties of green roof/façade in these studies were mainly represented by LAI, plant height, albedo, and soil depth. LAI and plant height were the most frequently used input parameters [61, 77, 113, 116] usually representing the characteristics of intensive [16, 75, 93, 117] and extensive [16, 65, 75, 84, 117] green roofs. However, many reviewed studies lacked explanations for setting or assuming LAI and plant height values [65, 93, 103, 116-118]. Moreover, some studies did not provide any modeling descriptions, because they focused mainly on the coverage ratio of green roofs [106, 115, 119] or vertical greenings

[120] or their combinations [92, 121], not the greening type itself.

ENVI-met V4.4 and above allows more detailed green roof/façade modeling. Aboelata et al. [122] built models for intensive and extensive green roofs by obtaining data on root depth, plant height, plant width, plant form, and leaf weight from a plant guidebook. To model the local green façade more accurately, Peng et al. [68, 123] obtained the LAD and leaf albedo from field measurements. They adopted the plant transmittance from the default values of three related species.

3.3.3. Building urban blue infrastructure models

Water bodies in ENVI-met are represented as a special soil type partly transparent to shortwave radiation [25]. Users can define its thermal properties in ENVI-met Database Manager, i.e. setting the heat capacity, heat conductivity, among others. For water depth setting, users can link water with a user-defined profile on the "profile" section in Database Manager, defining as water or water ground surface (sediment) material at different depths. The calculated processes inside the water include the transmission and absorption of shortwave radiation inside the water [25]. However, no second energy balance and no additional boundary conditions are respectively used for the water ground surface (sediment) and water bodies themselves. Therefore, the water grids are considered deep enough to allow attenuation of nearly all shortwave radiation inside the water bodies [25].

In ENVI-met V4.0 and above, water spray simulation, including fountains and water mist cooling is supported [33]. The default water fountain is a point source in 4m height. The placing height and source geometry (point, line, area) can be specified by the user. Also, ENVI-met includes the possibility to model water sprayed into the local atmosphere as a specific ‘‘particle dispersing source" [124]. The water nozzles can be inserted in the model as punctual "water sources" at the center of the grid cells [124]. The water source's features such as partical diameter and particle density were managed in the section ‘‘pollutant conditions" of the project advanced settings in ENVI-met [124].

3.3.4. Building background urban environment models

To build models of the urban background environment, approximately two-thirds of the studies employed case studies, namely real and particular place as the fundamental background environment. This method is commonly used in targeted research, analyzing whether a specific site's planting design can provide enough thermal comfort and determine the most effective modifications [18]. However, the conclusions from case studies have limited generality because their applicability to other locations is unknown [15].

About one-third of the reviewed studies used idealized environmental models. The physical characteristics of study areas, e.g., the aspect ratio of street canyons and building density of urban blocks were extracted from which some general findings can be distilled. To outline the morphological features of the studied areas, Liu et al. [15] and Rui et al. [104] summarized the morphological characteristics of residential areas from field measurements. They set up abstract models from statistical results. Peng et al. [123] developed some idealized urban blocks based on a spatial and statistical analysis of more than 13,000 realistic city blocks via ArcGIS. Furthermore, Morakinyo et al. [3, 22] combined parametric and case studies in one comprehensive research, which offers the advantages of both approaches.

3.4. Validation of ENVI-met'surban green and blue infrastructure models

3.4.1. Significance of validation

Although previous research have specifically evaluated the ENVI-met vegetation model [50, 52, 83, 112, 125, 126], a comprehensive validation must be made before conducting a simulation study for two reasons. First, while ENVI-met has a solid physical foundation [47, 48, 50, 51], simulation still cannot fully represent the real world because of the use of "approximations" [110]. To shorten simulation time, ENVI-met simplifies some calculations of vegetation models:

1) Radiation

- Plants do not influence the reflected shortwave radiation (i.e., tree canopies are neither considered as reflecting objects nor as obstructions to wall-reflected shortwave fluxes) [51].
- Plants do not influence the diffused shortwave radiation (i.e., shortwave radiation cannot be absorbed when passing through vegetation, and there is no scattering of direct shortwave radiation) [51].
- The shortwave radiation scattered upwards by the ground and vegetation is not taken into account [51].
- The incoming longwave radiation emitted by nearby plants and surfaces is not calculated based on the temperature of the single surfaces and leaves within the field of view, but instead on an average temperature [51]. As Huttner [51] noted, this may underestimate shaded areas or overestimate sunlit areas because ENVI-met will assign the same amount of emitted longwave radiation to both shaded and sunlit facades.

2) Evapotranspiration

- The heat convection between the leaf surface and surrounding air and the radiation heat transfer between the leaf surface, sky, and ground surfaces are not taken into account [51].
- The heat storage for leaves is not taken into account [50].

With these simplifications, how ENVI-met vegetation models perform in each study must be validated before conducting scenario simulations. Second, the existing evaluations primarily focused on common local tree species with characteristics that differ significantly from other studies. The special features, especially tree-crown geometries, leaf properties, generated tree models with quite different thermal effects in different study areas. Such results demand validation to assess the reliability of current simulation results and avoid misjudgment [83, 127].

3.4.2. Validation variables

Validation through in-situ measurements is vital, and 72.15% (54) of the reviewed literature did so. The information, including the evaluation parameters, calculated statistical metrics and temporal period, was extracted for this current study (cf. Appendix B). Air temperature (Ta) was the most frequently evaluated meteorological variable (50, 92.59% among the studies with validation), followed by relative humidity (RH, 15, 27.78%) and mean radiant temperature (Tmrt, 7, 12.96%). Surface temperature (Ts), wind speed (WS), solar radiation (SR), longwave radiation (LR), and physiological equivalent temperature (PET) were chosen by less than 10% of the validated studies. The instruments for measuring Ta and RH are relatively easy to obtain. Before *full forcing* was offered in V4.4 [127], *simple forcing* could only allow dynamic changes in the inflow values of Ta and RH [112]. Also, neither the observed SR nor WS can be matched hourly using the *simple forcing*, i.e., SR can only be adjusted from the built-in data by the adjustment factor (0.5-1.5) [51, 83, 128], and wind information (both speed and direction) can remain static throughout the simulation time based on the initial input value.

Notably, the diversity of Tmrt estimation methods may cause some deviations. ENVI-met calculates Tmrt for a cylindrically-shaped body, using the incoming longwave and shortwave radiation [129]. In some studies, Tmrt was generally estimated based on a global temperature measurement [3, 22, 24, 95, 97, 107] or six individual shortwave and longwave radiant flux measurements [130]. Therefore, when selecting Tmrt as the ENVI-met validation variable, the deviation between different calculation methods should be noted.

3.4.3. Statistical metrics

Except for a few studies that only used a simple comparison [81, 108], most studies with validation have applied statistical metrics. Thirty-five (64.81%) studies with validation used the coefficient of determination R^2, a key output of regression analysis describing the proportion of the total variance explained by a model [131]. Other commonly used metrics were RMSE (Root Mean Square Error, 31, 57.41%), *d* (index of agreement, 13, 24.07%), and MAE (Mean Absolute Error, 9，16.67%). The sub-level metrics of RMSE, i.e., RMSEs (Systematic Root Mean Square Error) and RMSEu (Unsystematic Root Mean Square Error), and MBE (Mean Bias Error), MAPE (Mean Absolute Percentage Error), NMSE (Normalized Mean Squared Error) were also used. However, only about 10% of the validated studies chose them. Detailed definitions of the above statistical metrics and their advantages and disadvantages for model evaluation can be found in previous studies [131-134]. Most of the reviewed studies employed two or three metrics, but some [20, 22, 75, 77, 92, 95, 116, 121] chose only R^2. Willmott et al. [133] remarked that this might result in misjudgment because R^2 can only assess the overall model performance. The value of R^2 does not verify that the simulated and observed values are consistent; its magnitude is not often related to the size of the differences between observation and simulation values [133].

3.4.4. Reported validation results of the vegetation model

Almost all the validation studies have confirmed the general reliability of ENVI-met. Even though the research topics were focused on GBI, most validation studies only compared several pairs of measured and observed points in an integrated thermal environment, rather than conducting a GBI-targeted validation. Only some studies performed the targeted validation and compared the results among open areas, vegetated areas, and their differences [3, 22, 24, 67, 68, 77, 95, 113, 123]. These study evaluated trees, green facades, and simple plants, including the parameters of Ta, Tmrt, RH, TS, etc. Particularly, Li et al. [67] evaluated the vertical Ta distribution from the ground surface to 2-m height in the open space and under the tree canopy and reported that the closer to the ground surface, the greater the differences between measured and simulated Ta under the canopy. Appendix C shows the GBI-targeted validation results. In most cases, the simulation performance in vegetated areas was slightly better than those in open areas [3, 22, 24, 68, 95, 123] (except some validation results of green façade [113, 123] and *simple plants* [77]).

Summarized from the reviewed studies, as well as the previous evaluations which focused on the simulation performance of GBI [50, 52, 83, 112, 125, 126], deviations between simulated and observed values may occur due to three reasons:

1) ENVI-met limitations:

- ENVI-met simplified tree model calculation methods (mentioned in 3.4.1)
- The hypothesis of static cloud and wind conditions in *simple forcing*

2) Modeling assumptions:

- The assumed rather than measured modeling input data due to the lack of scientific monitoring using instruments [3, 22, 24, 112, 113, 125, 135-137], including the thermal properties of surrounding buildings (e.g., emissivity, thermal conductivity, specific heat capacity, absorption coefficient of walls, etc.) and the properties of trees (e.g., foliage albedo, LAD, and root geometry).
- The simplified rotary tree crown models in *Albero* [83].
- Study domain trees' generalization: For a complex urban environment, choosing some typical vegetation on behalf of the study area's vegetation systems may also introduce a certain level of uncertainty [137].

3) Unsystematic errors from experimental operations:

- The anthropogenic heat generated by humans, vehicles, and mechanical cooling systems is not accounted for in ENVI-met [3, 22, 24, 138].
- The transmitted solar energy through a non-uniform canopy may overestimate SR, which would not occur in the simulation [83].
- The measurement error of LAD may influence the foliage distribution and may also introduce uncertainty [137].
- The initialization data of Ta and RH sometimes were obtained from nearby weather stations, which may be different from the experimental site [33].

For the differences between open and vegetated sites, the simulated reduction of both Ta and Tmrt under tree canopy were less significant than the observed values [22, 83]. This result may occur due to two reasons. First, ENVI-met can reflect the general trends well, but the simulation fluctuation is always more stable than the observation [139]. Second, as noted in previous validations [136], ENVI-met tends to overestimate the Ta of the ground layer, especially in tree-shaded areas, which means that the Ta reduction tends to be underestimated.

For the validation of blue infrastructures, most water-related studies just evaluated the overall simulation performance by choosing some comparison points but lacked a targeted validation for water [28, 63, 73, 76, 94]. In particular, Guiseppe et al. [124] focused on water mist cooling and showed a high prediction accuracy for Ta.

3.5. Main analytical aspects of simulation results

The analytical indicators and main analytical aspects of trees, green roofs, vertical greenings and water bodies were illustrated in Fig. 7.

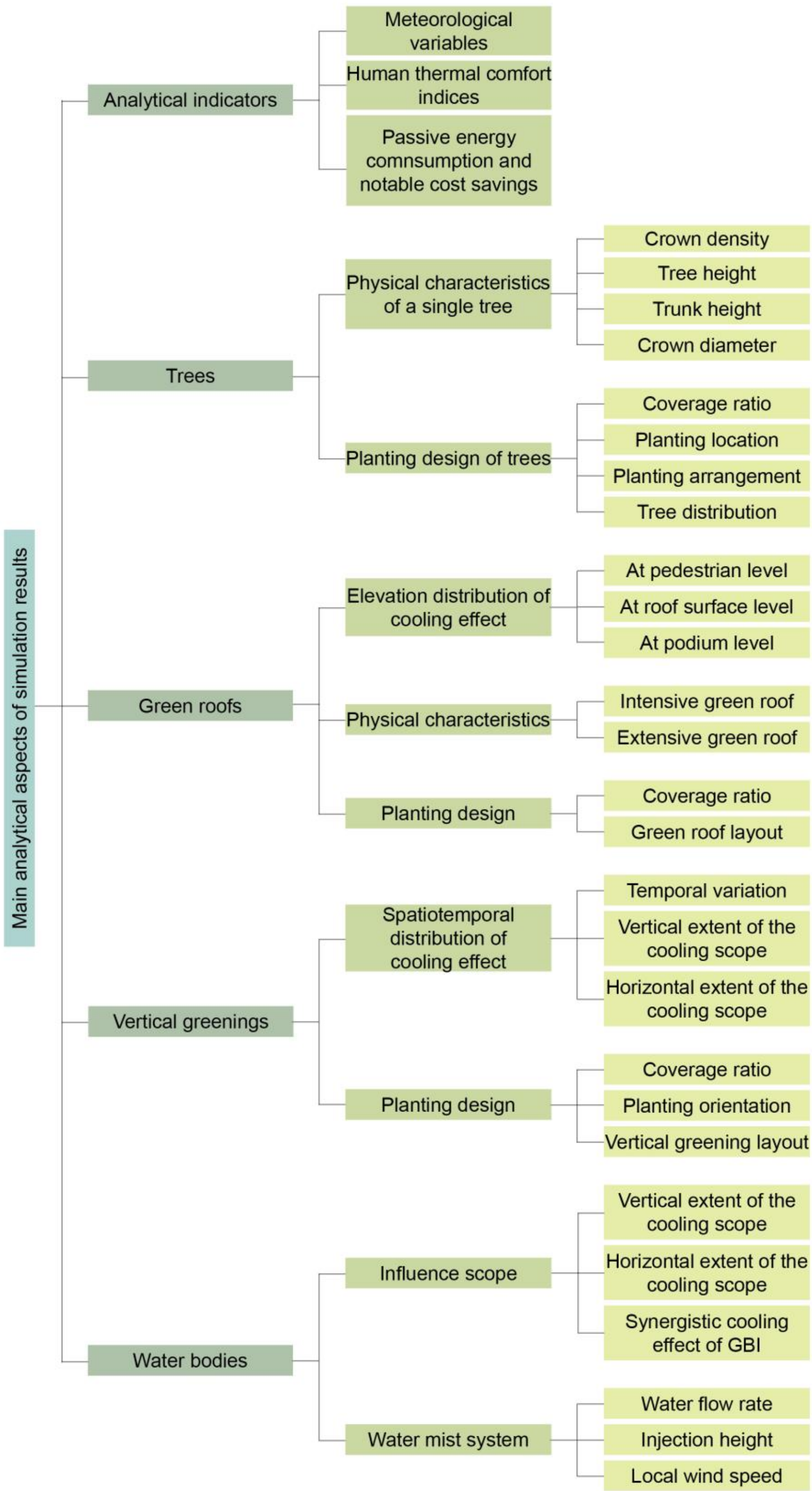

Fig. 7. Main analytical aspects of simulation results

3.5.1. Analytical indicators

a) Meteorological variables

In this study, Ta, Tmrt, RH, and WS were the most frequently used meteorological variables to evaluate the outdoor thermal environment because they can directly reflect microclimate changes [108]. As the most familiar and basic meteorological variable, Ta was selected by almost all studies (70, 88.61%), and 11 studies used Ta as the only analytical variable [54, 61, 65, 75, 106, 116, 118, 124, 140-142]. However, Rahul et al. [28] reported that using only Ta was insufficient for thermal stress investigation. Tmrt with more diverse spatial variations than Ta [66, 102] is strongly influenced by the tree-shading effect and by the human body exposed to shortwave and longwave radiation fluxes (especially direct shortwave radiation) [20, 23]. Because vegetation in ENVI-met is a living organism that interacts with the underlying surface and overlying air [24], the RH's value and distribution are related to the biophysical processes of transpiration and evapotranspiration of vegetation [91, 92]. WS was used as several studies indicated that the vegetation effect on the pedestrian thermal environment and human thermal comfort was associated with wind condition [96].

