Review

Green Infrastructure as an Urban Heat Island Mitigation Strategy - A Review

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Abstract: Research on urban heat mitigation has been growing in recent years with many of the studies focusing on green infrastructure (GI) as a strategy to mitigate the adverse effects of Urban Heat Island (UHI). This paper aims at presenting a review of the range of findings from GI research for urban heat mitigation through a review of scientific articles published during the years 2009-2019. This research includes a review of the different types of GI and its contribution for urban heat mitigation and human thermal comfort. In addition to analyzing different mitigation strategies, numerical simulation tools that are commonly used are also reviewed. It is seen that ENVI-met is one of the modelling tools that is considered as a reliable tool to simulate different mitigation strategies and hence has been widely used in the recent past. Considering its popularity in urban microclimate studies, this article also provides a review of ENVI-met simulation results that were reported in the reviewed papers. It was observed that the majority of the research was conducted on a limited spatial scale and focused on temperature and human thermal comfort.

Keywords: green infrastructure; urban heat island; human thermal comfort, modelling tools; ENVI-met.

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1. Introduction

Urban Heat Island (UHI) has drawn considerable attention in recent years and is becoming a critical issue worldwide as cities develop rapidly. UHI itself is defined as a phenomenon where temperature in urban areas is higher than that of in rural areas. The main cause of UHI is modification of energy balance in urban areas. This is caused by several factors such as substantial conversion of natural green areas to impervious surfaces as a consequences of rapid urban development as well as consequences of global climate change. The negative effect of UHI has been widely documented around the world. The UHI effect contributes to increasing energy consumption through cooling requirements [1-4], reducing air quality [5-8], morbidity and mortality effects due to heat stress [9-11], and increasing water demand [12]. Considering potential harmful impacts of UHI to human lives, mitigation approaches are currently a major priority for researchers. Several studies have proposed, developed and implemented mitigation strategies such as: (1) modification of building and surface material [13, 14], (2) alteration of urban morphology [15, 16], (3) installation of irrigation systems [17] and (5) inclusion of Green Infrastructure (GI) in the planning of cities [18-20]. In a broad term, GI is defined as "interconnected network of green spaces that conserve natural systems and provides assorted benefits to human population" [21]. It includes both natural and designed greening – from parks and street trees to green roofs, gardens and green laneways. GI is recognized as a critical urban infrastructure which is equally important to transport networks. It is considered to include effective strategies in mitigating the adverse effects of UHI. GI regulates microclimate (a local set of atmospheric conditions that differ from those in the surrounding areas) through shading and evapotranspiration. Shading reduce ambient air temperature by blocking solar radiation, thus restricting the increase of air temperature as well as ground surfaces temperature. Evapotranspiration refers to transpiration from plants and evaporation from water bodies and soils. The absorbed solar energy is converted into the latent heat of evaporation thus the temperature of surrounding area is cooled. Several studies have highlighted the role of vegetation in cooling air temperature in semiarid cities [22-24] and urban areas, such as inside and around buildings [25], urban parks [26-28], urban streets [29, 30] and private landscapes [31]. The temperature reduction is depending heavily on canopy covers [32, 33] and the health status of vegetation [34, 35]. The ability to reduce temperature is also emphasized by Muller [36] who found that vegetation reduces temperature rather than water surfaces. The benefit of GI to microclimate, however, varies by size, location and types of vegetation [37].

This paper presents a review of studies published during the years 2009 – 2019 that have used GI as an UHI mitigation strategy. The review is carried out in two phases. The first phase involved identifying different GI strategies that have been used in the reviewed studies to mitigate the effect of UHI and to improve human thermal comfort. Various non-GI mitigation strategies such as alteration of urban morphology (street orientation and aspect ratio) and modification of surface and building material are also common and included in many of the reviewed papers, hence this study will briefly review them also.

To analyze the performance of the mitigation strategies, modelling tools have been used in many of the reviewed studies. In the second phase of this review, commonly used modelling tools such as ENVI-met, TownScope, RayMan and SOLWEIG are reviewed. It was observed that the use of ENVI-met in microclimate studies has been increasing significantly during the last decade. Hence, ENVI-met was selected for a detailed review that analyzed the current research trends in UHI mitigation studies that used ENVI-met.

The paper is organized as follows. Section 2 provides an overview of the reviewed papers. This is followed by a presentation of different GI-based UHI mitigation strategies in Section 3. Section 4 presents a review of the modelling software, with an emphasis on ENVI-met, its main characteristics and key results from the reviewed studies that used ENVI-met. Finally, conclusions and recommendations for future research are presented in Section 5.

2. Overview of Reviewed Papers

This study is based on a review of 70 scientific papers that were published during the years 2009 - 2019. All the reviewed papers have considered GI strategies to mitigate the effect of urban heat and several of them have also evaluated the effect of GI on improving human thermal comfort. The majority of the papers have been published in scientific, peer-reviewed international journals and few are also from international conference proceedings. The main journals where the reviewed papers were published are presented in Figure 1.

