

Modeling microclimatic effects of trees and green roofs/façades in ENVI-met:

Sensitivity tests and proposed model library

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1 *Abstract:*

2 Urban green infrastructure furnishes one of the most effective ways to mitigate and adapt to climate change
3 and the consequent thermal environment deterioration. ENVI-met, a holistic computational fluid dynamics
4 model with various plant modules, has become a principal simulation tool to evaluate the thermal effects
5 of urban greenery. This study emphasized the significance of clear and accurate ENVI-met vegetation
6 modeling, aiming to formulate strategies to boost modeling data quality, veracity and rigor of ENVI-met-
7 based simulation studies. This study applied a two-step framework. First, a series of sensitivity tests were
8 conducted under hot and humid meteorological conditions to identify the microclimate-sensitive parameters
9 and their relative cooling effects at the pedestrian level. The results identified leaf area density as the most
10 significant parameter in ENVI-met tree modeling. Some compromises on roof properties' input accuracy
11 could be tolerated since they would not considerably hamper the overall simulation quality at the pedestrian
12 level. For green roof/façade modeling, leaf area index and leaf angle distribution were significant and
13 should be accurately input to ensure simulation quality. Second, for the microclimate-sensitive parameters
14 in modeling, this study used commonly-planted species in subtropical South China cities to demonstrate a
15 systematic workflow of developing an ENVI-met vegetation model library. The library could include basic
16 plant physical traits, plant albums, reference values of the microclimate-sensitive parameters, and
17 recommended alternative modeling data sources. The vegetation model library could provide a helpful and
18 actionable package from which researchers can quickly obtain accurate input values without highly
19 specialized knowledge or instruments.

20 *Keywords:* ENVI-met; Vegetation modeling; Microclimate; Urban tree; Green roof and façade; Model
21 library

22 **1. Introduction**

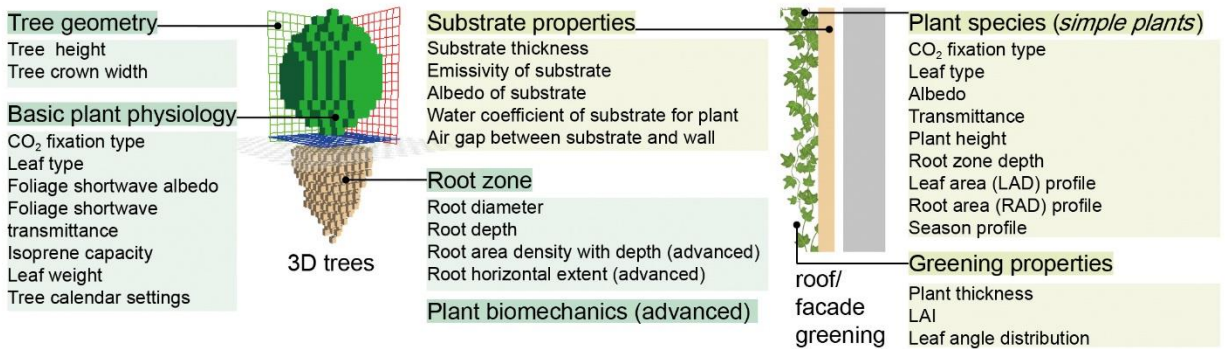
23 In recent decades, many cities have suffered from urban warming, which can be attributed to the
24 combined impacts of global climate change and the urban heat island (UHI) effect [1]. It leads to higher
25 urban temperatures and more frequent extreme heat events, exacerbating heatwaves and human-health risks
26 [2]. To mitigate and adapt to urban climate change, urban green infrastructure has been identified as one of
27 the most significant *Nature-based Solutions* due to its considerable cost-effective cooling potential [3].
28 Through evapotranspiration and shade provision, plants can intercept 70–90% of incoming solar radiation,
29 reduce 2–4 °C air temperature in parks, and reduce 11–22.4 °C peak building surface temperatures,
30 depending on their physical traits and planting designs [4].