Most measured and simulated meteorological variables were set at the pedestrian height (typical 1.5 – 2 m). However, green roof studies tend to focuse on the microclimate at the roof or podium level. For temporal variations, representative hours were commonly used. Many studies selected 15:00 data [3, 16, 22, 23, 25, 79, 81, 91, 97, 98, 111, 116, 143] for three reasons. First, 15:00 is often the hottest and most uncomfortable hour in a real situation [16, 25, 81, 91, 97, 98, 116, 143]. Second, the maximum difference between the thermal comfort of open and vegetated areas generally occur at this moment [93]. Third, it is a time that residents tend to engage in outdoor activities [15].

Other studies used different hours. Besides 15:00, 14:00 was viewed as the hottest hour in some studies [18, 19, 63, 65, 68, 78, 93, 101, 124]. The 12:00 data represented the noon scenario [19, 22, 23, 70, 81]. Regarding nocturnal representative hours, 20:00 [25, 65, 101], 00:00 [3, 16] and 05:00 [18, 78] were commonly adopted. However, Wu et al. [72] observed that assessing the thermal status of a continuous period would be more meaningful for outdoor activities planning than a single time point.

b) Human thermal comfort indices

Human thermal comfort indices were computed. In order of usage frequency, they included PET (physiological equivalent temperature) (36, 45.57%), PMV (predicted mean vote) (11, 13.92%), UTCI (universal thermal climate index)(3, 3.80%), COMFA (COMfort FormulA) (1, 1.27%) and TEP (temperature of equivalent perception) (1, 1.27%). The definitions of these indices have been summarized in a paper [144]. The indices can be calculated from the ENVI-met meteorological output values or extracted from BioMet directly, which is a post-processor tool in ENVI-met.

PET was widely selected for four reasons. First, PET embraces comprehensive outdoor microclimate and human elements, making it more acceptable and suitable for assessing outdoor human thermal comfort. It is a function of four main meteorological variables of Ta, RH, WS, and Tmrt. Tmrt considers radiation fluxes on body heat balance from all possible directions and wavelengths (including shortwave and longwave radiation) [3, 22-24, 74, 85, 93, 97, 102, 110, 113]. For human elements, PET considers gender, height, age, weight, clothing heat resistance, and metabolic heat [97, 110, 145]. Second, PET is the most widely used index in urban climatology [78, 93, 101, 102], and recommended by German guidelines for urban and regional planners [99, 101, 111]. As diverse studies have used PET to evaluate the thermal environment, researchers can compare different regions and climate zones. Third, many previous subjective thermal sensation studies have developed human thermal sensation scales for different regions and climate zones [3, 22, 102], making them more suitable for evaluating the human thermal sensation. Fourth, expressed in Celsius (°C), the results are comprehensible to people who may not be familiar with human-biometeorological terminology [93, 145, 146].

PMV is also a frequently used index chosen for three reasons. First, meteorological variables of Ta, RH, WS, and Tmrt, and personal factors (e.g., clothing heat resistance and human activity) are considered comprehensively [20, 71, 104, 147]. By extending the clothing and activity factors and radiation fluxes (including shortwave and longwave radiation), the indoor PMV index can be applied to the outdoor environment [18, 20, 147]. Second, it has been adopted worldwide and used in various studies [18, 147, 148], making it easy to compare different studies. Third, the PMV numerical results denote directly human thermal sensation and do not need categories or scales. However, in some extreme thermal conditions, the calculated PMV value may be above +4. This means that although the result is numerically correct, it is off-scale vis-à-vis the original Fanger experimental data (-4 to +4) [105]. For this reason, the ENVI-met website suggests using PET as a thermal comfort scale (see, https://envi-met.info/doku.php?id=apps: biomet_pmv).

UTCI was considered better in representing specific climates, weather, locations and depicted temporal variability of thermal conditions [72]. Moreover, UTCI is more sensitive to WS and RH, whereas PET is more sensitive to Tmrt [149]. Therefore, some studies used both UTCI and PET [28, 95]. Only one study chose COMFA because of comprehensive consideration, relatively high scale resolution, and detailed human energy budget description [15]. One study chose TEP because it is an index based on a linear equation developed for local conditions [57].

c) Passive energy consumption and notable cost savings

Passive energy-saving performance presents a way to evaluate the cooling effect of GBI. It is commonly estimated from the simulated Ta reduction between open and greened areas at a vertical extent by the equations in some papers [24, 73, 85, 137, 150]. Notably, Morakinyo et al. [24] proposed that the selected vertical calculation extent should fulfill two conditions: higher than the tallest tree in the domain; and shows stability in vertical Ta gradient. In the reviewed studies, at the top of the next vertical grid above the tallest trees [24, 85], mean building height [150], and vertical cooling effect extent from simulation results [73] were also used.

Furthermore, similar to the theoretical estimation approach mentioned above, passive indoor energy saving from vertical greenings can be estimated via ENVI-met simulated indoor air temperature [151]. The energy-saving power (in kWh) and air-conditioner refrigeration power can be converted according to energy conservation values to demonstrate intuitively the cooling efficiency of vertical greenings.

The coupled outdoor-indoor simulation was a further approach to understand the interaction of the outdoor environment with indoor cooling-heating energy demand and the energy-saving effect of GBI. As ENVI-met is not a Building Energy Simulation (BES) tool, DesignBuilder and EnergyPlus are often employed but driven by ENVI-met simulated micro-climate data. Specifically, DesignBuilder, a model for building energy consumption calculation, can connect with ENVI-met using ENVI-met outputted EPW weather files as its input weather data (Ta, WS, and RH are required) [53, 58, 84, 122]. EnergyPlus, an indoor energy use model, can co-simulate with ENVI-met via its outputted EPW weather file as a boundary condition to estimate the energy-saving performance of green roof or vertical greening [16, 64, 100, 123]. Morakinyo et al. [16] reported that using ENVI-met output weather files is more accurate and targeted than using a conventional city's representative EPW file.

Notable cost savings is another evaluation index. Yang et al. [110] compared the economics of different greening patterns by estimate the expense of reducing 1 °C PET, including the purchase and the maintenance prices.

3.5.2. Main analytical aspects of trees

a) Physical characteristics of a single tree

When analyzing the thermal effect from physical characteristics of a tree, crown density, tree height, trunk height, and crown diameter are the main analytical factors.

Crown density is the primary determinant of a tree's heat reduction potential [3, 22, 24, 72], contributing about 60% of Ta reduction [24]. In general, a tree with high foliage density is a high heat mitigator and vice-versa, as confirmed by previous studies [3, 60].

In reality, the number, type, size, and arrangement of leaves affect collectively crown density. In ENVI-met, this combined metric is generally represented by LAI [91], a relatively easy-to-obtained physical characteristic to describe the whole crown's density. The strong positive correlations between LAI and solar radiation attenuation [22-24], and reduction in Ta [23, 78], Tmrt [24, 109], PET [23, 24, 58], and TS [109] under the canopy have been confirmed. However, a tree with a dense crown may block the wind and increase Ta [59], an effect that should be assessed critically. Also, more longwave radiation is trapped at nighttime due to higher LAI, which may lead to less nocturnal cooling beneath tree canopies [22, 102]. Furthermore, crown density distribution per height (i.e., LAD) was investigated for further analysis [15, 20, 23]. The trees with similar LAI but different vertical LAD distribution determined the magnitude of solar attenuation [23].

Tree height was an essential tree parameter for human thermal comfort improvement [22]. Weaker than LAI, a strong and positive correlation among tree height and Tmrt [24] and PET [22] reduction has been confirmed. When trees have the same LAI values, the tallest tree with a broad and scattered crown recorded the most solar attenuation [23].

Trunk height is the distance between the lower surface of the tree crown and the ground. The correlation between trunk height and solar radiation attenuation [23, 24] and PET reduction [23] was not as strong as crown density (LAI). However, it significantly affected the airflow and radiation blocking [21, 24]. Trunk height has a stronger correlation with wind speed than crown density or tree height [24], i.e., a crown at greater height can bring better ventilation [152]. In contrast, for more shading beneath the tree, the crown should be at a lower height [15, 24].

Due to the “umbrella effect” [153], broader tree crowns can provide more shading [15], more TS reduction [21], and more UHI depression [70] than narrower tree crowns. However, a wide tree crown may obstruct wind and ventilation [62].

b) Planting design of trees

Tree planting design is another important element influencing thermal effects [81]. Areas with similar tree cover but different planting design produced different thermal performance [15, 23, 96, 147] due to effects on wind speed, wind direction, and shading pattern [137, 154]. A good tree-planting design embodies the thermal benefits of both ventilation and shading [147].

The tree-planting design includes some key attributes: number of trees (tree coverage ratio) and tree planting patterns (including tree arrangement, planting orientation, intervals among trees, etc.). Additionally, some green indices could reflect the planting pattern quantitatively, such as the landscaping deviation index [105], landscaping isolation index [105], and land shape index [78], etc.

The number of trees in a particular place is generally quantitatively represented by tree coverage ratio (TCR) [95] or green coverage ratio (GCR) [24, 94]. Many reviewed studies confirmed linear correlations between TCR and the surrounding microclimate: a higher TCR lowering Ta [24, 54, 65, 143] and PET [94, 110], and raising RH [81, 146] in the daytime. However, some reviewed studies found that the correlations were non-linear because of WS and RH variations, indicator selection, tree planting pattern, background urban environment, and ENVI-met version [54, 95, 99, 143]. Overall, the impact of trees cannot be considered as *the more, the better*, especially in high-density urban areas [155].

A tree’s thermal contributions may be underutilized if planted in the wrong place, leading to wasted overlapped shadows or airflow blocking [3]. Also, in an urban environment, the background thermal environment was regulated by urban morphology, which may strengthen or weaken the thermal effects of trees. Therefore, planting design should incorporate appropriate tree planting location, arrangement, orientation, and inter-tree interval to optimize the shaded area and improve ventilation.

To increase the shaded area and reduce nocturnal trapping of longwave radiation [15, 95, 98], tree arrangement had been considered. Compared with the clustered and random patterns, the equal-interval arrangement (square or triangular pattern) showed better Ta and Tmrt reduction, and human thermal comfort improvement [15, 81, 98]. This is because scattered trees can provide more shade, avoid unnecessary overlapped tree crowns, and interact more with the surrounding environment. Also, every single tree's full transpirational cooling potential can be achieved due to the “oasis effect” [15, 54, 78, 98, 111].

Several studies have tackled the effects of tree distribution. Investigating the most suitable inter-tree distance, Zhang et al. [97] used a height-to-distance ratio of trees (as “Aspect ratio of trees”, ART) to characterize tree distribution. They proposed that ART < 2 could improve human thermal comfort. Zheng et al. [80] reported that optimum for cooling was achieved at a pedestrian level when the inter-tree distance equals the crown width. The shading effect of street trees varied with the morphology of street canyons and trees, as well as the time of the day [23]. Lee et al. [102] suggested not to plant trees in the north-facing sidewalk in N-S street canyons because the south-bordering buildings shaded them. Morakinyo et al. [3] reported that trees with high crown density were at their best when planted in open-areas because shading from buildings and trees may overlap in high-density urban areas to reduce the tree shading effect.

Concerning ventilation, trees can reduce wind speed. However, trees can be planted in wind paths to enhance ventilation [96]. Trees parallel to wind direction have a stronger cooling effect [78, 147] because of the fresh breeze effect due to air cooling after passing through trees [81]. Cooler areas can be found in the downwind direction in ENVI-met simulation [95]. Similarly, in the street canyon, the general belief is that vegetation can reduce in-canyon WS and its reduction magnitude was mostly dependent on the prevailing wind direction and vegetation density [23]. However, Lee et al. [102] reported that in deep street canyons the effect of increasing airflow speed was much lower than that of increasing tree coverage.

3.5.3. Main analytical aspects of green roofs

a) Elevation distribution of cooling effect

Green roofs' thermal performance was often analyzed at two levels, namely the pedestrian and roof surface levels. For buildings with podiums, the thermal performance at the podium level was also evaluated.

At the pedestrian level, green roofs' cooling effect was very low [93, 99, 103] because they do not provide additional shade at the street level and are not located close to pedestrians [99, 138]. Many reviewed studies found that the green-roof cooling effect decreased significantly with the increase in vertical distance between the green roofs and the ground [65, 75, 92, 93, 99, 117, 138, 156, 157]. The inflection point was approximately 10 m [93, 117, 158, 159]. Moreover, Zhang et al. [75] reported that when the vertical distance (building height) exceeded 60 m, the effects on pedestrian Ta were negligible. Furthermore, urban density also affected the pedestrian cooling effect of green roofs. They had a negative correlation, i.e., green roofs' cooling effect on pedestrians was insignificant in a high-rise and high-density urban environment [16, 117, 156].

In contrast, green roofs' cooling effect is more pronounced at the roof surface level than the pedestrian level [118]. Vegetation can significantly modify the radiation regime, enhance turbulence near the roof surface and intensify heat exchanges between the roof surface and near-roof air [93]. Ta reduction, however, was mostly restricted to the roof level [93].

Green roofs on building podiums can increase the thermal comfort at the podium level where the cooling intensity was independent of roof height [93].

b) Physical characteristics of green roofs

Green roofs can be regarded as a constant heat sink via evapotranspiration, radiative energy absorption, and heat fluxes [19, 92, 160]. Previous studies have confirmed the thermal effects of physical characteristics, including vegetation type, albedo, leaf density (generally represented by LAI), plant height, and soil depth. The roof vegetation increased surface albedo, reduced shortwave-radiation uptake [93], and lowered roof-surface temperature significantly, especially during intense daytime solar radiation[16, 61]. Increasing LAI had a positive impact on the cooling effect at the pedestrian level [138]. However, green roofs' energy-saving capacity was more influenced by soil depth than LAI [138]. Zhang et al. [75] found that plant height played a critical role in cooling. When the plant height was < 1 m, the TA reduction induced by green roofs was insignificant at pedestrian level [75].