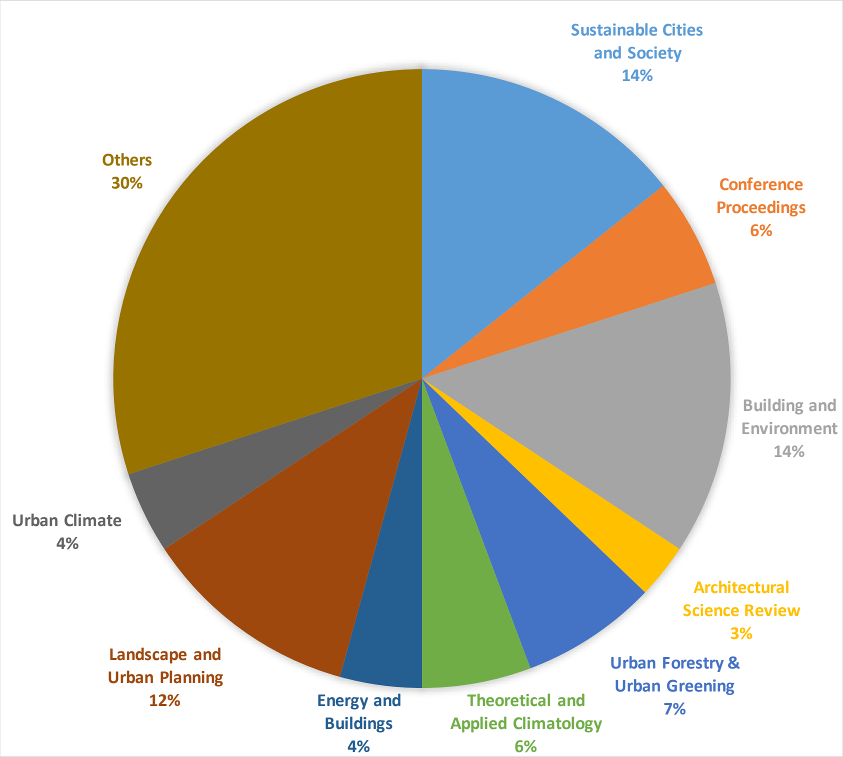

Figure 1. The main journals where the reviewed papers were published

As can be seen in Figure 1, the majority of the reviewed papers were published in the journals *Sustainable Cities and Society* (14% of reviewed papers), *Building and Environment* (14%) and *Landscape and Urban Planning* (12%). Among academic scholars, ranking of journals is considered important as it reflects the standing and repute of a journal within its field. In addition, journal rankings give information about the difficulty in publishing in a journal and the prestige associated with it. Several institutions have proposed databases that rank journals, such as the SJR (Scimago Journal Rankings), Journal Impact Factor rankings (Journal Citation Report) and Google Scholar Rankings. The SJR for example, assigns different values to citations depending on the importance of the journal from where the citation comes from. This way, citations coming from important journals will be more valuable and hence will provide more prestige to the journals receiving them. Information regarding ranking of journals of the reviewed studies based on SJR rankings are given in Table 1. It can be observed that majority of reviewed papers come from highly ranked journals.

Table 1. Ranking of main reviewed journals based on their Scimago Journal Ranking (as per 2018 rankings) (scimagojr.com)

Journal name	Country	SJR	Best quartile	Percentage of reviewed papers (%)
Sustainable Cities and Society	The Netherlands	1.1	Q1	14
Building and Environment	UK	1.88	Q1	14
Landscape and Urban Planning	The Netherlands	1.83	Q1	12
Urban Forestry & Urban Greening	Germany	0.95	Q1	7
Theoretical and Applied Climatology	Germany	0.98	Q2	6
Energy and Buildings	The Netherlands	1.93	Q1	4
Urban Climate	The Netherlands	0.89	Q1	4
Architectural Science Review	UK	0.43	Q1	4

3. UHI Mitigation Strategies

GI is increasingly considered as an essential strategy for UHI mitigation. Vegetation in GI regulates microclimate through evapotranspiration from plant foliage and shading of the surfaces and it positively influences human thermal comfort. The majority of reviewed studies proposed multiple GI strategy as a way to reduce temperature and only a few of them dealt with a single GI strategy. Several studies showed that combination of multiple GI strategies give the best result towards improving microclimate and thermal comfort [24, 38, 39], whereas 'no greening' at all were used as the worst strategy [18]. The different types of GI included trees, grass, shrubs, greening on buildings (green roof and green walls) and parks. Although urban forests exist in some countries, very few studies dealing with such forests were found in this review. The percentage of different types of GI considered in the reviewed papers are given in Figure 2. As can be seen, trees are the most used GI strategy, following by grass and green roofs. Each of the reviewed GI is discussed in detail in the following sub-sections.

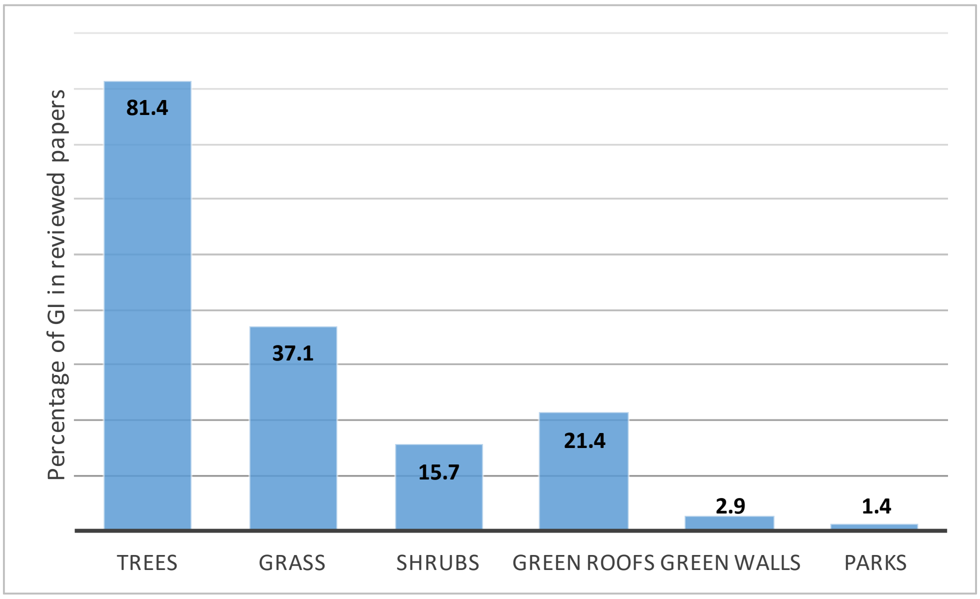

Figure 2. Types of GI in the reviewed studies

3.1. Trees

Trees are the most common GI strategy in the 70 reviewed papers, where 81.4% of the papers examine the cooling effect of trees. Trees are considered capable in reducing temperature as well as improving human thermal comfort. Skelhorn et al. [18] in their study area in Manchester found that increasing 5% of mature deciduous trees can reduce the temperature by a degree. In Hong Kong, Ng et al. [42] suggested tree coverage for at least 1/3 of total area, which is needed to reduce 1°K temperature. Human thermal comfort is also slightly enhanced by increasing tree quantity [43-46]. Although species of tree affects its cooling effect [47] only a few of the reviewed studies discussed about the impact of tree species on microclimate. A study by Kong et al. [43] investigated the impact of 12 species of trees on thermal comfort condition in a high-density area. They found large crown, short trunk and dense canopy trees can effectively reduce mean radiant temperature, which eventually will improve thermal comfort condition. The research also found that trees were planted in high density areas are more effective in improving thermal comfort condition than those were planted in open spaces. Some studies regarding urban trees suggested that arrangement of trees led to sensible heat reduction and temperature variation [19, 48]. Although trees bring positive impact to the environment, especially on the microclimate and thermal comfort, trees can also act as barriers and decrease wind speed, which ultimately will increase heat stress at a pedestrian level [37, 46]. Trees also have potential to increase pollutant concentration [45].