31 Meanwhile, with the significant advancements in computation resources in recent decades, numerical
32 simulation has gradually become one of the principal research approaches to evaluate the thermal and
33 human-biometeorological effects of urban greenery [5]. EBM-based (Energy Balance Models) models such
34 as RayMan, SOLWEIG, green-CTTC, and CFD-based (Computational Fluid Dynamic) models such as
35 OpenFOAM, FLUENT, PHOENICS, ENVI-met are commonly used tools to simulate greenery effects [6].
36 Compared to EBM-based models, CFD-based models offer a twofold advantage: explicit coupling
37 simulation capability and high-resolution [7]; they have been widely applied to more urban greening-related
38 studies [6]. Concerning plant representations in CFD-based models, PHOENICS and FLUENT employ the
39 Ideal canopy model with a limited representation of a tree by its crown height, trunk height, and basic
40 canopy geometry such as spherical, oval, or conical shape. OpenFOAM, the FOLIAGE module of
41 PHOENICS, employs the Statistical method by associating LAI with plant morphology [5]. With various
42 plant modules and detailed in-canopy radiation calculations, ENVI-met can provide a more accurate and
43 detailed plant characterization. It has been used in over half of the greenery-led urban cooling simulation
44 studies [6].

45 ENVI-met is a holistic three-dimensional CFD model developed by Michael Bruse in 1998. With solid
46 physical fundamentals based on fluid mechanics, thermodynamics, and atmospheric physics laws, ENVI-
47 met can simulate surface-plant-air interactions in high resolution [8-11]. Currently, ENVI-met has four

48 plant modules: *simple plants* for grass and hedges; *green roof/façade module* for roof/façade greenings on
49 building envelopes; *3D-plants*, and *Lindenmayer-Systems* for trees. *Simple plants* represent vegetation as
50 one-dimensional columns featuring adjustable values for albedo, transmittance and plant height. Each
51 column consists of ten layers of LAD (leaf area density) and RAD (root area density). *Green roof/façade*
52 *module* combines buildings, greenings, and substrates, making it possible to consider heat and vapor
53 exchanges among greenery, substrate, and building surface layers. In green roof/façade modeling, plant
54 species can be edited by dragging and dropping a *simple plant* into the green roof/façade. The main greening
55 properties are plant thickness, LAI (leaf area index), and leaf angle distribution. Properties such as albedo
56 and transmittance of the vegetation are copied from the selected *simple plants*, while other properties only
57 fitting to individual plants, such as plant height, LAD and RAD, are omitted for the design of a roof/façade
58 greening. The substrate is optional and requires data on its properties, including emissivity, albedo, water
59 coefficient for plants, and air gap thickness between the substrate and wall (Fig. 1).

60 In tree modeling, 3D trees allow a plant-as-object simulation and can be digitized in a three-
61 dimensional plant editing tool named *Albero* [11], in which tree geometry, leaf properties, and root zone
62 geometry are needed (Fig. 1). The latest version (V5) of ENVI-met, released in November 2021, includes
63 the *Lindenmayer-Systems tree*. It can describe the more realistic position and arrangement of leaf clusters
64 and an hierarchical tree branching system [12]. Besides the advancements in vegetation modeling, a new
65 ACRT (advanced canopy radiation transfer) module in V5 allows diffuse radiation extinction simulations
66 and secondary sources of diffuse radiation due to the scattering of direct shortwave radiation within
67 vegetation canopies [12]. Recent developments in modeling and calculation have brought estimates of
68 greening-related microclimates closer to reality.



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Fig. 1. Modeling parameters of ENVI-met 3D trees and roof/façade greening.