Furthermore, green roofs can be categorized into two types, i.e., intensive and extensive, with different vegetation growth form and soil depth [16, 117, 122]. Intensive green roofs can reduce Ta more than extensive ones at both the pedestrian and roof surface levels due to thicker soil and greater foliage density and canopy height [16, 118, 122].

Overall, few studies on green-roof physical characteristics have been conducted because green roofs' detailed modeling function is only available in V4.4 and above.

c) Planting design of green roofs

The vegetation coverage ratio had a positive correlation with cooling performance. Kim et al. [141] surmised that installing green roofs in all buildings can have the greatest thermal effect at the city scale. Zhang et al. [75] reported that cooling performance might reach a threshold at a given coverage ratio which was determined to be 75%. Sahnoune et al. [106] arrived at a lower value of 50% as the best ratio. However, the coverage ratio was less affected by Ta reduction than foliage density and canopy height [16].

The green roof layout can influence the pedestrian thermal environment mainly due to the ventilation effect. Kim et al. [136] identified a linear green roof oriented perpendicular to the wind direction as the most effective configuration. Zhang et al. [75] proposed installing green roofs on the upwind side to bring more pedestrian-level cooling. The Ta may broadly fall, especially on the building's leeward side with a green roof [117].

To some extent, the green roof layout was largely based on the building layout, which presented a fundamental influence on the thermal environment. The enclosing layout of green roofs/buildings had the most significant cooling effect, followed by the array and scattered ones [117]. Also, a larger interval between the buildings brought a stronger green-roof cooling effect on the leeward block, and vice versa [93, 118]. When the building interval was large, ventilation could contribute notably to cooling.

3.5.4. Main analytical aspects of vertical greenings

a) Spatiotemporal distribution of cooling effect

The temporal variation and spatial distribution are the two general foci regarding the cooling effect of vertical greenings, which affect both outdoor and indoor thermal environments. Thermal comfort is essential in both diurnal and nocturnal periods. In the daytime, the cooling effect is attributed to shading, thermal insulation, and evaporative cooling of vegetation [68, 113]. Vertical greenings can provide effective thermal insulation in the daytime [68]. In the nighttime, they provide a passive warming effect by suppressing outgoing longwave radiation from the exterior building walls and the subdued vegetation evapotranspiration, resulting in a higher wall surface temperature than bare wall [68, 77].

The vertical extent of the cooling scope has been discussed frequently. Vertical greenings can provide a cooling effect spreading from the ground to 10–20 m above the building roofs [68]. Peng et al. [68] reported that block-scale green facades could improve the pedestrian-level microclimate more effectively than the upper-layer microclimate and identified three factors regulating the vertical distribution of cooling. First, more energy for evaporation can be provided by the higher ground-level Ta. Second, cool air may accumulate due to the low SR at the ground level. Third, due to the buoyancy effect, the cool air tends to sink and stay at the canyon's bottom. Many studies found no significant benefit to pedestrian comfort by increasing vertical greening height above a certain threshold [114, 140]. It is because the upper-layer airflow may weaken cooling due to its dispersion and dilution of the cooled air [68]. Acero et al. [114] recommended a critical height of 6 m.

For the horizontal extent of the cooling scope, “the closer to the green wall, the more cooling it will be” [77, 113]. Katsoulas et al. [77] recorded that the Tmrt difference between green and bare walls became insignificant at a distance > 2.5 m.

The cooling effect on the indoor thermal environment is generally represented by Ta and wall surface temperature [77, 113, 151, 161]. A lower wall surface temperature can reduce indoor cooling energy demand [113].

b) Planting design of vertical greenings

For the coverage ratio of vertical greenings, it was agreed that “the more, the better” [113, 123]. Moreover, the cooling effect of the coverage ratio was more substantial than orientation and position [113]. However, Morakinyo et al. [113] found that green walls might reduce WS to dampen cooling, especially near the greened surface. The magnitude varied depending on coverage ratio, orientation, and proximity to the pedestrian level.

Regarding the planting orientation, when the same quantity of vertical greenings is installed on East-West and North-South facades, the former can provide more cooling due to higher exposure to sunlight [113].

As a natural cover on the building envelope, the vertical greening cooling effect is contingent upon its intrinsic traits and building properties. Like green roofs, the vertical greening layout was also dependent on building layout, regulating the horizontal movement of cooling air and ventilation [68]. The amount of vertical greenings that can be installed was related to the density of the built-up urban fabric [113]. With increasing urban density, the percentage of vertical greenings exposed to direct solar radiation decreased. Similar to the assessment of trees, vertical greenings provided better cooling performance in low-density urban sites [123].

3.5.5. Main analytical aspects of water bodies

Water bodies have a strong impact on microclimate, especially on Ta reduction [76], due to their horizontal heat and water vapor exchange through evaporation, solar radiation absorption, and ventilation effect [73, 94]. Endowed with high heat storage and sizeable thermal inertia, many reviewed studies have confirmed both daytime cooling and nocturnal warming effects [25, 63, 76]. Two kinds of water bodies are recognized in ENVI-met, namely static water bodies and water mist systems. Most water-related studies covered the former. The morphological characteristics and influence scope of water bodies are commonly evaluated.

a) Influence scope of water bodies

Using Ta as an indicator, Jacobs et al. [25] found small Ta differences between watered and reference sites, especially at night, but the horizontal influence scope was slightly larger over the water area. Xu et al. [73] noticed the best cooling effect at the center of the water body, and it may decrease gradually from center to water edge [73]. Rahul et al. [28] found differences between the PET and UTCI trends due to differential sensitivity to RH (UTCI is very sensitive to RH, but PET is not). Jiang et al. [76] reported that water bodies' downwind direction experienced a more notable cooling effect. In a traditional Chinese garden, Xu et al. [73] detected the considerable horizontal extension of a cooling effect and 20-m vertical extension above the water surface.

There is a strong synergistic cooling effect between green and blue components. The water body's openness can increase the shading effect of trees and promote natural ventilation [25]. Shi et al. [63] suggested planting low LAI trees at the water edge to tap the reduced effect on WS and promote nighttime heat emission. The shading effect of waterfront greening can weaken the solar radiation reaching a water body. The influence scope of this synergistic cooling effect can extend 7–12 m from the water edge. To investigate the correlation between spatial structural factors of waterfront green space and the cooling effect, Jiang et al. [142] combined ArcGIS, ENVI-met, and the BRT (Boosted regression trees) machine learning method to analyze the pro-rata contributions of multidimensional spatial variables, marginal effect, and correlation relationship of each green space. They found the influence scope of the synergistic cooling effect of urban GBI to be 800–1000 m. The marginal effect of waterfront green space can reach its maximum at 20–25 m width and stabilise at > 55 m.

b) Water mist system

A water mist system has three key design factors: water flow rate, injection height, and local wind speed. The cooling capacity increases with increasing water flow rate and decreases with increasing WS [124]. However, with only up to 0.5 °C reductions on Ta and PET, Jacobs et al. [25] concluded that the cooling effect of vaporizing water at fountains (4 m high water jets) and sprays had limited magnitude and spatial spread.

4. Discussion and conclusion

Modeling, validating, and scenario simulating are three essential parts in investigating the thermal performance of urban green and blue infrastructures using ENVI-met. This study reviewed 79 relevant recent studies that used ENVI-met V4 and above, analyzed and summarized the pertinent findings. The following observations and recommendations can be distilled from the comprehensive review of the three research steps.

(a) Modeling

Modeling with real data is recommended. The more detailed and accurate plant models, the better ENVI-met can denote reality. Although it is understandable to use cited values or ENVI-met default values due to the comprehensiveness of the ENVI-met vegetation modeling platform and the lack of scientific instruments, this study suggests at least using the LAI and plant height values from field measurement, for accurately simulating the parameters with the most significant impact on microclimate. For the other plant parameters such as root geometry, a sensitivity test can be conducted to see whether they have a considerable impact on the user's research topics.

For water body modeling, similar to the modeling of vegetation, a more accurate setting of water body characteristics leads to more realistic simulation results. We suggest measuring the characteristics (i.e., the depth and turbidity) of the water body in the study area and set the extinction coefficient and heat exchange coefficient for the water body in the model correspondingly.

When reporting, a more detailed description of the modeling process can be provided. In some studies, the modeling values (e.g., LAI, tree height, among others) were assigned without explanation, i.e., it is not known whether they were extracted from other references or just used as simply defined values. The omission may raise queries regarding the appropriateness of the citations. This study recommends an adequate assessment of the cited or default values' suitability to the research questions.

(b) Validating

The content of validation can be more consistent with the research topic. For the validation plan, many studies investigated the thermal effect of greenery as the differences between greenery and open areas. It follows that the validation should focus on the ENVI-met simulation of the performance of greenery and open areas and their differences. However, some reviewed studies just validated the entire thermal environment rather than focusing on the gist of the research. Targeted and comprehensive validation is still lacking, especially for water bodies. The water temperature, as well as air temperature, relative humidity and wind speed above and near the water bodies are details that can be focused on in validation.

Most studies selected air temperature as their primary validation variable. However, when it comes to scenario simulation analysis, the plant's radiation obstruction effect and ventilation guiding effect as well as water bodies' evaporation cooling effect were usually mentioned as key discussion points. For such GBI studies, we suggest adding at least one radiation-related variable (e.g., shortwave radiation downward, Tmrt) or one ventilation-related variable (e.g., wind speed) when validating, consisting with the user's research discussion. For statistical metrics, only choosing R^2 is not enough and may result in misjudgment [133]. Combining two or three metrics such as RMSE, *d*, and MAE is suggested.

Furthermore, the validation can play its due role. The validation results can not only provide ENVI-met a simple evaluation as accurate or reliable, but it can also additionally be combined with a scenario simulation discussion, reporting the overestimated or underestimated values and providing more accurate planting recommendations.

(c) Scenario simulation

The main analytical aspects of scenario simulations clearly demonstrated the mechanisms of the cooling effect of urban green and blue infrastructures. However, using only air temperature as the performance indicator is insufficient [28]. Analyzing together with radiation and ventilation related variables such as shortwave radiation, longwave radiation, wind speed, and wind direction, will provide a comprehensive perspective. For human thermal comfort, ENVI-met website suggests using PET as a thermal comfort scale. However, this study suggests systematically and critically analyzing the index’s characteristics and suitability (i.e., how, why, when, and for whom/under what conditions a model can or should be applied [162]) before utilization and discussion. Moreover, other multidimensional indicators such as the extent of energy-saving, cost-saving, air quality improvement can be adopted by supplementing ENVI-met analysis with other tools. This expanded approach can better inform planting-design recommendations and serve multiple objectives.

Additionally, the temporal variations, growing process, and seasonal variations of greenery can be investigated using an extended thermal performance period [98]. Besides comparing different greenery settings, horizontal comparisons under different background conditions can be conducted. For instance, the greenery effects in different climatic regions, seasons, or weather scenarios can be compared and contrasted.

Cities are diverse, in which the urban greenery, water bodies, buildings, paved areas, and other urban elements interact jointly, independently, synergistically, or antagonistically with each other to beget the resultant outdoor thermal environment. The continuous advancements in numerical simulation technology can improve understanding of the elaborate mechanisms of the urban thermal environment. The research findings can provide more detailed and targeted recommendations for policymakers, urban planners, and landscape designers. This review comprehensively evaluated and summarized ENVI-met applications to urban green and blue infrastructures, identified some limitations, and proposed some alternatives and improvements. Studies from a relatively large scale to a micro-scale, combining ENVI-met with Weather Research and Forecasting (WRF) and remote sensing, were not reviewed here. They constitute another research domain worthy of attention.

Acknowledgement

This research is supported by the General Research Fund (RGC Ref No. 14617220) from the Research Grants Council (RGC) of Hong Kong.

References

[1] T.R. Oke, The energetic basis of the urban heat island, Quarterly Journal of the Royal Meteorological Society 108(455) (1982) 1-24.

[2] K. Brysse, N. Oreskes, J. O’Reilly, M. Oppenheimer, Climate change prediction: Erring on the side of least drama?, Global environmental change 23(1) (2013) 327-337.

[3] T.E. Morakinyo, K.K.-L. Lau, C. Ren, E. Ng, W. Ouyang, Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation - development and evaluation, Science of the Total Environment 719 (2020).
[4] D.A. Hartz, A.J. Brazel, G.M. Heisler, A case study in resort climatology of Phoenix, Arizona, USA, international Journal of biometeorology 51(1) (2006) 73-83.
[5] L. Shashua‐Bar, D. Pearlmutter, E. Erell, The influence of trees and grass on outdoor thermal comfort in a hot‐arid environment, International journal of climatology 31(10) (2011) 1498-1506.
[6] S.L. Harlan, A.J. Brazel, L. Prashad, W.L. Stefanov, L. Larsen, Neighborhood microclimates and vulnerability to heat stress, Social science & medicine 63(11) (2006) 2847-2863.
[7] J.S. Golden, D. Hartz, A. Brazel, G. Luber, P. Phelan, A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006, International journal of biometeorology 52(6) (2008) 471-480.
[8] D. Wang, K.K.-L. Lau, C. Ren, W.B.I. Goggins, Y. Shi, H.C. Ho, T.-C. Lee, L.-S. Lee, J. Woo, E. Ng, The impact of extremely hot weather events on all-cause mortality in a highly urbanized and densely populated subtropical city: a 10-year time-series study (2006–2015), Science of The Total Environment 690 (2019) 923-931.
[9] B. Stone Jr, Urban heat and air pollution: An emerging role for planners in the climate change debate, Journal of the American planning association 71(1) (2005) 13-25.
[10] C. Sarrat, A. Lemonsu, V. Masson, D. Guedalia, Impact of urban heat island on regional atmospheric pollution, Atmospheric Environment 40(10) (2006) 1743-1758.
[11] L.-W. Lai, W.-L. Cheng, Air quality influenced by urban heat island coupled with synoptic weather patterns, Science of the total environment 407(8) (2009) 2724-2733.
[12] H. Akbari, M. Pomerantz, H. Taha, Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas, Solar energy 70(3) (2001) 295-310.
[13] H. Akbari, Shade trees reduce building energy use and CO2 emissions from power plants, Environmental pollution 116 (2002) S119-S126.
[14] M. Santamouris, G. Ban-Weiss, P. Osmond, R. Paolini, A. Synnefa, C. Cartalis, A. Muscio, M. Zinzi, T.E. Morakinyo, E. Ng, Progress in urban greenery mitigation science–assessment methodologies advanced technologies and impact on cities, Journal of Civil Engineering and Management 24(8) (2018) 638-671.
[15] Z. Liu, R.D. Brown, S. Zheng, Y. Jiang, L. Zhao, An in-depth analysis of the effect of trees on human energy fluxes, Urban For. Urban Greening 50 (2020).
[16] T.E. Morakinyo, K. Dahanayake, E. Ng, C.L. Chow, Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study, Energy and Buildings 145 (2017) 226-237.
[17] T.R. Oke, The micrometeorology of the urban forest, Philosophical Transactions of the Royal Society of London. B, Biological Sciences 324(1223) (1989) 335-349.
[18] C. Altunkasa, C. Uslu, Use of outdoor microclimate simulation maps for a planting design to improve thermal comfort, Sustainable Cities Soc. 57 (2020).
[19] D. Antoniadis, N. Katsoulas, C. Kittas, Simulation of schoolyard's microclimate and human thermal comfort under Mediterranean climate conditions: effects of trees and green structures, International Journal of Biometeorology 62(11) (2018) 2025-2036.
[20] E. Gatto, R. Buccolieri, E. Aarrevaara, F. Ippolito, R. Emmanuel, L. Perronace, J.L. Santiago, Impact of Urban vegetation on outdoor thermal comfort: Comparison between a Mediterranean city (Lecce, Italy)

and a northern European city (Lahti, Finland), Forests 11(2) (2020).