3.2. Grass

As much as 37.1% of the reviewed studies incorporated grass as their UHI mitigation strategy. The studies showed that the application of the grass led to a varied result on microclimate and thermal comfort condition depending on the location. Ng et al. [42] found that grass on the ground is not as effective as grass on the roof top towards improving the microclimate. This result is emphasized by Lee et al. [49] who examined the effectiveness of grass in Germany on mitigating heat stress. They also found that compared to just grass land, trees are more effective in mitigating human heat stress. However, a combination of grass and other GI may yield a better result. Lobaccaro and Acero [39] found that among the scenarios they simulated to reduce temperature, the highest reduction of temperature was achieved by combining trees and grass. The capability of grass in improving thermal comfort in winter is also shown by Afshar et al. [50]. Their study found that applying more percentage of deciduous trees and grass in a park design will increase temperature and improve thermal comfort in winter.

3.3. Shrubs

Shrubs can be distinguished from trees by their stem and height. Woody plants that are less than 6 m high are normally categorized as shrubs, while trees are over 6 m in height. Shrubs usually have multiple stems arising at or near the base without a main trunk. Several reviewed studies have examined the cooling effect of shrubs. Most of the studies indicated that applying shrubs result in moderate temperature reduction. In some cases, shrubs only bring a very small improvement in the microclimate. A study by Rui et al. [61] found that a reduction in the quantity of grass and shrubs, replaced by trees, had a little impact on the improvement of microclimate. However, shrubs are found capable of reducing soil surface temperature. Edmondson et al. [62] showed that a combination of trees and shrubs in non-domestic greenspace reduced mean maximum daily soil surface temperatures in the summer by 5.7°C compared to herbaceous vegetation. Skelhorn et al. [18] found that an additional 5% of green area cover by shrubs or new trees reduced surface temperature by approximately 0.5°C. Although performance of shrubs in reducing temperature has been observed, trees seem more effective in doing so. It is probably the shading effect of trees which is greater than that of shrubs.

3.4. Green roofs

Green roofs are often indicated as the most suitable GI implemented in urban areas where open spaces are limited [51]. There are two types of green roofs: intensive and extensive green roofs. Intensive green roofs have a deep soil layer which allows the roofs to accommodate large plants, although it has a large weight loading. This type of roof requires significant amount of irrigation and maintenance. On the other hand, extensive green roofs or eco-roofs only have a shallow soil layer. Such roofs require little or no irrigation and low maintenance. As they have a thin soil layer, the plant choices are limited. As roofs constitute approximately 20%-25% of the urban surface [52], conversion from conventional roofs to green roofs has the potential to bring benefits on a large scale. Numerous studies have highlighted the benefits of green roofs, such as reducing temperature which in turn reduces the cooling demand of buildings in the summer [53], contributing to air quality improvement [54, 55], enhancing energy performance of buildings [56] and reduction of storm water runoff [57, 58]. Although green roofs have been proven to reduce temperature, some studies, however have indicated that green roofs do not necessarily improve thermal comfort, especially on the street level. Jamei and Rajagopalan [59] investigated the effect of mitigation plans on thermal comfort in the city of Melbourne. They found that increasing building height and adding tree canopy will improve Physiological Equivalent Temperature (PET), yet implementing green rooftop didn’t improve PET. A similar study was conducted by Ng et al. [42], which indicated that implementing green roof on high buildings is not effective for improvement of human thermal comfort at a pedestrian level.

3.5. Green walls

Green walls are often referred to as ‘living walls’, ‘bio-walls’ or ‘vertical gardens’. These types of walls are comprised of plants grown in supported vertical systems that are commonly attached to an internal or external wall. In some cases, green walls can be freestanding. Like many green roofs, green walls incorporate vegetation, growing medium, irrigation and drainage into a single system. Some benefits of green walls include providing an attractive design feature and adding to building insulation by providing direct shading of the wall surface. They create a cooler microclimate and improve local air quality, and provide the possibility of growing plants in locations that would not normally support vegetation. A wide range of plants are used for green walls, which usually include herbaceous and some small shrubs. There are relatively few studies (among the reviewed studies) that incorporate green walls as part of their UHI mitigation strategies. Herath et al. [38] implemented green walls as an UHI adaption strategy in the city of Bambalapitiya, Sri Lanka and found that the addition of 50% green walls in the target area will result in temperature reduction of up to 1.86 °C. Meanwhile, a maximum temperature reduction of 8.4 °C in humid climate of Hong Kong with the use of vertical greenery systems was reported in an urban canyon [60].

3.6. Parks

Urban parks often have a cooler temperature than their surrounding area. A research by Yu and Hien [40] indicated that parks have a cooling impact not only in the vegetated areas, but also in the surrounding built environment (although the impact is limited by the distance). A similar research was conducted by Hwang et al. [41], who investigated the thermal performance of 10 urban parks in Singapore. They found that air temperature in the parks are 7.7 – 12 °C cooler than the surrounding areas. Factors influencing the cooling effect of the parks included parameters such as tree canopy and spatial arrangement of the parks. Lin and Lin [20] conducted computer simulations to investigate the influence of 8 spatial arrangement of parks on temperature reduction. The result indicated that a larger total park area, an evenly distributed park and a greater park diversity showed significant temperature reduction.

3.7. Other mitigation strategies

Some mitigation measures others than GI that were commonly used included modification of urban material, aspect ratio (AR) and street orientation. These are discussed in the following sub-sections.

3.7.1. Urban material

Urban materials commonly found in the literature are concrete, asphalt, tile, and glass. One of the important characteristics of urban materials is their albedo value, which is related to their colors. Albedo is the portion of sun light that is reflected back without being absorbed. To describe albedo, one can use qualitative terms such as "high" and "low", corresponding to "reflective/ light colours" and "absorptive/ dark colours", respectively, or use quantitative terms, i.e. values between 0 and 1. High-albedo materials can save cooling energy use by directly reducing the heat gained through a building's envelope (direct effect) and also by lowering the urban air temperature in the neighbourhood of the building (indirect effect). Concrete and asphalt which are usually dark colored, are known as material with low albedo (absorptive or material that do not reflect considerable amount of direct solar radiation) hence it can intensify the UHI. Replacement of conventional materials with cool materials led to a reduction of surface temperature by 6 - 9° C and 8.5° - 10 °C for exposed asphalt and concrete respectively [13, 63, 64].