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Due to the diversity of vegetation models and the complexity of plant-atmosphere-building interactions in ENVI-met, the importance of model accuracy cannot be overstated. The more detailed and accurate plant models are, the better ENVI-met can denote reality. Previous validation studies have summarized that modeling assumption as one of the primary reasons causing deviations between simulated and observed values, including but not limited to assumed input data and greenery generalization in study domains [5, 13, 14].

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Four approaches are commonly adopted to acquire physical plant properties in ENVI-met modeling. These include citing literature, actual measurements, parameterizing according to physical plant characteristics, and selecting existing vegetation models from the ENVI-met built-in library [5]. Liu et al. [5] recommended using real data in modeling; however, they are not easy to obtain due to the limited data sources. ENVI-met has provided default values in its modeling platform and listed various vegetation models in the built-in library for users' selection. Still, two issues in ENVI-met vegetation modeling have remained inadequately understood:

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(1) Which greening physical parameters are the microclimate simulation results more sensitive to and therefore demand the most accurate input values? Which parameters could accept a high tolerance for errors in estimating their numerical values if insufficient input data sources exist? To what extent will the approximations affect microclimate?

88 (2) Most plant species in the ENVI-met built-in library are from temperate climate regions. However,
89 the physical traits of plants vary tremendously in different climate regions and subregions. A tailor-made
90 ENVI-met vegetation model library for a specific climate zone is needed.

91 To solve these pending issues, this study aims to formulate strategies for ENVI-met vegetation
92 modeling to boost modeling data quality, simulation veracity, and rigor of ENVI-met studies. Sensitivity
93 tests were performed to investigate modeling parameter sensitivity to microclimate at the pedestrian level.
94 Also, this study applied common plant species in subtropical South China as an example to show a
95 systematic workflow of developing an ENVI-met vegetation model library.

96 **2. Literature review of ENVI-met vegetation modeling**

97 A condensed literature review was attempted to understand the state of ENVI-met greenery modeling
98 studies. This literature review aimed to ascertain the frequently employed modeling parameters and those
99 that tended to be disregarded in ENVI-met vegetation modeling. The literature-searching approach used in
100 a previous work [5] was adopted in this study. All included articles applied ENVI-met V4 and above as the
101 main research tool to evaluate the improvement of the outdoor thermal environment with urban greenery.
102 As plant characteristics vary tremendously among climate regions, only studies in the temperate climate
103 zone with a hot and humid summer (classified as *Cfa* in the Köppen-Geiger climate classification [15])
104 were included. In total, 47 peer-reviewed English journal articles were reviewed. Only half of the reviewed
105 studies (25, 53.2%) selected specific plant species, while the remaining parameterized vegetation according
106 to generic physical traits.

107 In digitizing specific tree species, most studies reported the use of tree height (18, 85.7%), followed
108 by crown diameter (15, 71.4%) and foliage density (12, 57.1% studies reported LAI and 10, 47.6% studies
109 reported LAD). Only a few studies reported bole height (5, 23.8%), foliage shortwave albedo (3, 14.3%),
110 foliage shortwave transmittance (2, 9.5%), and leaf type (4, 19.0%). None of the studies mentioned root-
111 related properties. Model input data sources can be categorized twofold: single data source and mixed data
112 source (model settings that were partially modified from a single source based on researchers' demands
113 would be classified as a mixed data source). About half of the specific tree species-related studies (11,

114 52.4%) acquired tree properties from a single data source, including actual measurements (9, 42.9%), citing
115 literature (1, 4.8%), and selecting existing tree models from *Albero* (1, 4.8%). One-third of the studies (7)
116 chose mixed data sources. Among them, six studies (28.6%) set vegetation models based on their study
117 foci, such as mid-size trees. Three studies (14.3%) didn't report any data source.