[21] A. Karimi, H. Sanaieian, H. Farhadi, S. Norouzian-Maleki, Evaluation of the thermal indices and thermal comfort improvement by different vegetation species and materials in a medium-sized urban park, Energy Rep. 6 (2020) 1670-1684.

[22] T.E. Morakinyo, L. Kong, K.K.-L. Lau, C. Yuan, E. Ng, A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort, Building and Environment 115 (2017) 1.

[23] T.E. Morakinyo, Y.F. Lam, Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort, Building and Environment 103 (2016) 262-275.

[24] T.E. Morakinyo, K.K.-L. Lau, C. Ren, E. Ng, Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving, Building and Environment 137 (2018) 157.

[25] C. Jacobs, L. Klok, M. Bruse, J. Cortesão, S. Lenzholzer, J. Kluck, Are urban water bodies really cooling?, Urban CLim. 32 (2020).

[26] M.S. Albdour, B. Baranyai, Water body effect on microclimate in summertime: A case study from PÉCS, Pollack Period. 14(3) (2019) 131-140.

[27] G. Manteghi, S.M. Shukri, H. Lamit, Street geometry and river width as design factors to improve thermal comfort in Melaka City, J. Advance Res. Fluid Mechanics Therm. Sciences 58(1) (2019) 15-22.

[28] A. Rahul, M. Mukherjee, A. Sood, Impact of ganga canal on thermal comfort in the city of Roorkee, India, Int J Biometeorol (2020).

[29] D.E. Bowler, L. Buyung-Ali, T.M. Knight, A.S. Pullin, Urban greening to cool towns and cities: A systematic review of the empirical evidence, Landscape and urban planning 97(3) (2010) 147-155.

[30] T. Zupancic, C. Westmacott, M. Bulthuis, The impact of green space on heat and air pollution in urban communities: A meta-narrative systematic review, David Suzuki Foundation Vancouver2015.

[31] A. Motazedian, P. Leardini, Impact of green infrastructures on urban microclimates. A critical review.

[32] C.B. Koc, P. Osmond, A. Peters, Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources, Solar Energy 166 (2018) 486-508.

[33] S. Tsoka, A. Tsikaloudaki, T. Theodosiou, Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review, Sustainable Cities Soc. 43 (2018) 55-76.

[34] A. Hami, B. Abdi, D. Zarehaghi, S.B. Maulan, Assessing the thermal comfort effects of green spaces: A systematic review of methods, parameters, and plants' attributes, Sustainable Cities Soc. 49 (2019) 101634.

[35] E. Jamei, P. Rajagopalan, M. Seyedmahmoudian, Y. Jamei, Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort, Renewable and Sustainable Energy Reviews 54 (2016) 1002-1017.

[36] M.A. Rahman, L.M. Stratopoulos, A. Moser-Reischl, T. Zölch, K.-H. Häberle, T. Rötzer, H. Pretzsch, S. Pauleit, Traits of trees for cooling urban heat islands: A meta-analysis, Building and Environment 170 (2020) 106606.

[37] K. Gunawardena, M. Wells, T. Kershaw, Utilising green and bluespace to mitigate urban heat island intensity, Science of the Total Environment 584 (2017) 1040-1055.

[38] G. Manteghi, H. bin Limit, D. Remaz, Water bodies an urban microclimate: A review, Modern Applied Science 9(6) (2015) 1.

[39] S. Völker, H. Baumeister, T. Classen, C. Hornberg, T. Kistemann, Evidence for the temperature-

mitigating capacity of urban blue space—A health geographic perspective, Erdkunde (2013) 355-371.
[40] J. Mullaney, T. Lucke, S.J. Trueman, A review of benefits and challenges in growing street trees in paved urban environments, Landscape and Urban Planning 134 (2015) 157-166.
[41] N. Meili, G. Manoli, P. Burlando, J. Carmeliet, W.T.L. Chow, A.M. Coutts, M. Roth, E. Velasco, E.R. Vivoni, S. Fatichi, Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects, Urban Forestry & Urban Greening 58 (2021).
[42] L. Manickathan, T. Defraeye, J. Allegrini, D. Derome, J. Carmeliet, Parametric study of the influence of environmental factors and tree properties on the transpirative cooling effect of trees, Agricultural and Forest Meteorology 248 (2018) 259-274.
[43] L. Manickathan, A. Kubilay, T. Defraeye, J. Allegrini, D. Derome, J. Carmeliet, Integrated vegetation model for studying the cooling potential of trees in urban street canyons, (2018).
[44] N. Meili, P. Burlando, J. Carmeliet, W.T. Chow, A.M. Coutts, G. Manoli, M. Roth, E. Velasco, E.R. Vivoni, S. Fatichi, Radiation, evapotranspiration, and roughness effects of urban trees on local microclimate: A modelling study, EGU General Assembly Conference Abstracts, 2020, p. 4339.
[45] Y. Yang, E. Gatto, Z. Gao, R. Buccolieri, T.E. Morakinyo, H. Lan, The “plant evaluation model” for the assessment of the impact of vegetation on outdoor microclimate in the urban environment, Building and Environment 159 (2019) 106151.
[46] Y. Toparlar, B. Blocken, B. Maiheu, G.J.F. van Heijst, A review on the CFD analysis of urban microclimate, Renewable and Sustainable Energy Reviews 80 (2017) 1613-1640.
[47] M. Bruse, ENVI-met 3.0: updated model overview, University of Bochum. Retrieved from: www. envi-met. com (2004).
[48] M. Bruse, ENVI-met implementation of the Jacobs A− gs Model to calculate the stomata conductance, Bochum, 2004.
[49] M. Bruse, H. Fleer, Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model, Environmental modelling & software 13(3-4) (1998) 373-384.
[50] H. Simon, Modeling urban microclimate: development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met, 2016.
[51] S. Huttner, Further development and application of the 3D microclimate simulation ENVI-met, Mainz University, Germany (2012).
[52] H. Simon, J. Lindén, D. Hoffmann, P. Braun, M. Bruse, J. Esper, Modeling transpiration and leaf temperature of urban trees – A case study evaluating the microclimate model ENVI-met against measurement data, Landscape and Urban Planning 174 (2018) 33-40.
[53] M. Fahmy, H. El-Hady, M. Mahdy, M.F. Abdelalim, On the green adaptation of urban developments in Egypt; predicting community future energy efficiency using coupled outdoor-indoor simulations, Energy and Buildings 153 (2017) 241-261.
[54] Z. Wu, P. Dou, L. Chen, Comparative and combinative cooling effects of different spatial arrangements of buildings and trees on microclimate, Sustainable Cities Soc. 51 (2019).
[55] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, (2007).
[56] H. Simon, T. Sinsel, M. Bruse, Introduction of Fractal-Based Tree Digitalization and Accurate In-Canopy Radiation Transfer Modelling to the Microclimate Model ENVI-met, Forests 11(8) (2020) 869.
[57] D.H.S. Duarte, P. Shinzato, C.D. Gusson, C.A. Alves, The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate, Urban CLim. 14 (2015)

224-239.

[58] A. Aboelata, Vegetation in different street orientations of aspect ratio (H/W 1:1) to mitigate UHI and reduce buildings' energy in arid climate, Building and Environment 172 (2020) 1.

[59] A. Aboelata, S. Sodoudi, Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo, Building and Environment 166 (2019) 1.

[60] A. Aboelata, S. Sodoudi, Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo, Building and Environment 168 (2020) 1.

[61] S.S. Cipolla, M. Maglionico, G. Semprini, V. Villani, A. Bonoli, Green roofs as a strategy for urban heat island mitigation in Bologna (Italy), Acta horticulturae (1215) (2018) 295-300.

[62] N. Karimi Afshar, Z. Karimian, R. Doostan, M. Habibi Nokhandan, Influence of planting designs on winter thermal comfort in an urban park, J. Environ. Eng. Landsc. Manage. 26(3) (2018) 232-240.

[63] D. Shi, J. Song, J. Huang, C. Zhuang, R. Guo, Y. Gao, Synergistic cooling effects (SCEs) of urban green-blue spaces on local thermal environment: A case study in Chongqing, China, Sustainable Cities Soc. 55 (2020).

[64] S. Tsoka, T. Leduc, A. Rodler, Assessing the effects of urban street trees on building cooling energy needs: The role of foliage density and planting pattern, Sustainable Cities Soc. 65 (2021).

[65] Y.P. Chen, B.H. Zheng, Y.Z. Hu, Numerical Simulation of Local Climate Zone Cooling Achieved through Modification of Trees, Albedo and Green Roofs-A Case Study of Changsha, China, Sustainability 12(7) (2020) 23.

[66] H. Lee, H. Mayer, L. Chen, Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany, Landscape and urban planning 148 (2016) 37-50.

[67] Y. Li, Y. Song, Optimization of vegetation arrangement to improve microclimate and thermal comfort in an urban park, Int. Rev. Spatial Plan. Sustain. Dev. 7(1) (2019) 18-30.

[68] L.L.H. Peng, Z. Jiang, X. Yang, Y. He, T. Xu, S.S. Chen, Cooling effects of block-scale facade greening and their relationship with urban form, Building and Environment 169 (2020) 1.

[69] J.D. Sjöman, A. Hirons, H. Sjöman, Branch Area Index of Solitary Trees: Understanding Its Significance in Regulating Ecosystem Services, Journal of environmental quality 45(1) (2016) 175-187.

[70] Y. Wang, H. Akbari, The effects of street tree planting on Urban Heat Island mitigation in Montreal, Sustainable Cities Soc. 27 (2016) 122-128.

[71] Y. Wang, F. Bakker, R. de Groot, H. Wortche, R. Leemans, Effects of urban trees on local outdoor microclimate: synthesizing field measurements by numerical modelling, Urban ecosystems 18(4) (2015) 1305-1331.

[72] Z. Wu, F. Kong, Y. Wang, R. Sun, L. Chen, The Impact of Greenspace on Thermal Comfort in a Residential Quarter of Beijing, China, Int J Environ Res Public Health 13(12) (2016).

[73] X. Xu, S. Liu, S. Sun, W. Zhang, Y. Liu, Z. Lao, G. Guo, K. Smith, Y. Cui, W. Liu, E.H. García, J. Zhu, Evaluation of energy saving potential of an urban green space and its water bodies, Energy and Buildings 0 (2019) 58.

[74] Y. Yang, D. Zhou, W. Gao, Z. Zhang, W. Chen, W. Peng, Simulation on the impacts of the street tree pattern on built summer thermal comfort in cold region of China, Sustainable Cities Soc. 37 (2018) 563-580.

[75] G. Zhang, H. Bao-Jie, Z. Zhu, D. Bart Julien, Impact of Morphological Characteristics of Green Roofs on Pedestrian Cooling in Subtropical Climates, International Journal of Environmental Research and Public Health 16(2) (2019).

[76] Y. Jiang, X. Han, T. Shi, D. Song, Adaptive Analysis of Green Space Network Planning for the Cooling Effect of Residential Blocks in Summer: A Case Study in Shanghai, Sustainability 10(9) (2018).
[77] N. Katsoulas, D. Antoniadis, I.L. Tsirogiannis, E. Labraki, T. Bartzanas, C. Kittas, Microclimatic effects of planted hydroponic structures in urban environment: measurements and simulations, International journal of biometeorology 61(5) (2017) 943-956.
[78] S. Sodoudi, H. Zhang, X. Chi, F. Müller, H. Li, The influence of spatial configuration of green areas on microclimate and thermal comfort, Urban forestry & urban greening 34 (2018) 85-96.
[79] J.M. Tukiran, J. Ariffin, A.N. Abdul Ghani, A Study on the cooling effects of greening for improving the outdoor thermal environment in penang, Malaysia, Int. J. GEOMATE 12(34) (2017) 62-70.
[80] B. Zheng, K.B. Bedra, J. Zheng, G. Wang, Combination of tree configuration with street configuration for thermal comfort optimization under extreme summer conditions in the urban center of Shantou City, China, Sustainability 10(11) (2018).
[81] S. Atwa, M.G. Ibrahim, R. Murata, Evaluation of plantation design methodology to improve the human thermal comfort in hot-arid climatic responsive open spaces, Sustainable Cities Soc. 59 (2020).
[82] S. Yilmaz, B.E. Mutlu, A. Aksu, E. Mutlu, A. Qaid, Street design scenarios using vegetation for sustainable thermal comfort in Erzurum, Turkey, Environ Sci Pollut Res Int (2020).
[83] Z. Liu, S. Zheng, L. Zhao, Evaluation of the ENVI-Met vegetation model of four common tree species in a subtropical hot-humid area, Atmosphere 9(5) (2018) 198.
[84] M. Fahmy, Y. Ibrahim, E. Hanafi, M. Barakat, Would LEED-UHI greenery and high albedo strategies mitigate climate change at neighborhood scale in Cairo, Egypt?, Building Simulation 11(6) (2018) 1273-1288.
[85] Y. Wang, Z. Ni, S. Chen, B. Xia, Microclimate regulation and energy saving potential from different urban green infrastructures in a subtropical city, Journal of cleaner production 226 (2019) 913-927.
[86] B. Lalic, D.T. Mihailovic, An Empirical Relation Describing Leaf-Area Density inside the Forest for Environmental Modeling, Journal of Applied Meteorology 43(4) (2004) 641-645.
[87] S.M. Asef, O. Tolba, A. Fahmy, The effect of leaf area index and leaf area density on urban microclimate, J. Eng. Appl. Sci. 67(2) (2020) 427-446.
[88] P.J. Peper, E.G. McPherson, S.M. Mori, Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees, journal of Arboriculture 27(6) (2001) 306-317.
[89] J.A. Moore, L. Zhang, D. Stuck, Height-diameter equations for ten tree species in the Inland Northwest, Western Journal of Applied Forestry 11(4) (1996) 132-137.
[90] K.C. Colbert, D.R. Larsen, J.R. Lootens, Height-diameter equations for thirteen midwestern bottomland hardwood species, Northern Journal of Applied Forestry 19(4) (2002) 171-176.
[91] K. Fabbri, G. Canuti, A. Ugolini, A methodology to evaluate outdoor microclimate of the archaeological site and vegetation role: A case study of the Roman Villa in Russi (Italy), Sustainable Cities Soc. 35 (2017) 107-133.
[92] H. Herath, R.U. Halwatura, G.Y. Jayasinghe, Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy, Urban Forestry & Urban Greening 29 (2018) 212-222.
[93] M. Knaus, D. Haase, Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany, Urban For. Urban Greening 53 (2020).
[94] J. Li, Y. Wang, Z. Ni, S. Chen, B. Xia, An integrated strategy to improve the microclimate regulation of green-blue-grey infrastructures in specific urban forms, Journal of Cleaner Production 271 (2020).
[95] W.L. Ouyang, T.E. Morakinyo, C. Ren, E. Ng, The cooling efficiency of variable greenery coverage

ratios in different urban densities: A study in a subtropical climate, Building and Environment 174 (2020) 13.