3.7.2. Aspect ratio

Aspect ratio (AR) or height-to-width ratio (H/W) is defined as the ratio of the canyon height to canyon width. AR is an important parameter that is usually be used to investigate the influence of urban geometry on outdoor environment, especially on temperature and building energy demand. The effect of aspect ratio on microclimate and thermal comfort has been widely investigated. Ali-Toudert [65] were one of the first scholars who investigated thermal comfort in an urban street canyon. Using ENVI-met modelling tool (discussed later in this paper), they investigated the effect of various AR values on thermal comfort in Ghardaia, Algeria. They found that temperature decreases slightly with the increase of AR and concluded that increasing AR can improve thermal comfort in hot and dry climate. This finding is confirmed with the outcomes of other studies also [16, 39, 66, 67].

3.7.3. Street orientation

Street orientation is considered as having an influential role in altering microclimate in urban areas. Street orientation will influence the exposure of the canyon surfaces to direct solar radiation. North-South (N-S) street orientation will be fully exposed to solar radiation at midday but mostly shaded in early morning and late afternoon. This is contrary to East-West (E-W) street orientation, which is fully exposed in the early morning and the late afternoon. Some of the reviewed studies examined the effect on street orientation on microclimate and thermal comfort. Rodríguez-Algeciras et al. [15] used RayMan tool to investigate the effect of asymmetrical street canyon on heat comfort. It was found that in asymmetrical streets, E-W street orientation is the most thermally stressed.

4. Modelling Software

Modelling has been widely used by researchers to study microclimate and human thermal comfort at different scales and in various regions. Modelling is used to simulate the performance of different types of mitigation measures. It is needed to examine a wider range of scenarios, technologies, and climatic benefits at a variety of scales. Application of numerical simulation in microclimate studies is increasing these days due to increasing capability of computational resources. Some software packages that are commonly employed in microclimate and thermal comfort studies include ENVI-met [68], SOLWEIG [69-71], SkyHelios [72], TownScope [73] and RayMan [74]. In Table 2, a comparison of the four most commonly used microclimate modelling tools is presented. In addition, remote sensing is frequently used to obtain information regarding land surface temperature (LST). Radhi [75] assessed modification in surface temperature and PMV (predicted mean vote) in one man-made island in Bahrain using the tool Phoenics (and its solver module Earth). Employing remote sensing techniques to derive LST of their study area was also carried out by Zhang et al. [76]. Vegetation has become the most complicated element in numerical analysis of microclimate due to its multi-faceted interaction with radiation, flow and evapotranspiration [77]. However, most of the softwares do not consider the complexity of vegetation such as types of vegetation on rooftop and wall vegetation in simulating microclimate. ENVI-met is considered as a holistic microclimate model which incorporates many urban complexities such as vegetation of different varieties, building materials and roads. As ENVI-met combines various climatic variables that influence thermal comfort, the software is considered as the most complete model in terms of calculation of human thermal comfort [78]. The software only requires a limited number of inputs to run the model with a large number of outputs [67]. In addition, ENVI-met is the most accepted and validated software for simulating urban outdoor microclimate and for calculating thermal comfort values [79]. Therefore, ENVI-met was selected in this study for a detailed review, which is presented in the following sub-sections.

Table 2. Comparison of common microclimate modelling tools.

Criteria	RayMan	SOLWEIG	Townscope	ENVI-met4.4
High spec. computer requirement	No	No	No	Yes
Vegetation	No	No	Yes	Yes
Forcing meteorological parameters	No	No	No	Yes
Thermal indices	PMV, PET, SET, UTCI, PT, mPET	PET	PMV	PMV, PET, UTCI, SET
Long simulation time	No	No	No	Yes
Cost	Free	Free	License	License
Website link	www.urbanclimate.net/rayman	gvc.gu.se	www.townscope.com	www.envi-met.com

4.1. Introduction to ENVI-met

ENVI-met [68] is a three-dimensional non-hydrostatic model based on Computational Fluid Dynamic (CFD) solving of Navier-Stokes equations using finite difference numeric methods. This model has a graphical user interface (GUI) to generate modelling domains and graph results. There are 2 levels of domain, namely 2D surface points and 3D atmospheric points. It is characterized by spatial resolution from 0.5 to 10 m and temporal resolution from 1 to 10 s. ENVI-met provides calculations of short and long wave radiation fluxes with respect to shading, reflection and re-radiation from buildings systems and vegetation. It also includes transpiration, evaporation and sensible heat flux from vegetation into the air, pollutant dispersion at different levels of the domain, and bio meteorological parameter values (www.envi-met.com). Variety of features including buildings of different materials, different types of vegetation (species and geometry), pervious and impervious surfaces, and configurable layers of soil moisture. The model is computationally intensive, runs in nearly real-time, which means 24 hours of simulation will require approximately 24 hours of computation depending on the size of simulation area and computer's specification. ENVI-met is the most widely used model for microclimate and thermal comfort studies. The model is considered as the most proper and validated tool for simulating the outdoor environment and evaluating thermal comfort which relates surface greenery, air temperature and outdoor environment [65]. It is also considered as the most complete model in human thermal comfort calculation [78]. The model is commonly used in the fields of urban climatology, urban planning and building design.

The first version of ENVI-met (v 3.0) was released on 1998. This model version has some limitations, such as all components being placed on flat ground, which makes it suitable only for level terrain [18]. Furthermore, the model could not set the variability of the wind, both in velocity and direction [39]. Also, the model's long running time will limit the number of simulations. For example, Jamei et al [80] reported in one of their studies that ENVI-met took approximately 7 to 8 days to simulate a case.

Improvements were made after few years and version 4.0 was released. Currently, the model is releasing its newest version (v 4.4.5) during the summer of 2020. Normally, the developer releases two updated versions in a year. One significant improvement of v. 4 is the possibility to include climate variables through "full forcing" mode. This function allows the users to use their measured meteorological data along the simulation. It is expected that ENVI-met v. 4 shows better performance than v. 3 when evaluating microclimate and thermal comfort. Version 4 also introduced the use of Monde, a new vector-based editor for building/ digitizing the model of the study area. Monde also offers the possibilities to import an ArcGIS shape file, CAD file or even a Street map file. Instead of using Space (which was the editor tool in previous versions), using Monde will save time in the rather time-consuming process of building a model.

