

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

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## 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.

## 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

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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).

## 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

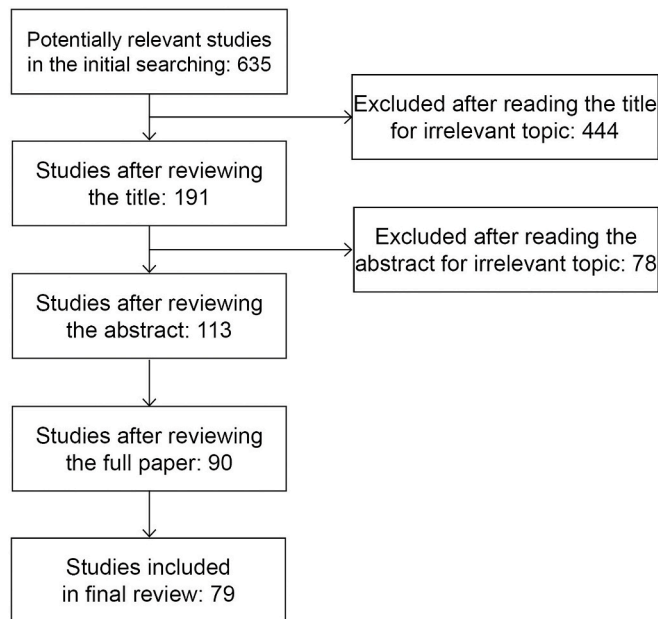


Fig. 1. The literature selection process.

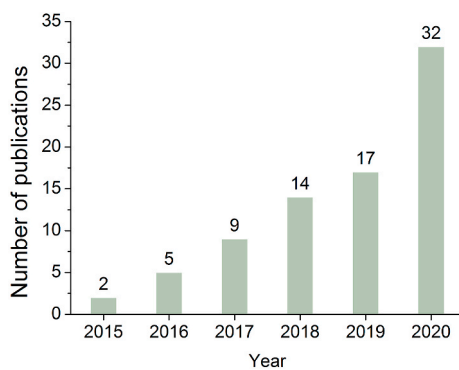


Fig. 2. Yearly distribution of the studies.

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).

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].

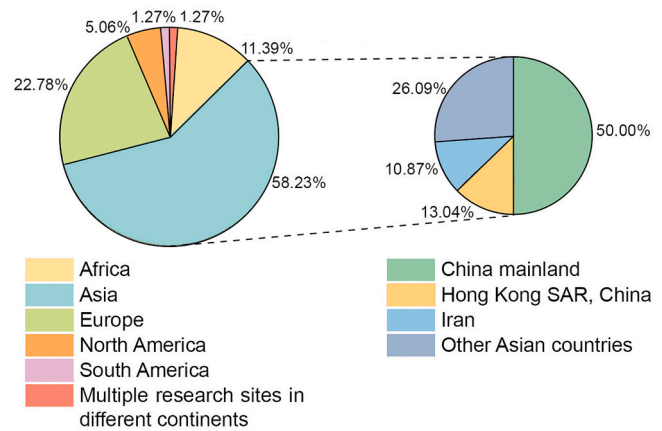


Fig. 3. Geographical distribution of the study areas.

### 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.

### 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].

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

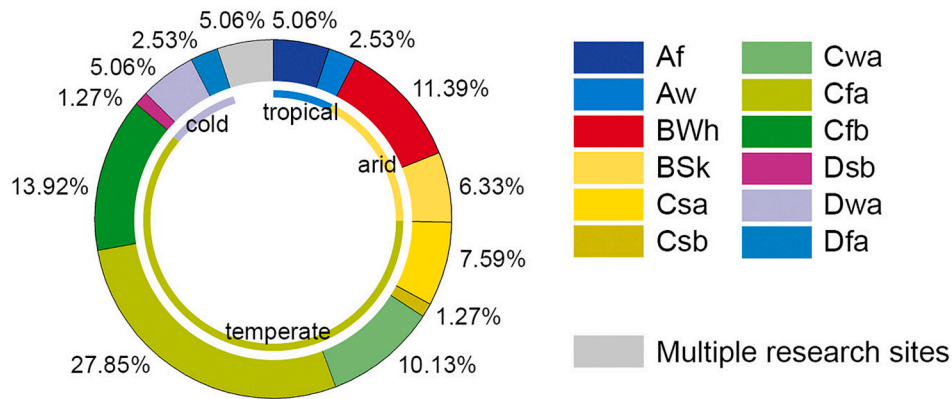


Fig. 4. Distribution of the reviewed studies by Köppen-Geiger climate zones.