[96] Z. Tan, K.K.L. Lau, E. Ng, Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment, Energy and Buildings 114 (2016) 265-274.

[97] L. Zhang, Q. Zhan, Y. Lan, Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters, Building and Environment 130 (2018) 27.

[98] Q. Zhao, D.J. Sailor, E.A. Wentz, Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment, Urban forestry & urban greening 32 (2018) 81-91.

[99] T. Zölch, J. Maderspacher, C. Wamsler, S. Pauleit, Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale, Urban For. Urban Greening 20 (2016) 305-316.

[100] U. Berardi, Z. Jandaghian, J. Graham, Effects of greenery enhancements for the resilience to heat waves: A comparison of analysis performed through mesoscale (WRF) and microscale (Envi-met) modeling, Sci Total Environ 747 (2020) 141300.

[101] A.D. Bochenek, K. Klemm, The Impact of Passive Green Technologies on the Microclimate of Historic Urban Structures: The Case Study of Lodz, Atmosphere 11(9) (2020) 974.

[102] H. Lee, H. Mayer, W. Kuttler, Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions, Urban forestry & urban greening 48 (2020).

[103] G. Lobaccaro, J.A. Acero, Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons, Urban CLim. 14 (2015) 251-267.

[104] L. Rui, R. Buccolieri, W. Ding, J. Shen, Z. Gao, The Impact of Green Space Layouts on Microclimate and Air Quality in Residential Districts of Nanjing, China, Forests 9(4) (2018).

[105] L. Rui, R. Buccolieri, Z. Gao, E. Gatto, W. Ding, Study of the effect of green quantity and structure on thermal comfort and air quality in an urban-like residential district by ENVI-met modelling, Building Simulation 12(2) (2019) 183-194.

[106] S. Sahnoune, N. Benhassine, Quantifying the Impact of Green-Roofs on Urban Heat Island Mitigation, International Journal of Environmental Science and Development 8(2) (2017) 116-123.

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

[108] X. Su, H. Cai, Z. Chen, Q. Feng, Influence of the Ground Greening Configuration on the Outdoor Thermal Environment in Residential Areas under Different Underground Space Overburden Thicknesses, Sustainability 9(9) (2017) 1656.

[109] K.M. Wai, T.Z. Tan, T.E. Morakinyo, T.C. Chan, A. Lai, Reduced effectiveness of tree planting on micro-climate cooling due to ozone pollution—A modeling study, Sustainable Cities Soc. 52 (2020).

[110] Y. Yang, D. Zhou, Y. Wang, D. Ma, W. Chen, D. Xu, Z. Zhu, Economical and outdoor thermal comfort analysis of greening in multistory residential areas in Xi'an, Sustainable Cities Soc. 51 (2019).

[111] T. Zölch, M.A. Rahman, E. Pfleiderer, G. Wagner, S. Pauleit, Designing public squares with green infrastructure to optimize human thermal comfort, Building and Environment 149 (2019) 640.

[112] H. Simon, D.H.S. Duarte, M. Bruse, P. Shinzato, Calibration process and parametrization of tropical plants using ENVI-met V4 -- Sao Paulo case study, Architectural science review 62(2) (2019) 112-125.

[113] T.E. Morakinyo, A. Lai, K.K.L. Lau, E. Ng, Thermal benefits of vertical greening in a high-density city: Case study of Hong Kong, Urban For. Urban Greening 37 (2019) 42-55.

[114] J.A. Acero, E.J.Y. Koh, X. Li, L.A. Ruefenacht, G. Pignatta, L.K. Norford, Thermal impact of the orientation and height of vertical greenery on pedestrians in a tropical area, Building Simulation 12(6) (2019) 973-984.

[115] A.B. Daemei, M. Azmoodeh, Z. Zamani, E.M. Khotbehsara, Experimental and simulation studies on the thermal behavior of vertical greenery system for temperature mitigation in urban spaces, J. Build. Eng. 20 (2018) 277-284.

[116] Y. Makido, D. Hellman, V. Shandas, Nature-Based Designs to Mitigate Urban Heat: The Efficacy of Green Infrastructure Treatments in Portland, Oregon, Atmosphere 10(5) (2019).

[117] C. Jin, X. Bai, T. Luo, M. Zou, Effects of green roofs' variations on the regional thermal environment using measurements and simulations in Chongqing, China, Urban forestry & urban greening 29 (2018) 223-237.

[118] M.D. Lalošević, M.S. Komatina, M.V. Miloš, N.R. Rudonja, Green roofs and cool materials as retrofitting strategies for urban heat island mitigation: Case study in Belgrade, Serbia, Thermal Science 22(6A) (2018) 2309-2324.

[119] H. Farhadi, M. Faizi, H. Sanaieian, Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings, Sustainable Cities Soc. 46 (2019).

[120] (!!! INVALID CITATION !!! [57, 86, 98]).

[121] S. Ziaul, S. Pal, Modeling the effects of green alternative on heat island mitigation of a meso level town, West Bengal, India, Adv. Space Res. 65(7) (2020) 1789-1802.

[122] A. Aboelata, Assessment of Green Roof Benefits on Buildings' Energy-Saving by Cooling Outdoor Spaces in Different Urban Densities in Arid Cities, Energy (2020) 119514.

[123] L.L.H. Peng, Z. Jiang, X. Yang, Q. Wang, Y. He, S.S. Chen, Energy savings of block-scale facade greening for different urban forms, Applied Energy 279 (2020).

[124] E. Di Giuseppe, G. Ulpiani, C. Cancellieri, C. Di Perna, M. D'Orazio, M. Zinzi, Numerical modelling and experimental validation of the microclimatic impacts of water mist cooling in urban areas, Energy and Buildings (2020) 110638.

[125] M. Fahmy, H. El-Hady, M. Mahdy, LAI and Albedo measurements based methodology for numerical simulation of urban tree's microclimate: A case study in Egypt, Int. J. Sci. Eng. Res 7 (2013) 790-797.

[126] J. Lindén, H. Simon, P. Fonti, J. Esper, M. Bruse, Observed and Modeled transpiration cooling from urban trees in Mainz, Germany, Proceedings of the ICUC9—International Conference on Urban Climate Jointly with Symposium on the Urban Environment, Toulouse, France, 2015, pp. 20-24.

[127] P.J. Crank, A. Middel, M. Wagner, D. Hoots, M. Smith, A. Brazel, Validation of seasonal mean radiant temperature simulations in hot arid urban climates, Science of the Total Environment 749 (2020).

[128] J.A. Acero, K. Herranz-Pascual, A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques, Building and Environment 93 (2015) 245-257.

[129] S. Huttner, Further development and application of the 3D microclimate simulation ENVI-met, Mainz: Johannes Gutenberg-Universitat in Mainz 147 (2012).

[130] S. Thorsson, F. Lindberg, I. Eliasson, B. Holmer, Different methods for estimating the mean radiant temperature in an outdoor urban setting, International Journal of Climatology: A Journal of the Royal Meteorological Society 27(14) (2007) 1983-1993.

[131] C. Willmott, On the validation of models, Physical Geography, Spatial statistic and models 18 (1981).

[132] M. Stunder, S. SethuRaman, A statistical evaluation and comparison of coastal point source dispersion models, Atmospheric Environment (1967) 20(2) (1986) 301-315.

[133] C.J. Willmott, Some comments on the evaluation of model performance, Bulletin of the American Meteorological Society 63(11) (1982) 1309-1313.

[134] C.J. Willmott, K. Matsuura, Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance, Climate research 30(1) (2005) 79-82.

[135] P. Shinzato, D. Yoshida, D. Duarte, Parametrization of tropical plants using ENVI-met V.4 and its impact on urban microclimates – Sao Paulo case study, 8nternational Conference on Countermeasures To Urban Heat Islands, 2016.

[136] X. Yang, L. Zhao, M. Bruse, Q. Meng, Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces, Building and Environment 60 (2013) 93-104.

[137] Z. Wu, L. Chen, Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: Integrating modeling with in-situ measurements, Landscape and urban planning 167 (2017) 463-472.

[138] U. Berardi, The outdoor microclimate benefits and energy saving resulting from green roofs retrofits, Energy and Buildings 121 (2016) 217-229.

[139] X. Fang, L. Shen, Q. Meng, The Study on Microclimate Simulation of Country Park Based on ENVI-met Software——Take the East Gate Entrance Area of Guangdong Tianlu Lake Country Park for Example, 3rd International Conference on Mechatronics, Robotics and Automation, Atlantis Press, 2015.

[140] A. Fikfak, K. Lavtižar, J.P. Grom, S. Kosanović, M. Zbašnik-Senegačnik, Study of Urban Greenery Models to Prevent Overheating of Parked Vehicles in P + R Facilities in Ljubljana, Slovenia, Sustainability 12(12) (2020) 5160.

[141] J. Kim, S.Y. Lee, J. Kang, Temperature Reduction Effects of Rooftop Garden Arrangements: A Case Study of Seoul National University, Sustainability 12(15) (2020) 6032.

[142] Y. Jiang, S. Jiang, T. Shi, Comparative study on the cooling effects of green space patterns in waterfront build-up blocks: An experience from Shanghai, International Journal of Environmental Research and Public Health 17(22) (2020) 1-29.

[143] A. Middel, N. Chhetri, R. Quay, Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods, Urban forestry & urban greening 14(1) (2015) 178-186.

[144] S. Coccolo, J. Kämpf, J.-L. Scartezzini, D. Pearlmutter, Outdoor human comfort and thermal stress: A comprehensive review on models and standards, Urban Climate 18 (2016) 33-57.

[145] A. Ahmadi Venhari, M. Tenpierik, M. Taleghani, The role of sky view factor and urban street greenery in human thermal comfort and heat stress in a desert climate, Journal of arid environments 166 (2019) 68-76.

[146] S. Teshnehdel, H. Akbari, E. Di Giuseppe, R.D. Brown, Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran, Building and Environment 178 (2020) 1.

[147] B. Abdi, A. Hami, D. Zarehaghi, Impact of small-scale tree planting patterns on outdoor cooling and thermal comfort, Sustainable Cities Soc. 56 (2020).

[148] A. Russo, F.J. Escobedo, S. Zerbe, Quantifying the local-scale ecosystem services provided by urban treed streetscapes in Bolzano, Italy, AIMS Environ. Sci. 3(1) (2016) 58-76.

[149] S. Provençal, O. Bergeron, R. Leduc, N. Barrette, Thermal comfort in Quebec City, Canada:

sensitivity analysis of the UTCI and other popular thermal comfort indices in a mid-latitude continental city, International journal of biometeorology 60(4) (2016) 591-603.

[150] F. Kong, A. Middel, C. Sun, C. Skelhorn, F. Jiang, F. Liu, G. Cavan, H. Yin, I. Dronova, Y. Pu, Energy saving potential of fragmented green spaces due to their temperature regulating ecosystem services in the summer, Applied energy 183 (2016) 1428-1440.

[151] J. Li, B. Zheng, W. Shen, Y. Xiang, X. Chen, Z. Qi, Cooling and Energy-Saving Performance of Different Green Wall Design: A Simulation Study of a Block, Energies 12(15) (2019) 2912.

[152] (!!! INVALID CITATION !!! [21, 22, 24]).

[153] R.D. Brown, T.J. Gillespie, Microclimatic landscape design: creating thermal comfort and energy efficiency, Wiley New York1995.

[154] W.M. El-Bardisy, M. Fahmy, G.F. El-Gohary, Climatic sensitive landscape design: Towards a better microclimate through plantation in public schools, Cairo, Egypt, Procedia-Social and Behavioral Sciences 216(October 2015) (2016) 206-216.

[155] Z. Tan, K.K.-L. Lau, E. Ng, Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas, Building and Environment 120 (2017) 93-109.

[156] E. Ng, L. Chen, Y. Wang, C. Yuan, A study on the cooling effects of greening in a high-density city: An experience from Hong Kong, Building and environment 47 (2012) 256-271.

[157] C. Rosenzweig, W. Solecki, R. Slosberg, Mitigating New York City’s heat island with urban forestry, living roofs, and light surfaces, A report to the New York State Energy Research and Development Authority (2006).

[158] N. Müller, W. Kuttler, A.-B. Barlag, Counteracting urban climate change: adaptation measures and their effect on thermal comfort, Theoretical and applied climatology 115(1-2) (2014) 243-257.

[159] N.H. Wong, Y. Chen, C.L. Ong, A. Sia, Investigation of thermal benefits of rooftop garden in the tropical environment, Building and environment 38(2) (2003) 261-270.

[160] S. Saiz, C. Kennedy, B. Bass, K. Pressnail, Comparative life cycle assessment of standard and green roofs, Environmental science & technology 40(13) (2006) 4312-4316.

[161] H. Akeiber, P. Nejat, M.Z.A. Majid, M.A. Wahid, F. Jomehzadeh, I.Z. Famileh, J.K. Calautit, B.R. Hughes, S.A. Zaki, A review on phase change material (PCM) for sustainable passive cooling in building envelopes, Renewable and Sustainable Energy Reviews 60 (2016) 1470-1497.