In the field of vegetation, version 4 was incorporating 3D vegetation models which enables the users to simulate their complex vegetation geometries. In addition, "full forcing" simulation mode now expects the relative humidity data instead of the absolute humidity, which is less common in measurement data. The new version also came with an automated updater, which will ensure that the users always have the current version of ENVI-met. However, with all the improved performance of the model, ENVI-met still presents limitations. The model cannot simulate precipitation during the simulation. Green roof in the model only considers the plant's transpiration without considering evaporation. Another limitation of ENVI-met is that the use of anthropogenic sources can only be applied in studies for emission, flux of gases and pollution particles, but it cannot be considered as heating spot which influence air temperature [81].

Furthermore, some studies examining the performance of ENVI-met have also been conducted. Hien et al. [82] compared the performance ENVI-met and STEVE, a microclimate model that was developed in Singapore, in predicting temperature in tropical regions. They found that predicted temperature from ENVI-met was lower than STEVE, yet concluded that STEVE could be suitable for predicting temperature in urban tropical environment. Another study [44] was conducted to identify a method that accurately estimate Mean Radiant Temperature (MRT). MRT is one climatic variable that was frequently predicted less accurately by ENVI-met [83-85]. The result indicated that by combining

ENVI-met and TRNSYS, more reliable result of MRT was achieved which led to increasing the accuracy of outdoor thermal comfort prediction, especially during night. In terms of boundary conditions in ENVI-met, Salata [86] compared some Lateral Boundary Condition (LBC) in the model. The results revealed that the best type of LBC is open LBC.

4.2. Overview of reviewed ENVI-met studies

The popularity of ENVI-met has increased in recent years. Figure 3 presents the distribution of reviewed publications (that used ENVI-met as the modelling tool) by the year of publication. As can be seen, there has been a strongly increasing trend in the number of papers published since 2014, with the majority of the studies being published during the last five to six years.

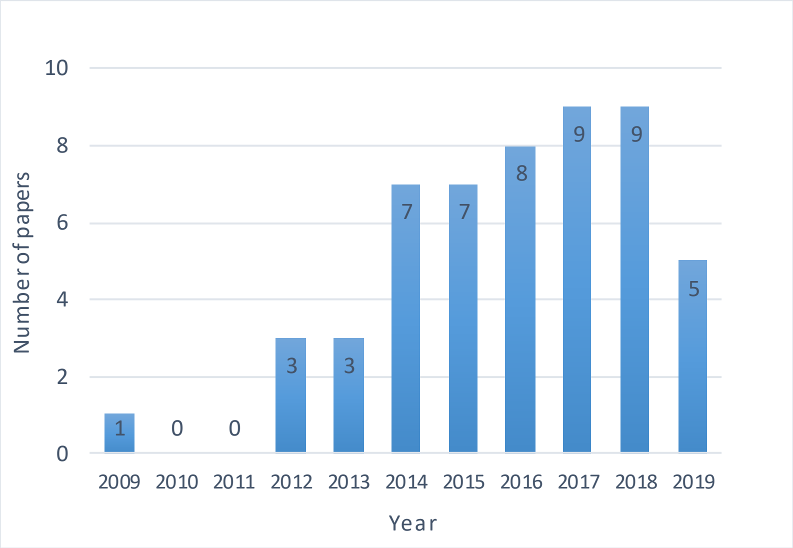

Figure 3. Distribution of reviewed ENVI-met studies by year of publication

The ENVI-met studies reviewed in this paper are distributed across 5 continents. The distribution of ENVI-met studies by region is presented in Figure 4. It can be seen from the figure that the majority of ENVI-met studies have been conducted in Asia and Europe. In Asia, the majority of the studies are carried out in China, Hong Kong and South Korea. Some of the Asian studies also came from Sri Lanka and Southeast Asian countries such as Singapore, Malaysia and Indonesia. In Europe, Germany, the country where the ENVI-met is developed, has the most studies using the model, followed by Italy, Spain and Greece. ENVI-met studies in Scandinavian countries are rarely encountered. In Australia, ENVI-met studies were dominated by the city of Melbourne. Studies in other Australian cities such as Sydney, Perth or Brisbane were not found in the reviewed papers. Among all continents, Africa has the fewest number of ENVI-met studies. From the 52 ENVI-met based papers that were reviewed, only two studies in Tanzania and Egypt have been found using the model.

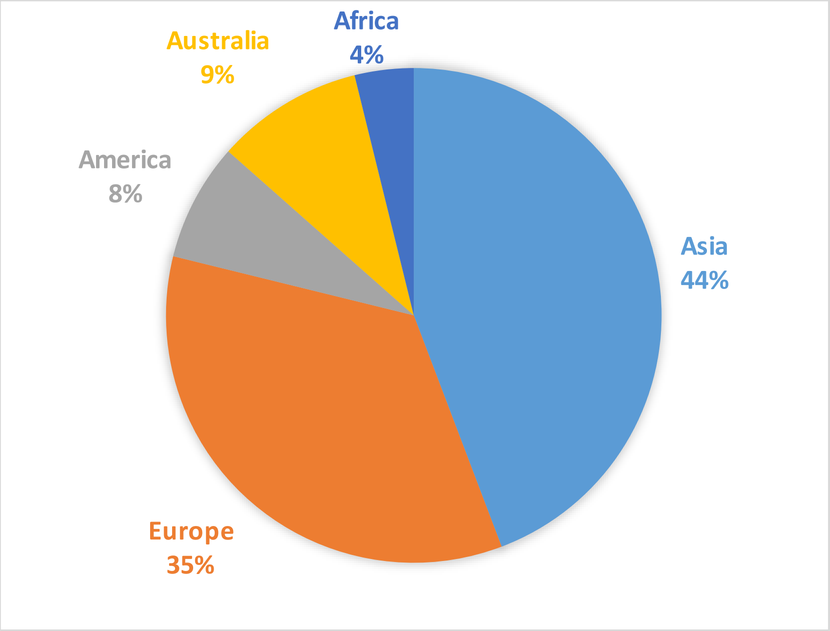

Figure 4. Distribution of ENVI-met studies by region

Based on Koppen-Geiger climate classification, research location in temperate and humid subtropical climate areas are quite significant (such as China and Hong Kong). Some of the studies come from tropical areas such as Singapore, Malaysia, Indonesia and Brazil. A considerable number of studies were also carried out in Mediterranean climate, such as in Italy, Greece and Spain. Studies from tropical arid climate were few, as not many studies were undertaken in such climatic conditions (Africa being an example). Regarding the target area of application, majority of the studies have been targeted in the urbanized city center [13, 15, 38, 56, 87, 88], where the UHI is known to be the most pronounced. University campuses were frequently used as field measurement areas [18, 84, 89, 90]. Some of the studies were performed in residential areas [19, 45, 61], heritage sites/old city [81, 91], urban parks [20] and coastal area [66].