118 Regarding the green roof/façade, only studies that used ENVI-met V4.4 and above were examined.
119 Until then, users had to place *simple plants* in front of buildings to replicate façade greening. However, this
120 approximation approach is no longer used because the dedicated new green roof/façade module can
121 consider the heat and vapor exchanges within and between the greenery and substrate layers [5]. This study
122 calculated the input data for green roofs and vertical greening modeling together due to the same module
123 (four studies). In *simple plants* modeling, the LAD profile was frequently reported (3, 75.0%). Plant height,
124 albedo, and root properties such as root depth and RAD profile were reported by two studies (50.0%). Only
125 one study (25.0%) mentioned transmittance. In terms of the greening properties in the green roof/façade
126 module, LAI, plant thickness, and leaf angle distribution were respectively reported by 75.0% (3), 50.0%
127 (2), and 75.0% (3) studies. Unlike tree modeling's data sources, most green roof/façade studies acquired
128 data from the literature (2, 50.0%) rather than actual measurements (0, 0%). One study only reported partial
129 data sources (from the literature). In another study, the authors defined modeling input values based on their
130 research aims.

131 Only one reviewed study modeled specific shrub/grass species [16], reporting plant height and LAD
132 selected from ENVI-met built-in library.

133 In reviewing the previous ENVI-met vegetation modeling procedures, three observations could be
134 addressed. First, the modeling process should be described more comprehensively. The essential
135 information should be reported in detail, including modeling settings, values, and data sources that may
136 significantly influence the simulation results. Second, actual measurements should be the primary data
137 source in modeling specific tree species. It is an accurate approach to digitizing a representative tree, but it
138 has limits, such as being time-consuming and demanding professional instruments. Among tree modeling
139 parameters, physical traits such as tree height and crown diameter can be easily obtained by tape measures

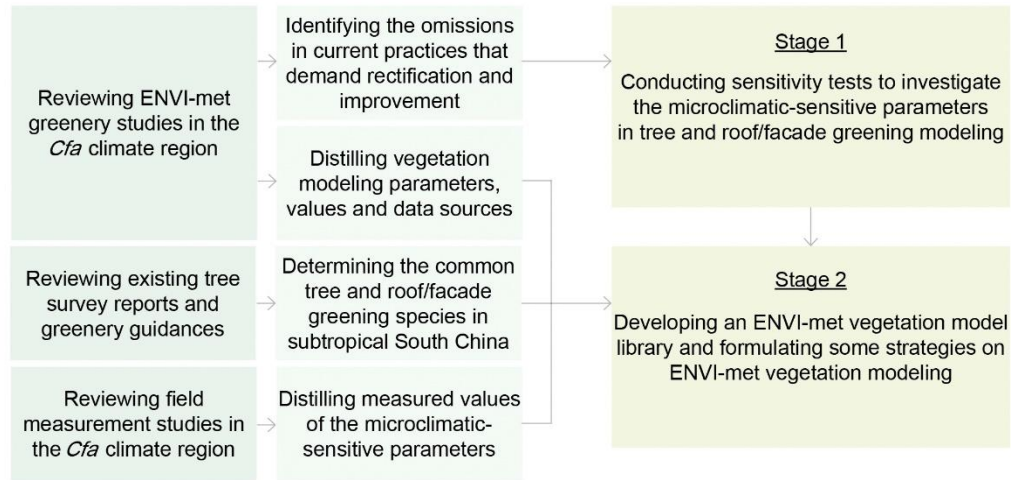
140 or laser rangefinders, so most studies reported them. However, the more sophisticated tree parameters were
141 reported only by a few reviewed studies, probably due to no access to expensive and professional
142 instruments. This may explain the use of parameterized tree models rather than modeling specific tree
143 species in about half of the reviewed studies. Third, in green roof/façade modeling, there were fewer studies
144 focusing on specific plant species than tree studies. This is because the new green roof/façade module was
145 released only four years ago. However, the lack of professional instruments for measuring some plant
146 physical traits is similar to tree studies. The reviewed studies usually introduced plant modeling but omitted
147 substrate descriptions. Substrates may influence the magnitude of the green roof/façade's thermal effect,
148 considered the main analytical aspect in relevant studies [17].