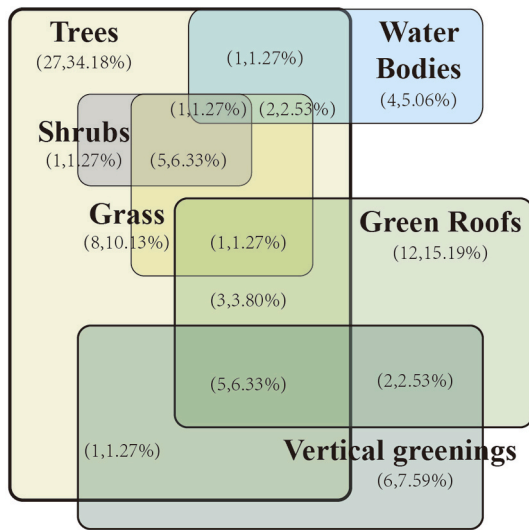


Fig. 5. The GBI research foci of the studies.

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:

$$LAI = \int_0^h LAD \cdot \Delta z \quad (1)$$

where  $h$  is tree height (m),  $\Delta z$  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

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	–	✓
Root geometry	CO <sub>2</sub> fixation type	✓	✓
	Tree calendar	–	✓
	Root Area Density (RAD)	✓	✓
	Root depth	✓	✓
	Root diameter	–	✓
	Root geometry	–	✓

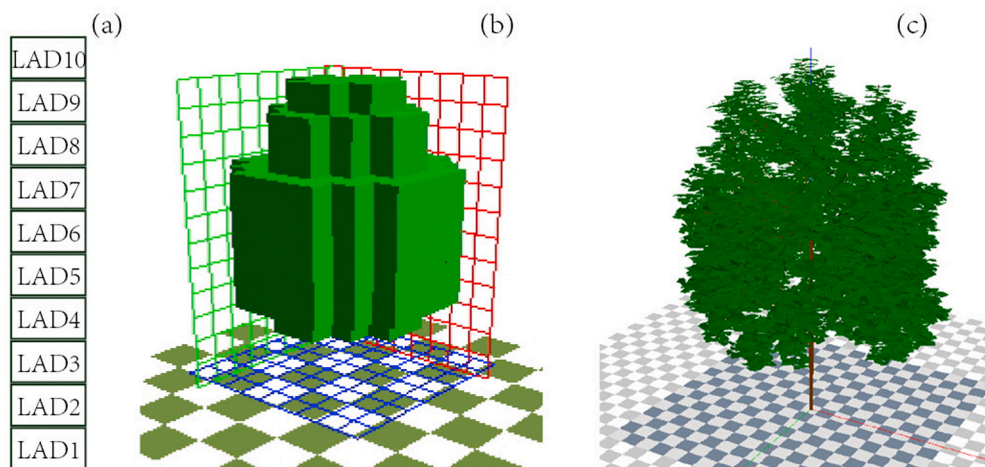


Fig. 6. ENVI-met tree models: (a) simple plants; (b) 3D-plants; and (c) the model using the Lindenmayer-System in a future version [56].

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 1 m × 1 m × 1 m 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/façade 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 or their combinations [92,120], not the greening type itself.

ENVI-met V4.4 and above allows more detailed green roof/façade modeling. Aboelata et al. [121] 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. [68,122] 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 4 m 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” [123]. The water nozzles can be inserted in the model as punctual “water sources” at the center of the grid cells [123]. The water source’s features such as particle diameter and particle density were managed in the section “pollutant conditions” of the project advanced settings in ENVI-met [123].

### 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. [122] 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’s urban green and blue infrastructure models

### 3.4.1. Significance of validation

Although previous research have specifically evaluated the ENVI-met vegetation model [50,52,83,112,124,125], 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, 126].

### 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 [126], *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) [51,83,127], 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 [128]. 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 [129]. 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 [130]. 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 [130–133]. Most of the reviewed studies employed two or three metrics, but some [20,22,75,77,92,95,116,120] chose only  $R^2$ . Willmott et al. [132] 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 [132].