In terms of application, the ENVI-met model has been applied for investigation of current microclimate and thermal comfort conditions as well as for comparative assessment of various mitigation strategies to mitigate the effect of UHI. Not only microclimate and thermal comfort, some studies also used the model to investigate air quality, which focused on pollutant deposition and dispersion [45, 61]. Regarding the scale of the research area, Saaroni et al. [92] classified the scale of research areas as micro/local (1-1000 m), urban (1-10 km) and regional (>10 km). Based on this classification, the majority of reviewed studies that use ENVI-met were performed at a micro scale or at a pedestrian scale [59, 84]. Due to resolution issue, simulating at city scale may take excessive time and is dependent on the capability of computers used. However, some studies were conducted on a bigger area or scale. A study at a larger scale was conducted by Lin and Lin [20], who investigated the influence of spatial arrangement of parks in an area of 308 ha or 3.08 km^2 on microclimate in the city of Taipei.

4.3. Calibration and Validation of ENVI-met

Calibration and validation are the processes undertaken to develop a reliable model that can represent the real environment of the research area. The accuracy of a model result is heavily dependent on the quality of the input data and the initial or boundary conditions. Therefore, it is important that sufficient and good quality data be prepared for the simulation. In general, 2 types of data are used in ENVI-met, namely weather data and geometry data of the study area. Most of the reviewed studies performed mobile measurement [13, 48, 59, 64, 84, 85, 87, 91, 93], while some retrieved the data from meteorological stations [20, 36, 44, 53]. Ng et al. [42] used two sets of verification data, one from on-site spot measurements and another from a long-term meteorological monitoring station. In term of validated variables, some studies only had a single variable validated such as temperature or mean radiant temperature [13, 42, 80, 85, 91]. Others had two validated variables: temperature and humidity or MRT [38, 64] and some had four validated variables: temperature, humidity, wind speed and MRT [83, 84]. Other variables validated are PMV [89] and solar irradiance [90]. To ensure the model reliability, an evaluation procedure is conducted by comparing the model result and measured values. Suitable statistical metrics are used to reflect the level of agreement between predicted and observed values, which included RMSE (Root Mean Square Error), MAE (Mean Absolute Error), MBE (Mean Bias Error) and coefficient of determination (R2). The majority of the reviewed studies showed a good agreement between predicted and observed values in some of the validated parameters. For example, a study by Acero and Arrizabalaga [83] showed a good agreement between temperature and humidity but not a good agreement for MRT and wind speed values.

Mean radiant temperature is considered as the most important meteorological variable to evaluate human thermal condition [44, 46, 94]. However, the variable seems to be less used as model assessment compared to air temperature (Ta). It is found that PET (Physiological Equivalent Temperature) is more sensitive to mean radiant temperature than wind speed. The deviation of PET value is highly influenced by deviation of MRT.

During the calibration process, some studies conducted a number of trials to determine the optimal settings for the initial/ boundary conditions. Teleghani [78] checked the accuracy of ENVI-met with modelling a courtyard model in 2 different grid sizes (180 x 180 m^2 and 90 x 90 m^2). The outcome showed the same result; hence the smaller grid size was chosen to reduce the simulation time. Another study by Forouzandeh [84] analyzed several grid sizes and time-steps to investigate how these arrangements affect the accuracy of the model. It was found that the model size did not give significant difference between measured and simulated temperature and humidity. However, bias in wind velocity existed for high resolution grid and small lateral domain extension. In some studies, however, some boundary configurations were left as the default values of the model.

4.4. Main results from reviewed ENVI-met studies

ENVI-met microclimate model has been widely used to examine the impact of different strategies of GI in mitigating urban heat. From a total of 70 reviewed papers, 52 of them used ENVI-met as their primary modelling software. A summary of the 52 reviewed studies that have used ENVI-met is presented in Table 3. The table provides information about the lead authors of the study, the country of origin, GI type used in the study, the measured parameters and the main findings from the study. As can be seen, a majority of the studies focused on cooling potential of street trees, green rooftop, grass and combination of some of these GI strategies. In addition, human thermal comfort also was considered in some of the papers. The analysis of reported simulation results can lead to the following remarks:

1. Validation of ENVI-met model showed varied results. Compared to temperature and relative humidity, mean radiant temperature (MRT) tend to be predicted less accurately. A study by Paramita and Fukuda [85] for example, found that the highest accuracy in predicting MRT was with RMSE values of 3.23 and 2.52 during peak solar-hours. Similarly, validation by Forouzandeh [84] showed a good agreement between model and observed values in temperature and wind speed, but the model tended to overestimated MRT values. Wind speed in some studies were also predicted less accurately [83].
2. Most of the reviewed studies highlighted the benefit of trees in regulating microclimate and improving thermal comfort. Application of trees led to temperature reduction and hence it will improve human thermal comfort. The ability of trees to improve thermal comfort is associated with its tree canopy [59]. However, trees also may increase concentration of pollutants by blocking the wind flow [61]. The effect of tree species, however, is not much discussed.
3. The cooling potential of green roofs were inconsistent and hence considered lower as compared to trees. Some studies found that green roofs were not an effective strategy to reduce outdoor temperature and were more effective in cooling the buildings.

4. Cooling potential of green walls has been assessed by only a small number of reviewed ENVI-met studies. From the 52 papers, only 1 paper examined the effect of green walls on microclimate [38]. The result showed that green walls may reduce temperature. Addition of 50% green walls will result in a daytime temperature reduction by 1.86 °C or 5.36% of temperature.
5. Shrubs were examined by several papers [45, 61, 63]. The cooling potential of shrubs however is not significant.
6. Some studies focused on improving human thermal comfort during the summer and not many focusing on winter or cold period. A study by Afshar et al. [50] focused on improving human thermal comfort during cold periods by applying different planting design.
7. Multiple GI strategies is proven as the best strategy to reduce temperature.

Table 3. Summary of reviewed studies that have used ENVI-met software as the modelling tool.