[162] A. Grundstein, J. Vanos, There is no 'Swiss Army Knife' of thermal indices: the importance of considering 'why?' and 'for whom?' when modelling heat stress in sport, Br J Sports Med (2020).

Appendix A. Basic information of the reviewed studies

Reference	Name of journal	Publication year	City	Continent	Climate zone	Season	GBI type	Validation	ENVI-met version	Combined with other software/model
(Abdi, Hami et al. 2020)	Sustainable Cities and Society	2020	Tabriz, Iran	Asia	BSk	Summer	Trees	√	4.1	-
(Aboelata 2020)	Building and Environment	2020	Cairo, Egypt	Africa	BWh	Summer	Trees, Grass	√	4.3.2	DesignBuilder
(Aboelata and Sodoudi 2019)	Building and Environment	2019	Cairo, Egypt	Africa	BWh	Summer	Trees, Grass	√	4.3.2	DesignBuilder
(Aboelata and Sodoudi 2020)	Building and Environment	2020	Cairo, Egypt	Africa	BWh	Summer	Trees, Grass	√	4.3.2	DesignBuilder
(Acero, Koh et al. 2019)	Building Simulation	2019	Singapore	Asia	Af	Summer	Vertical greenings	-	4.3	-
(Al Jadaa, Abu Raed et al. 2019)	Journal of Mechanical and Industrial Engineering	2019	Abu Dhabi, UAE	Asia	BWh	Summer, Winter	Green roofs	-	4+ (Academic version)	-
(Altunkasa and Uslu 2020)	Sustainable Cities and Society	2020	Adana, Turkey	Asia	Csa	Summer, Winter	Trees	-	4+	-
(Antoniadis, Katsoulas et al. 2018)	International Journal of Biometeorology	2019	Volos, Greece	Europe	Csa	Summer	Trees	√	4	-
(Atwa, Ibrahim et al. 2020)	Sustainable Cities and Society	2020	New Borg El Arab, Egypt	Africa	BWh	Summer	Trees	√	4+	-
(Berardi 2016)	Energy and Buildings	2016	Toronto, Canada	North America	Dfa	Summer	Green roofs	√	4	EnergyPlus
(Berardi, Jandaghian et al. 2020)	Science of the Total Environment	2020	Toronto, Canada	North America	Dfa	Summer	Trees	√	4.4	WRF-UCM
(Bochenek and Klemm 2020)	atmosphere	2020	Lodz, Poland	Europe	Cfb	Summer	Trees, Green roofs, Vertical greenings	-	4+ (Science version)	-
(Chen, Zheng et al. 2020)	sustainability	2020	Changsha, China	Asia	Cfa	Summer	Trees, Green roofs	√	4	-
(Cipolla, Maglionico et al. 2018)	Acta Horticulturae	2018	Bologna, Italy	Europe	Cfa	autumn	Green roofs	-	4+	-
(Daemei, Azmoodeh et al. 2018)	Journal of Building Engineering	2018	Tehran, Iran	Asia	BSk	Summer, Winter	Vertical greenings	√	4	-

(Duarte, Shinzato et al. 2015)	Urban Climate	2015	Sao Paulo, Brazil	South America	Cfb	Summer, Autumn	Trees	√	4	-
(Fabbri, Canuti et al. 2017)	Sustainable Cities and Society	2017	Russi, Italy	Europe	Cfa	Summer, Winter	Trees	-	4	-
(Fahmy, El-Hady et al. 2017)	Energy and Buildings	2017	New Borg El-Arab, 6th of October , Egypt	Africa	-	Summer	Trees, Green roofs, Vertical greenings	-	4	DesignBuilder
(Fahmy, Ibrahim et al. 2018)	Building Simulation	2018	Cairo, Egypt	Africa	BWh	summer	Trees, Green roofs, Vertical greenings	-	4+	-
(Farhadi, Faizi et al. 2019)	Sustainable Cities and Society	2019	Tehran, Iran	Asia	BSk	Summer	Green roofs	√	4.3	-
(Fikfak, Lavtižar et al. 2020)	Sustainability	2020	Ljubljana, Slovenia	Europe	Cfb	Summer	Trees, Vertical greenings	-	4+(Science version)	-
(Gatto, Buccolieri et al. 2020)	Forests	2020	Lecce, Italy Lahti, Finland	Europe	-	Summer, Winter	Trees	√	4+	-
(Herath, Halwatura et al. 2018)	Urban Forestry & Urban Greening	2018	Bambalapitiya, Sri Lanka	Asia	Af	Summer	Trees, Green roofs, Vertical greenings	√	4	-
(Jacobs, Klok et al. 2020)	Urban Climate	2020	Various cities, Netherlands	Europe	Cfb	summer	Water bodies	-	4.1.3	-
(Jiang, Han et al. 2018)	Sustainability	2018	Shanghai, China	Asia	Cfa	Summer	Trees, Grass, Shrubs, Water bodies	√	4	-
(Jin, Bai et al. 2018)	Urban Forestry & Urban Greening	2018	Chongqing, China	Asia	Cfa	Summer	Green roofs	√	4	-
(Karimi, Sanaieian et al. 2020)	Energy Reports	2020	Tehran, Iran	Asia	BSk	Summer	Trees	√	4.3.2	-
(Katsoulas, Antoniadis et al. 2017)	International journal of biometeorology	2017	Arta, Greece	Europe	Csa	Summer	Green roofs, Vertical greenings	√	4	-
(Kim, Lee et al. 2020)	Sustainability	2020	Seoul, Korea	Asia	Dwa	Summer	Green roofs	-	4+	-
(Knaus and Haase 2020)	Urban Forestry & Urban Greening	2020	Berlin, Germany	Europe	Cfb	Summer	Green roofs	-	4.4	-
(Kong, Middel et al. 2016)	Applied Energy	2016	Nanjing, China	Asia	Cfa	Summer	Trees, Grass, Shrubs	√	4+	
(Lalošević, Komatina et al. 2018)	Thermal Science	2018	Belgrade, Serbia	Europe	Cfa	Summer	Green roofs	-	4	-
(Lee, Mayer et al. 2016)	Landscape and Urban Planning	2016	Freiburg, Germany	Europe	Cfb	Summer	Trees, Grass	√	4	-

(Lee, Mayer et al. 2020)	Urban Forestry & Urban Greening	2020	Freiburg, Germany	Europe	Cfb	Summer	Trees	-	4	-
(Li, Wang et al. 2020)	Journal of Cleaner Production	2020	Guangzhou, China	Asia	Cfa	Summer	Trees, Grass, Water bodies	√	4+	-
(Li, Zheng et al. 2019)	Energies	2019	Changsha, China	Asia	Cfa	Summer	Vertical greenings	-	4.4.1	-
(Li and Song 2019)	International Review for Spatial Planning and Sustainable Development	2019	Seoul, Korea	Asia	Dwa	Summer	Trees, Shrubs	√	4	-
(Liu, Brown et al. 2020)	Urban Forestry & Urban Greening	2020	Guangzhou, China	Asia	Cfa	Summer	Trees	-	4.2	-
(Lobaccaro and Acero 2015)	Urban Climate	2015	Bilbao, Spain	Europe	Cfb	Summer	Trees, Green roofs, Grass	-	4	-
(Makido, Hellman et al. 2019)	Atmosphere	2019	Portland, USA	North America	Csb	Summer	Trees, Green roofs	√	4.2	-
(Manteghi, Shukri et al. 2019)	Journal of Advanced Research in Fluid Mechanics and Thermal Sciences	2019	Melaka, Malaysia	Asia	Af	Summer	Water bodies	-	4	
(Morakinyo, Dahanayake et al. 2017)	Energy and Buildings	2017	Hong Kong SAR, China Cairo, Egypt Tokyo, Japan Paris, France	Asia	-	Summer	Green roofs	-	4	EnergyPlus
(Morakinyo, Kong et al. 2017)	Building and Environment	2017	Hong Kong SAR, China	Asia	Cwa	Summer	Trees	√	4	-
(Morakinyo, Lai et al. 2019)	Urban Forestry & Urban Greening	2019	Hong Kong SAR, China	Asia	Cwa	Summer	Vertical greenings	√	4	-
(Morakinyo and Lam 2016)	Building and Environment	2016	Hong Kong SAR, China	Asia	Cwa	Summer	Trees	-	4	-
(Morakinyo, Lau et al. 2018)	Building and Environment	2018	Hong Kong SAR, China	Asia	Cwa	Summer	Trees	√	4	-
(Morakinyo, Lau et al. 2020)	Science of the Total Environment	2020	Hong Kong SAR, China	Asia	Cwa	Summer	Trees	√	4	-

(Ouyang, Morakinyo et al. 2020)	Building and Environment	2020	Hong Kong SAR, China	Asia	Cwa	Summer	Trees	√	4.3	-
(Peng, Jiang et al. 2020)	Building and Environment	2020	Nanjing, China	Asia	Cfa	Summer	Vertical greenings	√	4.4	-
(Rahul, Mukherjee et al. 2020)	International Journal of Biometeorology	2020	Roorkee, India	Asia	Cfa	Summer	Water bodies	√	4.4.4	-
(Rui, Buccolieri et al. 2018)	Forests	2018	Nanjing, China	Asia	Cfa	Summer	Trees, Grass	-	4.3	-
(Rui, Buccolieri et al. 2019)	Building Simulation	2019	Nanjing, China	Asia	Cfa	Summer	Trees, Grass, Shrubs	-	4	-
(Sahnoune and Benhassine 2017)	International Journal of Environmental Science and Development	2017	Constantine, Algeria	Africa	Csa	Summer	Green roofs	-	4	-
(Shi, Song et al. 2020)	Sustainable Cities and Society	2020	Chongqing, China	Asia	Cfa	Summer	Trees, Grass, Water bodies	√	4.4	-
(Sodoudi, Zhang et al. 2018)	Urban Forestry & Urban Greening	2018	Berlin, Germany	Europe	Cfb	Summer	Trees, Grass, Shrubs	√	4	-
(Srivanit and Jareemit 2020)	Journal of Building Engineering	2020	Bangkok, Thailand	Asia	Aw	Summer	Trees	√	4+	-
(Su, Cai et al. 2017)	Sustainability	2017	Nanjing, China	Asia	Cfa	Summer	Trees, Grass, Shrubs	√	4+	-
(Teshnehdel, Akbari et al. 2020)	Building and Environment	2020	Tabriz, Iran	Asia	BSk	Summer, Winter	Trees	√	4	-
(Tukiran, Ariffin et al. 2017)	International Journal of GEOMATE	2017	Penang, Malaysia	Asia	Af	Winter	Trees	√	4	-
(Wang, Ni et al. 2019)	Journal of Cleaner Production	2019	Shenzhen, China	Asia	Cwa	Summer, Winter, Autumn	Trees, Green roofs	√	4.3.2	-
(Wu and Chen 2017)	Landscape and Urban Planning	2017	Beijing, China	Asia	Dwa	Summer	Trees	√	4+	-
(Wu, Dou et al. 2019)	Sustainable Cities and Society	2019	Beijing, Xiamen, Changchun, China	Asia	-	Summer	Trees	√	4+	-
(Xu, Liu et al. 2019)	Energy & Buildings	2019	Beijing, China	Asia	Dwa	Summer	Trees, Water bodies	√	4+	-

(Yang, Zhou et al. 2018)	Sustainable Cities and Society	2018	Xi'an, China	Asia	Cfa	Summer	Trees	√	4	-
(Yang, Zhou et al. 2019)	Sustainable Cities and Society	2019	Xi'an, China	Asia	Cfa	Summer	Trees, Grass, Shrubs	√	4.3.2	-
(Yilmaz, Mutlu et al. 2020)	Environmental Science and Pollution Research	2020	Erzurum, Turkey	Asia	Dsb	Summer, Winter	Trees	√	4.4.2	-
(Zhang, Bao-Jie et al. 2019)	International Journal of Environmental Research and Public Health	2019	Hangzhou, China	Asia	Cfa	Summer	Green roofs	√	4.3.1	-
(Zhang, Zhan et al. 2018)	Building and Environment	2018	Wuhan, China	Asia	Cfa	Summer, Winter	Trees	√	4	-
(Zhao, Sailor et al. 2018)	Urban Forestry & Urban Greening	2018	Tempe, USA	North America	BWh	Summer	Trees	√	4+	-
(Zheng, Bedra et al. 2018)	Sustainability	2018	Shantou, China	Asia	Cwa	Summer	Trees	-	4.3.2	-
(Ziaul and Pal 2020)	Advances in Space Research	2020	West Bengal, India	Asia	Aw	Summer	Green roofs, Vertical greenings	√	4.1	Landsat
(Zölch, Maderspacher et al. 2016)	Urban Forestry & Urban Greening	2016	Munich, Germany	Europe	Cfb	Summer	Trees, Green roofs, Vertical greenings	-	4	-
(Zölch, Rahman et al. 2019)	Building and Environment	2019	Munich, Germany	Europe	Cfb	Summer	Trees, Grass	√	4.2	-
(Di Giuseppe, Ulpiani et al. 2020)	Energy & Buildings	2020	Rome, Italy	Europe	Csa	Summer	Water bodies	√	4.4.3	-
(Fahmy and Abdelghany 2020)	Journal of Engineering and Applied Science	2020	New Cairo, Egypt	Africa	BWh	Summer	Trees, Grass	-	4.3.2	-
(Jiang, Jiang et al. 2020)	International Journal of Environmental Research and Public Health	2020	Shanghai, China	Asia	Cfa	Summer	Trees, Grass	-	4.3	ArcGIS, machine learning
(Peng, Jiang et al. 2020)	Applied Energy	2020	Nanjing, China	Asia	Cfa	Summer	Vertical greenings	√	4.4	Energy plus

(Aboelata 2020)	Energy	2020	Cairo, Egypt	Africa	BWh	Summer	Green roofs	√	4.4.4	DesignBuilder
(Tsoka, Leduc et al. 2021)	Sustainable Cities and Society	2020	Thessaloniki, Greece	Europe	Csa	Summer	Trees	√	4	Energy plus