### 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 [3,22,24,67,68,77,95,113,122]. 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, 122] (except some validation results of green façade [113,122] 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, 83,112,124,125], 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, 124,134–136], 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 [136].

#### 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, 24,137].
- 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 [136].
- 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  $T_a$  and  $T_{mrt}$  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 [138]. Second, as noted in previous validations [135], ENVI-met tends to overestimate the  $T_a$  of the ground layer, especially in tree-shaded areas, which means that the  $T_a$  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. [123] focused on water mist cooling and showed a high prediction accuracy for  $T_a$ .

### 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.

#### 3.5.1. Analytical indicators

**3.5.1.1. Meteorological variables.** In this study,  $T_a$ ,  $T_{mrt}$ , 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,  $T_a$  was selected by almost all studies (70, 88.61%), and 11 studies used  $T_a$  as the only analytical variable [54,61,65,75,106,116,118,123,139–141]. However, Rahul et al. [28] reported that using only  $T_a$  was insufficient for thermal stress investigation.  $T_{mrt}$  with more diverse spatial variations than  $T_a$  [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 focus on the microclimate at the roof or podium level. For temporal variations, representative hours were commonly used. Many studies selected 15:00 data [3,16,22,23,25,79,81,91,97,98,111,116,142] for three reasons. First, 15:00 is often the hottest and most uncomfortable hour in a real situation [16,25,81,91,97,98,116,142]. 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 [18,19,63,65,68,78,93,101,123]. 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.

**3.5.1.2. 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 [143]. 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  $T_a$ , RH, WS, and  $T_{mrt}$ .  $T_{mrt}$  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 [97,110,144]. 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 ( $^{\circ}\text{C}$ ), the results are comprehensible to people who may not be familiar with human-biometeorological terminology [93,144,145].

PMV is also a frequently used index chosen for three reasons. First, meteorological variables of  $T_a$ , RH, WS, and  $T_{mrt}$ , and personal factors (e.g., clothing heat resistance and human activity) are considered comprehensively [20,71,104,146]. 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 [18,20,146]. Second, it has been adopted worldwide and used in various studies [18,146,147], 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:biometpmv>).

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  $T_{mrt}$  [148]. 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].

**3.5.1.3. 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  $T_a$  reduction between open and greened areas at a vertical extent by the equations in some papers [24,73,85,136,149]. 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  $T_a$  gradient. In the reviewed studies, at the top of the next vertical grid above the tallest trees [24,85], mean building height [149], 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 [150]. 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