No	Author	Country	GI type	Parameters measured	Main findings
1	Tsoka [13]	Greece	Tree, grass, shrubs	Ta	A reduction of Ta up to 0.6^{0}C and Ts (asphalt) up to 15^{0}C with additional trees.
2	Sodoudi et al. [14]	Iran	Tree, grass, green roofs	Ta, RH	All the mitigation strategies, High Albedo Material, Vegetation, combination of them showed higher cooling effect during the day time. The average nocturnal cooling effect of vegetation and combination are higher than the High Albedo scenario.
3	Chatzidimitriou and Yannas [16]	Greece	Tree, grass	Ts, MRT, PET	Aspect ratio has strong effect on PET and is significant for courtyard. Water, wet soil and grass have similar effect for square and courtyard.
4	Skelhorn et al. [18]	UK	Tree, grass, shrubs, green roofs	Ta, Ts	Increasing 5% of mature deciduous trees can reduce 1°C temperature. The worst scenario is having no green space.
5	Wu and Chen [19]	China	Tree, grass	Ta, solar irradiance, sensible heat	Different spatial arrangement had different effects on intercepting shortwave radiation and led to sensible heat reduction and Ta variation.
6	Lin and Lin [20]	Taiwan	Parks	Ta	A larger total park area, a greater area of the largest park, evenly distributed park spaces and more park diversity led to significant outdoor cooling effect.
7	Müller et al. [36]	Germany	Tree, grass, green roofs	Ta, RH, PET	Increasing WS reduced PET significantly during day and night. Vegetation achieved higher PET reduction compared to water.
8	Herath et al. [38]	Sri Lanka	Tree, green roofs, green walls	Ta, RH	Combination of trees at curbsides, 50% green roofs and green walls led to maximum temperature reduction of 1.9^{0}C
9	Lobaccaro and Acero [39]	Spain	Tree, grass, green roofs	Ta, Ts, MRT, RH, WS	The highest PET reduction by combining trees and grass (reduced two PET classes). Aspect ratio and materials of urban canyon affect the intensity and duration of discomfort.
10	Nget al. [42]	Hong Kong	Tree, grass	Ta	At least 33% tree coverage of total area is needed to reduce 1^{0}C of Ta.
11	Perini et al. [44]	Germany	Tree	MRT, UTCI	Combination of ENVI-met and TRNSYS result in more reliable value of MRT, which will increase the accuracy of outdoor thermal comfort, especially during night.
12	Rui et al. [45]	China	Tree, grass, shrubs	Ta, RH, MRT, WS, PMV	Increasing tree quantity will improve PMV slightly, although it increases pollutant concentration slightly.
13	Yahia et al. [46]	Tanzania	Tree	Ta, RH, MRT, WS, PET	PET is more sensitive to MRT than wind speed. Area with low-rise buildings lead to more heat stress than in high-rise buildings. Dense trees enhance thermal comfort condition.
14	Zhang et al. [48]	China	Tree	Ta, MRT, WS, PET	The impact of vegetation on thermal comfort depend on tree arrangement, LAI, crown width and height. Trees with aspect ratio < 2 improve PET significantly.
15	Lee et al. [49]	Germany	Tree, grass	Ta, MRT, PET	Trees are more effective in mitigating human heat stress than just grass land.
16	Afshar et al. [50]	Iran	Tree, grass	Ta, RH, WS	More percentage of deciduous trees and grass will increase temperature and improve thermal comfort in winter.

17	Razzaghmanesh et al. [53]	Australia	Green roofs	Ta, heat flux,	Green roofs are able to increase albedo and reduce temperature. Additional 30% of green roofs would reduce electricity consumption by 2.57 W/m^2/day in the area.
18	Perini and Magliocco [56]	Italy	Tree, grass, shrubs, green roofs	Ta, MRT, PMV	Greening on the ground (tree, grass, shrubs) are more effective in reducing Ta, MRT, PMV at street level (1.6 m high) than application of green roofs.
19	Jamei and Rajagopalan [59]	Australia	Tree, green roofs	MRT, PET	Increasing building height and tree canopy improve PET yet implementing green roofs do not improve PET at pedestrian level.
20	Rui et al. [61]	China	Tree, grass, shrubs	Ta, RH, MRT, WS, PMV	Reduction of grass and shrubs replaced by trees (under the same green coverage ratio) impact thermal comfort, wind speed, air pollution.
21	O'Malley et al. [63]	UK	Tree, grass, shrubs	Ta	Vegetation is the most effective strategy while water bodies are the most resilient in mitigating the effect of UHI.
22	Yang et al. [64]	China	Tree, grass	Ta, RH, Ts, WS	ENVI-met is capable of modelling the diurnal thermal behaviour of different ground surfaces and their effect on T and RH.
23	Al-hagla and El-sayad [66]	Egypt	None	Ta, RH, WS, PMV	Urban block oriented at 15 degree achieved comfort that 30 degree north and north-facing blocks. Courtyard with low aspect ratio make exposure to the sunlight, hence the area couldn't reach comfort zone.
24	Jamei and Rajagopalan [67]	Australia	Tree, grass	Ta, MRT	Higher AR decrease temperature and improve thermal comfort.
25	Taleghani et al. [78]	The Netherlands	Tree	Ta, MRT	Courtyard shape provides the most comfortable hours in summer while singular shape causes the worst comfort situation.
26	Jamei et al. [80]	Australia	Tree	Ta	Increasing 4% of green cover led to reduction of 0.2°C temperature. Maximum cooling effect occurs at mid-afternoon.
27	Ambrosini et al. [81]	Italy	Tree, grass, shrubs, green roofs	Ta, RH, WS	Mitigation scenarios by using green or cool roofs showed reduction in temperature.
28	Hien et al. [82]	Singapore	Tree, grass, shrubs	Ta, WS	Predicted temperatures by ENVI-met are lower compared to those of STEVE. STEVE is considered more suitable for urban tropical studies.
29	Acero and Arrizabalaga [83]	Spain	Tree	Ta, RH, MRT, WS	A good agreement of T and RH between measured and modelled result. MRT and wind speed showed some differences.
30	Forouzandeh [84]	Germany	Trees, shrubs	Ta, RH, MRT, WS	RMSE value at the center of the shaded courtyard was 0.73^{0}C for Ta, 3.34% for RH, 0.01 m/s for WS, 8.44^{0}C for MRT
31	Paramita and Fukuda [85]	Indonesia	Tree	MRT	ENVI-met is less accurate in predicting MRT during peak solar hours.
32	Salata et al. [86]	Italy	Tree	Ta, RH, MRT, global radiation, PMV	Deviation between the modelling and measured values are 0.6% for Ta, 0.9% for MRT, about 2.0% for RH and about 10% for the global radiation.
33	Tan et al. [87]	Hong Kong	Tree	Ta, Ts, sensible heat flux, longwave radiation	High SVF scenario resulted the highest air temperature reduction (1.5^{0}C).