149 The literature review reveals that systematic scientific strategies for proper ENVI-met vegetation
150 modeling are urgently needed. Currently, the varied modeling data sources in reviewed studies were based
151 on researchers' measurements or literature surveys. The appropriation and accuracy of modeling input
152 values demand attention, particularly for microclimate-sensitive parameters. A tailor-made ENVI-met
153 vegetation model library can facilitate and save time for ENVI-met users.

154 **3. Methods**

155 *3.1. Study framework*

156 This study has two broad stages: sensitivity tests and developing an ENVI-met vegetation model
157 library. The sensitivity tests aim to investigate the magnitude of each vegetation modeling parameter's
158 microclimate influence. The ENVI-met vegetation model library aims to provide a helpful and actionable
159 package for users. An overview of the methodological framework is depicted in Fig.2. The study area was
160 set to Hong Kong (22 °15 ' N, 114°10' E), a high-density metropolis in a humid subtropical climate with a
161 *Cfa* Köppen-Geiger climate classification [18]. All ENVI-met simulations were performed using the V5.0
162 Science version.



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Fig. 2 The methodological framework of this study.

165 3.2. Sensitivity tests

166 3.2.1. Sensitivity test method determination

167 A sensitivity test, also known as a sensitivity analysis, is a method used to assess the sensitivity or
 168 responsiveness of a system or model to changes in its input parameters or assumptions. There are four
 169 commonly-used experiment methods: randomization designs, one-factor-at-a-time (1FAT) designs, full
 170 factorial designs, and orthogonal fractional factorial designs [19]. Referring to relevant research [20], this
 171 study selected the 1FAT method because it is widely applied in both academic and industrial design of
 172 experiments courses and can help isolate and understand the influence of each factor independently [21].
 173 This study applied three levels of each modeling parameter, i.e., high, medium, and low, to build a series
 174 of test cases.

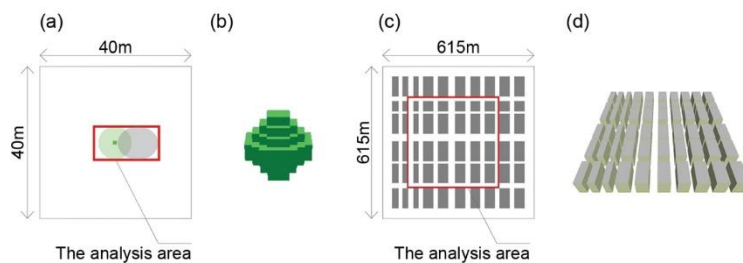
175 3.2.2. Test cases

176 3.2.2.1. Tree models

177 Four parameters, including LAD, foliage shortwave albedo, root depth, and root diameter, were tested
 178 in the tree sensitivity tests. All sample trees' height and crown diameter were respectively set as 10 m and
 179 8 m, referring to the general size of *Acacia confusa* [22], which is the most frequently planted tree species
 180 in Hong Kong public housing estates [23] and tree management information systems [24]. The omission of
 181 tree dimensions in the sensitivity analysis in this study was based on the assumption that landscape

182 practitioners can easily obtain accurate measurements of tree height and crown width using simple and
 183 inexpensive tools such as tape measures or laser rangefinders, while the main focus of this study was to
 184 investigate the impact of modeling parameters that are less easily obtained on microclimate. In this study,
 185 three levels of LAD, foliage shortwave albedo, root depth, and root diameter, were set referring to the
 186 ENVI-met built-in tree library. The maximum, minimum, and average values of the 29 tree species in the
 187 library were applied as the high, low, and medium levels in sensitivity tests. In terms of foliage shortwave
 188 transmittance, due to the constant value (0.30) in the ENVI-met built-in library, this study referred to the
 189 transmittance of crops to set the low (0.10) and high levels (0.52) [25]. The tree samples were categorized
 190 twofold: one *standard tree* was modeled through medium levels of all input parameters, and ten *test trees*
 191 were modeled by varying one parameter into a higher or lower class. The values of each test case are listed
 192 in Table 1. The size of the simulation domain was 40 m×40 m×30 m with 1 m resolution in the X, Y, and
 193 Z axis (Fig. 3(a) (b)). All test trees were planted in the center of an open loamy soil area to maximize their
 194 microclimatic effects. In vertical grid generation, the lowest gridbox was split into five subcells.