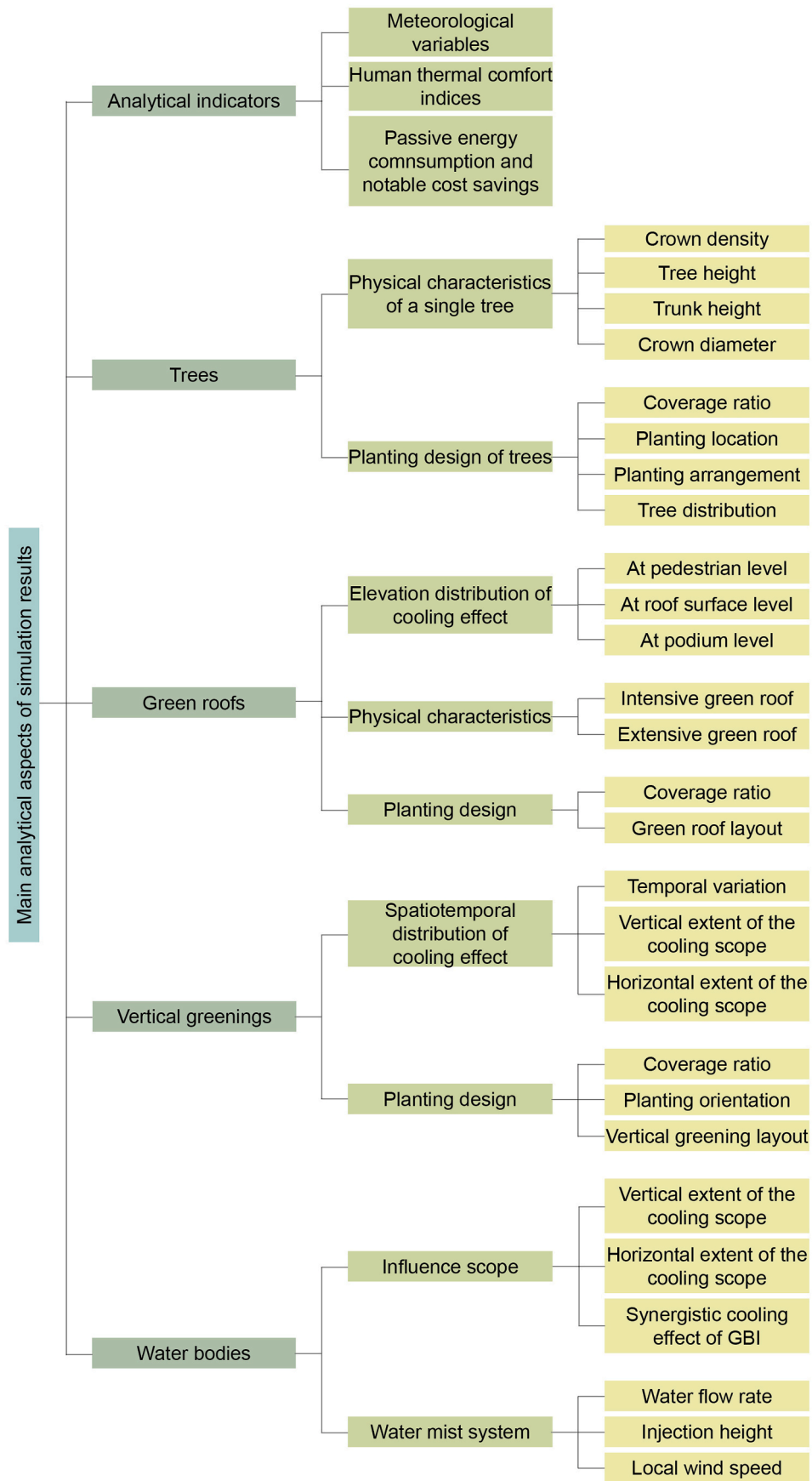


Fig. 7. Main analytical aspects of simulation results.

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) [53,58,84,121]. 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 [16,64,100,122]. 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

**3.5.2.1. 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. In contrast, for more shading beneath the tree, the crown should be at a lower height [15,24].

Due to the "umbrella effect" [151], 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].

**3.5.2.2. 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 [15,23,96,146] due to effects on wind speed, wind

direction, and shading pattern [136,152]. A good tree-planting design embodies the thermal benefits of both ventilation and shading [146].

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 [24,54,65,142] and PET [94,110], and raising RH [81,145] 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 [54,95,99,142]. Overall, the impact of trees cannot be considered as *the more, the better*, especially in high-density urban areas [153].

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 long-wave 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 [78,146] 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

**3.5.3.1. 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, 137]. 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, 137, 154, 155]. The inflection point was approximately 10 m [93, 117, 156, 157]. Moreover, Zhang et al. [75] reported that when the vertical distance (building height) exceeded 60 m, the effects on pedestrian  $T_a$  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, 154].

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].  $T_a$  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].

**3.5.3.2. 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, 158]. 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 [137]. However, green roofs' energy-saving capacity was more influenced by soil depth than LAI [137]. Zhang et al. [75] found that plant height played a critical role in cooling. When the plant height was <1 m, the  $T_a$  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, 121]. Intensive green roofs can reduce  $T_a$  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, 121].

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.

**3.5.3.3. Planting design of green roofs.** The vegetation coverage ratio had a positive correlation with cooling performance. Kim et al. [140] 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  $T_a$  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. [135] 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  $T_a$  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

**3.5.4.1. 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  $T_a$ . 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, 139]. 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  $T_{mrt}$  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  $T_a$  and wall surface temperature [77, 113, 150, 159]. A lower wall surface temperature can reduce indoor cooling energy demand [113].

**3.5.4.2. Planting design of vertical greenings.** For the coverage ratio of vertical greenings, it was agreed that "the more, the better" [113, 122]. 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 [122].

### 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.

**3.5.5.1. 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. [141] 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.

**3.5.5.2. 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 [123]. 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 [132]. 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 [160]) 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.

### Declaration of competing interest

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

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### Appendix A. Supplementary data

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