34	Zhao and Fong [88]	Hong Kong	Tree, grass	Ta, RH, MRT	The grey areas have the highest possibility in uncomfortable thermal environment generation. Green and blue areas demonstrate potential for heat mitigation.
35	Dain et al. [89]	Korea	Tree, grass	PMV	PMV values from modelling and measurement are mostly similar.
36	Jamei et al. [91]	Malaysia	Tree	Ta	Daytime air temperature decreased with increasing aspect ratio (AR).
37	Acero and Herranz-Pascual [94]	Spain	Tree	Ta, RH, MRT, WS	Some differences of MRT and wind speed between modelled and measurement result in a deviation in PET. Inaccuracy of PET is highly influenced by deviation of MRT
38	Katzschner and Thorsson [95]	Germany	Tree	MRT	SOLWEIG and ENVI-met show similar pattern of MRT and very good agreement with measurement data.
39	Johansson and Yahia [96]	Ecuador	Tree	PET	Lower PET in increased building height (only in noon), horizontal shadings and trees along the street. Increased albedo will make higher PET values.
40	Srivanit and Hokao [97]	Japan	Tree, green roofs	Ta, RH, WS, solar irradiance	The maximum average temperature decrease by 2.2°C when the quantity of trees was increased by 20%
41	Yahia and Johansson [98]	Syria	Tree	Ts, PET	The influence of street orientation, aspect ratio on thermal comfort of urban environment with detached buildings is less important as compared to that with attached buildings.
42	D'Sousa [99]	UEA	Green roofs	SA, RH, MRT, WS, PMV	Implementing green roof increase Surface Albedo and decrease T and MRT, which can improve thermal comfort.
43	Duarte et al. [100]	Brazil	Tree	Ta, MRT, Ts, PET	In summer, scenario of trees along sidewalk result in lowest temperature. Decreasing MRT in central park scenario (park being a cool island).
44	Emmanuel and Loconsole [101]	UK	Tree	Ta, PMV	Increasing green cover area by 20% led to reduction in surface temperature by up to 2°C.
45	Gusson and Duarte [102]	Brazil	Tree	Ta	Close result between measured and simulated data for Ta in 2 study areas, with RMSE values of 1.6°C and 1.9°C, MAE as 1.4°C and 1°C and Index of Agreement as 0.85 and 0.92.
46	Morakinyo and Lam [103]	Hong Kong	Tree	Ta, MRT, solar attenuation, PET	TCA improved thermal comfort, magnitude varies depends on pattern. In TCA=0.6, PET with double-rows planting is higher than center tree planting.
47	Kleerekoper et al. [104]	The Netherlands	Tree, grass	Ta, WS	Vegetation has the most effective cooling, with the max. cooling effect with trees is 20°C and grass 8°C. Increase in wind speed will lower PET. Building form and height are less significant compared to vegetation, WS and amount of buildings.
48	Roth and Lim [105]	Singapore	Tree, grass	Ta, MRT	Ta prediction is closer to observation during wet days. The values of MRT are varying but peaks are well predicted.
49	Salata et al. [106]	Italy	Tree, grass, shrubs	Ta, MRT, MOCI	Significant decrease in MOCI with combination scenario (vegetation, cool roof, cool pavement), The worst scenario is using asphalt and without vegetation.
50	Karakounos et al. [107]	Greece	Tree	Ta, MRT, PMV	Vegetation has a positive impact on thermal comfort under hot summer conditions.
51	Jamei et al. [108]	Australia	Tree, grass	Ta, RH, WS	ENVI-met achieves the optimum performance by altering the short wave adjustment factor from 0.5 to 1.
52	Shinzato et al. [109]	Brazil	Tree	Ta	Parameters of trees such as albedo of leaves, LAD, geometry of the crown show a significant influence on temperature.

Abbreviations:

AR = Aspect Ratio

LAD = Leaf Angle Distribution

MAE = Mean Absolute Error

MOCI = Mediterranean Outdoor Comfort Index

MRT = Mean Radiant Temperature

PET = Physiological Equivalent Temperature

PMV = Predicted Mean Vote

RH = Relative Humidity

RMSE = Root Mean Square Error

SA = Surface Albedo

SOLWEIG = The Solar and Longwave Environmental Irradiance Geometry

SVF = Sky View Factor

Ta = Air temperature

TCA = Tree-planting covered area

TRNSYS = Transient System Simulation Tool

Ts = Surface temperature

UTCI = Universal Thermal Comfort Index

WS = Wind speed

5. Summary and Conclusions

With increasing urbanization and the challenge of global warming, Urban Heat Island (UHI) mitigation strategies have attracted a lot of interest from researchers and scientists worldwide. Green Infrastructure (GI) is currently receiving growing attention from urban planners and policy makers as an important strategy to overcome the rising temperatures in urban areas. Therefore, research in this area is important in order to implement the strategies effectively.

This study firstly aims to provide an overview of GI as a strategy to mitigate the effect of urban heat. A review of results from numerous studies that applied different GI strategies to reduce temperature and improve human thermal comfort is presented. It is observed that certain GIs (like trees and grass) are studied much more than the others. In general, trees showed promising capability to reduce temperature and improve human thermal comfort as compared to other types of GIs. It is also observed that certain regions (mainly in Asia and Europe) have undertaken much more research in this area than the other regions. The regions which are prone to negative effects of UHI tend to have a greater number of mitigation studies.

Secondly, this study also identifies ENVI-met modelling software as a reliable tool to simulate surface-plant-air interaction, which is widely used to evaluate different scenarios of urban planning. In this paper, studies that have used ENVI-met in the last decade are reviewed and a summary of the simulation results are presented. It is revealed that even though ENVI-met is regarded as a reliable tool to simulate urban planning scenarios, some microclimate parameters such as mean radiant temperature and wind speed tend to be over or underestimated. Therefore, some adjustments in the configuration needs to be undertaken to ensure accurate results. ENVI-met also is computationally intensive and could take days to simulate a case. This time-consuming computational requirement is a major challenge in the implementation of ENVI-met.

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