Appendix B. Validation results of the reviewed studies

Reference	Period of records	Evaluation parameter	R^2	RMSE	$RMSE_s$	$RMSE_u$	d	MAE	MBE	Maximum difference between observation and simulation	MAPE	Note
(Abdi, Hami et al. 2020)	Summer	Ta	0.96	0.96	-	-	-	-	-	-	-	-
		RH	0.89	3.83	-	-	-	-	-	-	-	-
(Aboelata 2020)	Summer	Ta	0.96	0.46	-	-	-	-	-	-	-	-
(Aboelata and Sodoudi 2019)	Summer	Ta	0.96	0.46	-	-	-	-	-	-	-	-
(Aboelata and Sodoudi 2020)	Summer	Ta	0.96	0.46	-	-	-	-	-	-	-	-
(Antoniadis, Katsoulas et al. 2018)	Summer	SW	0.97	45	-	-	-	-	-	-	-	-
		PET	-	1.79	-	-	-	-	-	-	-	-
		Ta	-	-	-	-	-	-	-	0.8	-	-
		RH	-	-	-	-	-	-	-	3%	-	-
(Atwa, Ibrahim et al. 2020)	Summer	Ta	-	-	-	-	-	-	-	-	-	Simple quantitative analysis
(Berardi 2016)	Summer	Ta	0.92	-	-	-	-	-	-	2.5	-	-
		SVF	-	-	-	-	-	-	-	-	-	Simple quantitative analysis
(Berardi, Jandaghian et al. 2020)	Summer	Ta	-	-	-	-	-	-	-	0.5	-	-
(Chen, Zheng et al. 2020)	Summer	Ta	0.88-0.97	0.67-1.44	-	-	-	-	-	-	-	-
(Daemei, Azmoodeh et al. 2018)	Combined with summer and winter	Ta	-	-	-	-	-	-	-	0.24	-	-
(Duarte, Shinzato et al. 2015)	Summer	Ta	-	1.61	-	-	0.85	1.41	-	-	-	-
(Farhadi, Faizi et al. 2019)	Summer	Ta	0.92	-	-	-	-	-	-	0.39	-	-
(Gatto, Buccolieri et al. 2020)	Winter	Ta	0.9	-	-	-	-	-	-	-	-	-
	Summer	RH	0.9	-	-	-	-	-	-	-	-	-
(Herath, Halwatura et al. 2018)	Summer	Ta	0.78-0.96	-	-	-	-	-	-	-	-	-
(Jiang, Han et al. 2018)	Summer	Ta	-	0.45-1.43	-	-	-	-	-	-	-	-

(Jin, Bai et al. 2018)	Summer	Ta	-	0.68-1.21	-	-	-	-	-	-	-	-
		RH	-	2.92%-6.13%	-	-	-	-	-	-	-	-
(Karimi, Sanaieian et al. 2020)	Summer	Ta	0.826	-	-	-	-	0.25	-	2.6	-	-
(Katsoulas, Antoniadis et al. 2017)	Summer	Ta	0.93-0.98	-	-	-	-	-	-	-	-	-
		RH	0.8-0.86	-	-	-	-	-	-	-	-	-
		SR	0.97	8.50%	-	-	-	-	-	-	-	-
(Kong, Middel et al. 2016)	Summer	Ta	-	1.14	0.43	1.06	0.95	-	-	-	-	-
(Lee, Mayer et al. 2016)	Summer	Ta	0.85	0.66	0.19	0.62	0.95	-	-	-	-	-
		Tmrt	0.86	5.49	2.39	4.94	0.95	-	-	-	-	-
		PET	0.77	3.98	3.06	2.52	0.84	-	-	-	-	-
(Li, Wang et al. 2020)	Summer	Ta	0.9-0.96	0.37-1.14	-	-	0.86-0.97	1-2.84	-	-	-	-
		RH	0.63-0.75	2.73-3.32	-	-	0.71-0.77	4.65-5.61	-	-	-	-
(Li and Song 2019)	Summer	Ta	-	1.59-2.16	-	-	0.7-0.8	1.4-2.01	1.27-2.01	-	-	-
(Makido, Hellman et al. 2019)	Summer	Ta	0.66-0.93	-	-	-	-	-	-	-	-	-
(Morakinyo, Kong et al. 2017)	Summer, autumn	Ta	0.79-0.81	-	-	-	-	-	-	-	-	-
	Summer, autumn	Tmrt	0.69-0.74	-	-	-	-	-	-	-	-	-
(Morakinyo, Lai et al. 2019)	Summer	Ta	0.89	0.5	-	-	-	-	-	-	1.1	-
		RH	0.76	11.10%	-	-	-	-	-	-	13.9	-
		Emitted longwave flux	0.66-0.7	40.7-42.0	-	-	-	-	-	-	7.7-8.5	-
		Ts	0.6-0.74	2.3-5.1	-	-	-	-	-	-	5.8-12.1	-
(Morakinyo, Lau et al. 2018)	Summer	Ta	0.79-0.81	1-1.4	-	-	-	-	-	-	3.7-5.1	-
		Tmrt	0.69-0.74	2.2-3.9	-	-	-	-	-	-	7.7-13.2	-

(Morakinyo, Lau et al. 2020)	Summer	Ta	0.79-0.81	-	-	-	-	-	-	-	3.7-5.1	-
		Tmrt	0.69-0.74	-	-	-	-	-	-	-	7.7-13.2	-
(Ouyang, Morakinyo et al. 2020)	Summer	T	0.79-0.81	-	-	-	-	-	-	-	-	-
		Tmrt	0.69-0.74	-	-	-	-	-	-	-	-	-
(Peng, Jiang et al. 2020)	Summer	Ts	-	1.4-1.81	-	-	-	-	-	-	-	-
		Ta	-	0.31-0.35	-	-	-	-	-	-	-	-
(Rahul, Mukherjee et al. 2020)	Summer	Ta	0.96-0.98	0.7-3.7	-	-	0.96-0.98	-	-	-	-	-
(Shi, Song et al. 2020)	Summer	Ta	-	1.02-1.95	-	-	-	-	-	-	-	-
		RH	-	-	-	-	-	-	-	-	1.86-6.45	-
(Sodoudi, Zhang et al. 2018)	Summer	Ta	0.92	1.26	-	-	-	-	-	-	-	-
(Srivanit and Jareemit 2020)	Summer	Tmrt	0.91	-	-	-	-	-	-	-	-	Normalized mean squared error :0.17
(Su, Cai et al. 2017)	Autumn	Ts	-	-	-	-	-	-	-	-	-	Simple quantitative analysis
(Teshnehdel, Akbari et al. 2020)	Winter	Ta	over 0.89	0.78	-	-	-	-	-	-	-	
		RH	0.90	1.71%	-	-	-	-	-	-	-	
(Tukiran, Ariffin et al. 2017)	Winter	Ta	-	-	-	-	-	-	-	-	-	Paired difference Mean:0.50 StD:0.98
		RH	-	-	-	-	-	-	-	-	-	Paired difference Mean:2.44 StD:4.58
		WS	-	-	-	-	-	-	-	-	-	Paired difference Mean:0.06 StD:0.33
		SR	-	-	-	-	-	-	-	-	-	Paired difference Mean:17.35 StD:28.89
(Wang, Ni et al. 2019)	Summer	Ta	0.62-0.93	0.54-1.45	-	-	0.65-0.99	0.41-1.26	-	-	-	-
	Autumn	Ta	0.66-0.79	0.46-0.72	-	-	0.71-0.87	0.40-0.61	-	-	-	-
	Winter	Ta	0.71-0.78	0.31-0.70	-	-	0.83-0.93	0.26-0.63	-	-	-	-
(Wu and Chen 2017)	Summer	Ta	-	1.05	-	-	0.93	0.95	-0.49	-	-	-
(Wu, Dou et al. 2019)	Summer	Ta	-	1.05	-	-	0.93	0.95	-0.49	-	-	-

(Xu, Liu et al. 2019)	Summer	Ta	0.79-0.89	-	-	-	-	-		-	-	-
(Yang, Zhou et al. 2018)	Summer	Ta	0.92-0.0.98	0.94-2.34	0.39-1.81	0.85-1.49	-	-	0.38-1.58	-	-	-
		RH	0.87-0.92	2.04%-2.94%	0.58%-2.58%	1.4%-1.95%	-	-	(-2.54%)-(-0.77%)	-	-	-
(Yang, Zhou et al. 2019)	Summer	Ta	0.79	3.72	2.14	5.68	-	-	-	-	8.90%	-
		RH	2.65%	1.25%	3.53%	4.76%	-	-	-	-	4.76%	-
(Yilmaz, Mutlu et al. 2020)	Summer	Ta	0.77-0.78	-	-	-	1.00	-	-	-	-	-
	Winter	Ta	0.81-0.92	-	-	-	0.88-0.91	-	-	-	-	-
(Zhang, Bao-Jie et al. 2019)	Summer	Ta	0.89	-	-	-		-	-	-	-	-
(Zhang, Zhan et al. 2018)	Summer	Ta	0.89	1.46	-	-	0.91	0.77	-	-	-	-
		WS	0.71	0.19	-	-	0.77	0.14	-	-	-	-
		Tmrt	0.89	5.21	-	-	0.78	4.82	-	-	-	-
	Winter	Ta	0.71	0.97	-	-	0.72	0.9	-	-	-	-
		WS	0.51	0.14	-	-	0.81	0.1	-	-	-	-
		Tmrt	0.89	5.03	-	-	0.76	4.71	-	-	-	-
(Zhao, Sailor et al. 2018)	Summer	Ta	-	1.1-2.1	1.1-2.1	0.1-0.2	-	1.1-2	-	-	-	-
(Ziaul and Pal 2020)	Summer	Ta	0.72-0.92	-	-	-	-	-	-	-	-	-
(Zölch, Rahman et al. 2019)	Summer	Ta	0.93-0.94	1.28-1.36	-	-	-	-	-	-	-	-
(Di Giuseppe, Ulpiani et al. 2020)	Summer	Ta	0.81-0.93	0.73-0.98	-	-	0.93-0.98	-	-	-	-	-
(Peng, Jiang et al. 2020)	Summer	Ta	0.99	0.31-0.35	-	-	-	-	-	-	-	-
		RH	0.97-0.98	4.09%-4.22%	-	-	-	-	-	-	-	-
		Ts	0.51-0.97	1.4-1.81	-	-	-	-	-	-	-	-

Note: The difference measure terms have the units of the corresponding variable.

Appendix C. The reported GBI-targeted validation results

GBI type	Evaluation parameter	Evaluation target	R^2	RMSE	d	MAE	MBE	MAPE	Reference
Tree	Ta	Unshaded area	-	1.59	0.8	1.4	1.27	-	(Li and Song 2019)
Tree	Ta	Unshaded area	0.79	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
Tree	Ta	Unshaded area	0.79	1.4	-	-	-	5.1	(Morakinyo, Lau et al. 2018)
Tree	Ta	Unshaded area	0.79	-	-	-	-	5.1	(Morakinyo, Lau et al. 2020)
Tree	Ta	Unshaded area	0.79	-	-	-	-	-	(Ouyang, Morakinyo et al. 2020)
Tree	Ta	Tree-shaded area	-	2.16	0.7	2.01	2.01	-	(Li and Song 2019)
Tree	Ta	Tree-shaded area	0.81	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
Tree	Ta	Tree-shaded area	0.81	1	-	-	-	3.7	(Morakinyo, Lau et al. 2018)
Tree	Ta	Tree-shaded area	0.81	-	-	-	-	3.7	(Morakinyo, Lau et al. 2020)
Tree	Ta	Tree-shaded area	0.81	-	-	-	-	-	(Ouyang, Morakinyo et al. 2020)
Tree	Tmrt	Unshaded area	0.69	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
Tree	Tmrt	Unshaded area	0.69	3.9	-	-	-	13.2	(Morakinyo, Lau et al. 2018)
Tree	Tmrt	Unshaded area	0.69	-	-	-	-	13.2	(Morakinyo, Lau et al. 2020)
Tree	Tmrt	Unshaded area	0.69	-	-	-	-	-	(Ouyang, Morakinyo et al. 2020)
Tree	Tmrt	Tree-shaded area	0.74	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
Tree	Tmrt	Tree-shaded area	0.74	2.2	-	-	-	7.7	(Morakinyo, Lau et al. 2018)
Tree	Tmrt	Tree-shaded area	0.74	-	-	-	-	7.7	(Morakinyo, Lau et al. 2020)
Tree	Tmrt	Tree-shaded area	0.74	-	-	-	-	-	(Ouyang, Morakinyo et al. 2020)
Green façade	Ta	Near bare façade	-	0.35	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	Ta	Near bare façade	0.99	0.35	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	Ta	Near green façade	-	0.31	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	Ta	Near green façade	0.99	0.31	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	Ta	Differences between bare and green façade	-	0.16	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	RH	Near bare façade	0.97	4.22	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	RH	Near green façade	0.98	4.09	-	-	-	-	(Peng, Jiang et al. 2020)
Green façade	TS	Bare façade	0.6	5.1	-	-	-	12.1	(Morakinyo, Lai et al. 2019)
Green façade	TS	Bare façade	-	1.81	-	-	-	-	(Peng, Jiang et al. 2020)

			0.97	1.81	-	-	-	-	(Peng, Jiang et al. 2020)
		Green façade	0.74	2.3	-	-	-	5.8	(Morakinyo, Lai et al. 2019)
			-	1.4	-	-	-	-	(Peng, Jiang et al. 2020)
			0.51	1.4	-	-	-	-	(Peng, Jiang et al. 2020)
		Differences between bare and green façade	-	1.24	-	-	-	-	(Peng, Jiang et al. 2020)
	Emitted long wave flux	Bare façade	0.7	40.7	-	-	-	7.7	(Morakinyo, Lai et al. 2019)
		Green façade	0.66	42.0	-	-	-	8.5	(Morakinyo, Lai et al. 2019)
Simple plant	Ta	Atrium without planted hydroponic pergola	0.98	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
		Atrium with planted hydroponic pergola	0.86	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
	RH	Atrium without planted hydroponic pergola	0.93	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)
		Atrium with planted hydroponic pergola	0.8	-	-	-	-	-	(Katsoulas, Antoniadis et al. 2017)

Note: The difference measure terms have the units of the corresponding variable

References

Abdi, B., A. Hami and D. Zarehaghi (2020). "Impact of small-scale tree planting patterns on outdoor cooling and thermal comfort." Sustainable Cities and Society **56**.

Aboelata, A. (2020). "Assessment of Green Roof Benefits on Buildings' Energy-Saving by Cooling Outdoor Spaces in Different Urban Densities in Arid Cities." Energy: 119514.

Aboelata, A. (2020). "Vegetation in different street orientations of aspect ratio (H/W 1:1) to mitigate UHI and reduce buildings' energy in arid climate." Building and Environment **172**: 1.

Aboelata, A. and S. Sodoudi (2019). "Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo." Building and Environment **166**: 1.

Aboelata, A. and S. Sodoudi (2020). "Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo." Building and Environment **168**: 1.

Acero, J. A., E. J. Y. Koh, X. Li, L. A. Ruefenacht, G. Pignatta and L. K. Norford (2019). "Thermal impact of the orientation and height of vertical greenery on pedestrians in a tropical area." Building Simulation **12**(6): 973-984.

Al Jadaa, D., A. Abu Raed and H. Taleb (2019). "Assessing the Thermal Effectiveness of Implementing Green Roofs in the Urban Neighborhood." Jordan Journal of Mechanical and Industrial Engineering **13**(3): 161-174.