195 Tree height, bole height, and crown diameter were not included in sensitivity tests for the following
 196 reasons. First, their accurate values can be obtained through measure tapes or rangefinders, which are
 197 affordable for researchers and landscape practitioners. Second, the significant influences of these tree
 198 physical traits on tree shade provisions and surrounding microclimate have been found by many studies
 199 [26-28].



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 201 Fig. 3 The ENVI-met models of the test cases (a) 2D model of the tree cases (the grey circle represents
 202 the tree shading at 15:00 h), (b) 3D model of the tree cases, (c) 2D model of the façade greening cases,
 203 and (d) 3D model of the façade greening cases.

Table 1. The modeling values of each tree test case.

Test cases	LAD of each grid cell (m ² /m ³)	Foliage shortwave albedo	Foliage shortwave transmittance	Root diameter (m)	Root depth (m)
The standard tree (all medium levels)	1.15	0.44	0.31	14	10.4
The test tree (high-level LAD)	2.00	0.44	0.31	14	10.4
The test tree (low-level LAD)	0.3	0.44	0.31	14	10.4
The test tree (high-level albedo)	1.15	0.70	0.31	14	10.4
The test tree (low-level albedo)	1.15	0.18	0.31	14	10.4
The test tree (high-level transmittance)	1.15	0.44	0.52	14	10.4
The test tree (low-level transmittance)	1.15	0.44	0.10	14	10.4
The test tree (high-level root diameter)	1.15	0.44	0.31	25	10.4
The test tree (low-level root diameter)	1.15	0.44	0.31	3	10.4
The test tree (high-level root depth)	1.15	0.44	0.31	14	20.0
The test tree (low-level root depth)	1.15	0.44	0.31	14	0.8

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3.2.2.2. Green roof/façade models

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Regarding roof/façade greening, the sensitivity tests had two aspects: *simple plants* in roof/façade greening and roof/façade greening properties. The former tested five parameters, including *simple plants'* albedo, transmittance, root zone depth, LAD and RAD; the latter tested six parameters, including LAD, leaf angle distribution, emissivity of substrate, albedo of substrate, water coefficient of substrate for plant, and air gap thickness between substrate and wall. Similar to trees, the physical traits of all roof/façade greening samples were set consistently. The plant height of all *simple plants* samples was consistently set as 0.4m. The plant thickness, substrate thickness, and substrate materials of all roof/façade greening samples were respectively set as 0.3m, 0.15m, and sandy loam.

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Three levels of input parameters were applied in the roof/façade greening modeling. Due to the similarity of the ENVI-met built-in green roof/façade models, input values of leaf albedo, leaf transmittance, LAI, emissivity and albedo of the substrate from Ref. [29] were applied to set the high, low, and medium levels. Regarding leaf angle distribution, 0 means the leaf is parallel to the façade, and 1 is perpendicular following the ENVI-met Database Manager. Considering the extreme values cannot be set in ENVI-met,

220 this study applied 0.9, 0.5, and 0.1 to the high, medium, and low levels of leaf angle distribution. The water
 221 coefficient of substrate for plants is a dimensionless factor that determines the water availability of plants,
 222 ranging from 0 (no water available) to 1 (full water accessible for plants). This study set it to 0.9, 0.5, and
 223 0.1. Regarding the air gap width between the substrate and wall, the maximum and minimum values in the
 224 ENVI-met built-in library are 0.10 m and 0.01 m. Therefore, a medium level of 0.06 m was set in sensitivity
 225 tests. The values of each *simple plants* and roof/façade greening test case are listed in Tables 2 and 3.