Altunkasa, C. and C. Uslu (2020). "Use of outdoor microclimate simulation maps for a planting design to improve thermal comfort." Sustainable Cities and Society **57**.

Antoniadis, D., N. Katsoulas and C. Kittas (2018). "Simulation of schoolyard's microclimate and human thermal comfort under Mediterranean climate conditions: effects of trees and green structures." International Journal of Biometeorology **62**(11): 2025-2036.

Atwa, S., M. G. Ibrahim and R. Murata (2020). "Evaluation of plantation design methodology to improve the human thermal comfort in hot-arid climatic responsive open spaces." Sustainable Cities and Society **59**.

Berardi, U. (2016). "The outdoor microclimate benefits and energy saving resulting from green roofs retrofits." Energy and Buildings **121**: 217-229.

Berardi, U., Z. Jandaghian and J. Graham (2020). "Effects of greenery enhancements for the resilience to heat waves: A comparison of analysis performed through mesoscale (WRF) and microscale (Envi-met) modeling." Sci Total Environ **747**: 141300.

Bochenek, A. D. and K. Klemm (2020). "The Impact of Passive Green Technologies on the Microclimate of Historic Urban Structures: The Case Study of Lodz." Atmosphere **11**(9): 974.

Chen, Y. P., B. H. Zheng and Y. Z. Hu (2020). "Numerical Simulation of Local Climate Zone Cooling Achieved through Modification of Trees, Albedo and Green Roofs-A Case Study of Changsha, China." Sustainability **12**(7): 23.

Cipolla, S. S., M. Maglionico, G. Semprini, V. Villani and A. Bonoli (2018). "Green roofs as a strategy for urban heat island mitigation in Bologna (Italy)." Acta horticulturae(1215): 295-300.

Daemei, A. B., M. Azmoodeh, Z. Zamani and E. M. Khotbehsara (2018). "Experimental and simulation studies on the thermal behavior of vertical greenery system for temperature mitigation in urban spaces." Journal of Building Engineering **20**: 277-284.

Di Giuseppe, E., G. Ulpiani, C. Cancellieri, C. Di Perna, M. D'Orazio and M. Zinzi (2020). "Numerical modelling and experimental validation of the microclimatic impacts of water mist cooling in urban areas." Energy and Buildings: 110638.

Duarte, D. H. S., P. Shinzato, C. D. Gusson and C. A. Alves (2015). "The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate." Urban Climate **14**: 224-239.
Fabbri, K., G. Canuti and A. Ugolini (2017). "A methodology to evaluate outdoor microclimate of the archaeological site and vegetation role: A case study of the Roman Villa in Russi (Italy)." Sustainable Cities and Society **35**: 107-133.
Fahmy, A. and D. Abdelghany (2020). "Effect of grass and trees on outdoor thermal comfort in outdoor entertainment venues in hot arid climate." Journal of Engineering and Applied Science **67**(6): 1269-1284.
Fahmy, M., H. El-Hady, M. Mahdy and M. F. Abdelalim (2017). "On the green adaptation of urban developments in Egypt; predicting community future energy efficiency using coupled outdoor-indoor simulations." Energy and Buildings **153**: 241-261.
Fahmy, M., Y. Ibrahim, E. Hanafi and M. Barakat (2018). "Would LEED-UHI greenery and high albedo strategies mitigate climate change at neighborhood scale in Cairo, Egypt?" Building Simulation **11**(6): 1273-1288.
Farhadi, H., M. Faizi and H. Sanaieian (2019). "Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings." Sustainable Cities and Society **46**.
Fikfak, A., K. Lavtižar, J. P. Grom, S. Kosanović and M. Zbašnik-Senegačnik (2020). "Study of Urban Greenery Models to Prevent Overheating of Parked Vehicles in P + R Facilities in Ljubljana, Slovenia." Sustainability **12**(12): 5160.
Gatto, E., R. Buccolieri, E. Aarrevaara, F. Ippolito, R. Emmanuel, L. Perronace and J. L. Santiago (2020). "Impact of Urban vegetation on outdoor thermal comfort: Comparison between a Mediterranean city (Lecce, Italy) and a northern European city (Lahti, Finland)." Forests **11**(2).
Herath, H., R. U. Halwatura and G. Y. Jayasinghe (2018). "Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy." Urban Forestry & Urban Greening **29**: 212-222.
Jacobs, C., L. Klok, M. Bruse, J. Cortesão, S. Lenzholzer and J. Kluck (2020). "Are urban water bodies really cooling?" Urban Climate **32**.
Jiang, Y., X. Han, T. Shi and D. Song (2018). "Adaptive Analysis of Green Space Network Planning for the Cooling Effect of Residential Blocks in Summer: A Case Study in Shanghai." Sustainability **10**(9).
Jiang, Y., S. Jiang and T. Shi (2020). "Comparative study on the cooling effects of green space patterns in waterfront build-up blocks: An experience from Shanghai." International Journal of Environmental Research and Public Health **17**(22): 1-29.
Jin, C., X. Bai, T. Luo and M. Zou (2018). "Effects of green roofs' variations on the regional thermal environment using measurements and simulations in Chongqing, China." Urban forestry & urban greening **29**: 223-237.
Karimi, A., H. Sanaieian, H. Farhadi and S. Norouzian-Maleki (2020). "Evaluation of the thermal indices and thermal comfort improvement by different vegetation species and materials in a medium-sized urban park." Energy Reports **6**: 1670-1684.
Katsoulas, N., D. Antoniadis, I. L. Tsirogiannis, E. Labraki, T. Bartzanas and C. Kittas (2017). "Microclimatic effects of planted hydroponic structures in urban environment: measurements and simulations." International journal of biometeorology **61**(5): 943-956.
Kim, J., S. Y. Lee and J. Kang (2020). "Temperature Reduction Effects of Rooftop Garden Arrangements: A Case Study of Seoul National University." Sustainability **12**(15): 6032.
Knaus, M. and D. Haase (2020). "Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany." Urban Forestry and Urban Greening **53**.
Kong, F., A. Middel, C. Sun, C. Skelhorn, F. Jiang, F. Liu, G. Cavan, H. Yin, I. Dronova and Y. Pu (2016). "Energy saving potential of fragmented green spaces due to their temperature regulating ecosystem services in the summer." Applied energy **183**: 1428-1440.

Lalošević, M. D., M. S. Komatina, M. V. Miloš and N. R. Rudonja (2018). "Green roofs and cool materials as retrofitting strategies for urban heat island mitigation: Case study in Belgrade, Serbia." Thermal Science **22**(6A): 2309-2324.
Lee, H., H. Mayer and L. Chen (2016). "Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany." Landscape and urban planning **148**: 37-50.
Lee, H., H. Mayer and W. Kuttler (2020). "Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions." Urban forestry & urban greening **48**.
Li, J., Y. Wang, Z. Ni, S. Chen and B. Xia (2020). "An integrated strategy to improve the microclimate regulation of green-blue-grey infrastructures in specific urban forms." Journal of Cleaner Production **271**.
Li, J., B. Zheng, W. Shen, Y. Xiang, X. Chen and Z. Qi (2019). "Cooling and Energy-Saving Performance of Different Green Wall Design: A Simulation Study of a Block." Energies **12**(15): 2912.
Li, Y. and Y. Song (2019). "Optimization of vegetation arrangement to improve microclimate and thermal comfort in an urban park." International Review for Spatial Planning and Sustainable Development **7**(1): 18-30.
Liu, Z., R. D. Brown, S. Zheng, Y. Jiang and L. Zhao (2020). "An in-depth analysis of the effect of trees on human energy fluxes." Urban Forestry and Urban Greening **50**.
Lobaccaro, G. and J. A. Acero (2015). "Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons." Urban Climate **14**: 251-267.
Makido, Y., D. Hellman and V. Shandas (2019). "Nature-Based Designs to Mitigate Urban Heat: The Efficacy of Green Infrastructure Treatments in Portland, Oregon." Atmosphere **10**(5).
Manteghi, G., S. M. Shukri and H. Lamit (2019). "Street geometry and river width as design factors to improve thermal comfort in Melaka City." Journal of Advanced Research in Fluid Mechanics and Thermal Sciences **58**(1): 15-22.
Morakinyo, T. E., K. Dahanayake, E. Ng and C. L. Chow (2017). "Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study." Energy and Buildings **145**: 226-237.
Morakinyo, T. E., L. Kong, K. K.-L. Lau, C. Yuan and E. Ng (2017). "A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort." Building and Environment **115**: 1.
Morakinyo, T. E., A. Lai, K. K. L. Lau and E. Ng (2019). "Thermal benefits of vertical greening in a high-density city: Case study of Hong Kong." Urban Forestry and Urban Greening **37**: 42-55.
Morakinyo, T. E. and Y. F. Lam (2016). "Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort." Building and Environment **103**: 262-275.
Morakinyo, T. E., K. K.-L. Lau, C. Ren and E. Ng (2018). "Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving." Building and Environment **137**: 157.
Morakinyo, T. E., K. K.-L. Lau, C. Ren, E. Ng and W. Ouyang (2020). "Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation - development and evaluation." Science of the Total Environment **719**.
Ouyang, W. L., T. E. Morakinyo, C. Ren and E. Ng (2020). "The cooling efficiency of variable greenery coverage ratios in different urban densities: A study in a subtropical climate." Building and Environment **174**: 13.
Peng, L. L. H., Z. Jiang, X. Yang, Y. He, T. Xu and S. S. Chen (2020). "Cooling effects of block-scale facade greening and their relationship with urban form." Building and Environment **169**: 1.

Peng, L. L. H., Z. Jiang, X. Yang, Q. Wang, Y. He and S. S. Chen (2020). "Energy savings of block-scale facade greening for different urban forms." Applied Energy **279**.
Rahul, A., M. Mukherjee and A. Sood (2020). "Impact of ganga canal on thermal comfort in the city of Roorkee, India." Int J Biometeorol.
Rui, L., R. Buccolieri, W. Ding, J. Shen and Z. Gao (2018). "The Impact of Green Space Layouts on Microclimate and Air Quality in Residential Districts of Nanjing, China." Forests **9**(4).
Rui, L., R. Buccolieri, Z. Gao, E. Gatto and W. Ding (2019). "Study of the effect of green quantity and structure on thermal comfort and air quality in an urban-like residential district by ENVI-met modelling." Building Simulation **12**(2): 183-194.
Sahnoune, S. and N. Benhassine (2017). "Quantifying the Impact of Green-Roofs on Urban Heat Island Mitigation." International Journal of Environmental Science and Development **8**(2): 116-123.
Shi, D., J. Song, J. Huang, C. Zhuang, R. Guo and Y. Gao (2020). "Synergistic cooling effects (SCEs) of urban green-blue spaces on local thermal environment: A case study in Chongqing, China." Sustainable Cities and Society **55**.
Sodoudi, S., H. Zhang, X. Chi, F. Müller and H. Li (2018). "The influence of spatial configuration of green areas on microclimate and thermal comfort." Urban forestry & urban greening **34**: 85-96.
Srivanit, M. and D. Jareemit (2020). "Modeling the influences of layouts of residential townhouses and tree-planting patterns on outdoor thermal comfort in Bangkok suburb." Journal of Building Engineering **30**.
Su, X., H. Cai, Z. Chen and Q. Feng (2017). "Influence of the Ground Greening Configuration on the Outdoor Thermal Environment in Residential Areas under Different Underground Space Overburden Thicknesses." Sustainability **9**(9): 1656.
Teshnehdel, S., H. Akbari, E. Di Giuseppe and R. D. Brown (2020). "Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran." Building and Environment **178**: 1.
Tsoka, S., T. Leduc and A. Rodler (2021). "Assessing the effects of urban street trees on building cooling energy needs: The role of foliage density and planting pattern." Sustainable Cities and Society **65**.
Tukiran, J. M., J. Ariffin and A. N. Abdul Ghani (2017). "A Study on the cooling effects of greening for improving the outdoor thermal environment in penang, Malaysia." International Journal of GEOMATE **12**(34): 62-70.
Wang, Y., Z. Ni, S. Chen and B. Xia (2019). "Microclimate regulation and energy saving potential from different urban green infrastructures in a subtropical city." Journal of cleaner production **226**: 913-927.
Wu, Z. and L. Chen (2017). "Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: Integrating modeling with in-situ measurements." Landscape and urban planning **167**: 463-472.
Wu, Z., P. Dou and L. Chen (2019). "Comparative and combinative cooling effects of different spatial arrangements of buildings and trees on microclimate." Sustainable Cities and Society **51**.
Xu, X., S. Liu, S. Sun, W. Zhang, Y. Liu, Z. Lao, G. Guo, K. Smith, Y. Cui, W. Liu, E. H. García and J. Zhu (2019). "Evaluation of energy saving potential of an urban green space and its water bodies." Energy and Buildings **0**: 58.
Yang, Y., D. Zhou, W. Gao, Z. Zhang, W. Chen and W. Peng (2018). "Simulation on the impacts of the street tree pattern on built summer thermal comfort in cold region of China." Sustainable Cities and Society **37**: 563-580.
Yang, Y., D. Zhou, Y. Wang, D. Ma, W. Chen, D. Xu and Z. Zhu (2019). "Economical and outdoor thermal comfort analysis of greening in multistory residential areas in Xi'an." Sustainable Cities and Society **51**.

Yilmaz, S., B. E. Mutlu, A. Aksu, E. Mutlu and A. Qaid (2020). "Street design scenarios using vegetation for sustainable thermal comfort in Erzurum, Turkey." Environ Sci Pollut Res Int.

Zhang, G., H. Bao-Jie, Z. Zhu and D. Bart Julien (2019). "Impact of Morphological Characteristics of Green Roofs on Pedestrian Cooling in Subtropical Climates." International Journal of Environmental Research and Public Health **16**(2).

Zhang, L., Q. Zhan and Y. Lan (2018). "Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters." Building and Environment **130**: 27.

Zhao, Q., D. J. Sailor and E. A. Wentz (2018). "Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment." Urban forestry & urban greening **32**: 81-91.

Zheng, B., K. B. Bedra, J. Zheng and G. Wang (2018). "Combination of tree configuration with street configuration for thermal comfort optimization under extreme summer conditions in the urban center of Shantou City, China." Sustainability (Switzerland) **10**(11).

Ziaul, S. and S. Pal (2020). "Modeling the effects of green alternative on heat island mitigation of a meso level town, West Bengal, India." Advances in Space Research **65**(7): 1789-1802.

Zölch, T., J. Maderspacher, C. Wamsler and S. Pauleit (2016). "Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale." Urban Forestry and Urban Greening **20**: 305-316.

Zölch, T., M. A. Rahman, E. Pfleiderer, G. Wagner and S. Pauleit (2019). "Designing public squares with green infrastructure to optimize human thermal comfort." Building and Environment **149**: 640.