226 Table 2. The modeling values of each *simple plants* test case.

<i>Simple plant models</i>	Albedo	Transmittance	Root zone depth (m)	LAD profile (10 layers) (m ² /m ³)	RAD profile (10 layers) (m ² /m ³)
The standard simple plant (all medium level)	0.28	0.24	0.35	0.32	0.15
The test simple plant (high-level albedo)	0.36	0.24	0.35	0.32	0.15
The test simple plant (low-level albedo)	0.20	0.24	0.35	0.32	0.15
The test simple plant (high-level transmittance)	0.28	0.30	0.35	0.32	0.15
The test simple plant (low-level transmittance)	0.28	0.18	0.35	0.32	0.15
The test simple plant (high-level root zone depth)	0.28	0.24	0.50	0.32	0.15
The test simple plant (low-level root zone depth)	0.28	0.24	0.20	0.32	0.15
The test simple plant (high-level LAD)	0.28	0.24	0.35	0.48	0.15
The test simple plant (low-level LAD)	0.28	0.24	0.35	0.15	0.15
The test simple plant (high-level RAD)	0.28	0.24	0.35	0.32	0.20
The test simple plant (low-level RAD)	0.28	0.24	0.35	0.32	0.10

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228 Table 3. The modeling values of each roof/façade greening test case.

<i>Green roof/façade models</i>	LAI (m ² /m ²)	Leaf angle distribution	Emissivity of substrate	Albedo of substrate	Water coefficient of substrate for plant	Air gap between substrate and wall (m)
The standard green roof/façade (all medium level)	3.15	0.5	0.93	0.28	0.5	0.06
The test green roof/façade (high-level LAI)	4.8	0.5	0.93	0.28	0.5	0.06

The test green roof/façade (low-level LAI)	1.5	0.5	0.93	0.28	0.5	0.06
The test green roof/façade (high-level leaf angle distribution)	3.15	0.9	0.93	0.28	0.5	0.06
The test green roof/façade (low-level leaf angle distribution)	3.15	0.1	0.93	0.28	0.5	0.06
The test green roof/façade (high-level emissivity of substrate)	3.15	0.5	0.95	0.28	0.5	0.06
The test green roof/façade (low-level emissivity of substrate)	3.15	0.5	0.90	0.28	0.5	0.06
The test green roof/façade (high-level albedo of substrate)	3.15	0.5	0.93	0.30	0.5	0.06
The test green roof/façade (low-level albedo of substrate)	3.15	0.5	0.93	0.26	0.5	0.06
The test green roof/façade (high-level water coefficient of substrate for plant)	3.15	0.5	0.93	0.28	0.9	0.06
The test green roof/façade (low-level water coefficient of substrate for plant)	3.15	0.5	0.93	0.28	0.1	0.06
The test green roof/façade (high-level air gap between substrate and wall)	3.15	0.5	0.93	0.28	0.5	0.10
The test green roof/façade (low-level air gap between substrate and wall)	3.15	0.5	0.93	0.28	0.5	0.01

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230 In ENVI-met, the model domain was 615 m×615 m×130 m with a 3 m resolution in the X, Y, and Z
231 axis (Fig. 3(c) (d)). A generic layout plan based on the urban morphology of Mong Kok, Hong Kong [18]
232 was applied. The widths of streets between buildings were 10, 15, 20, and 30 m. The building heights were
233 homogeneous at 60 m (the mean building height of the area [18]), and the aspect ratio varied from 2 to 6,
234 representing typical urban morphology characteristics in high-rise and high-density Hong Kong. Besides,
235 considering the medium or low-density urban areas, another model with a 20 m building height and 0.5 to
236 1.5 aspect ratio was built. In ENVI-met models, telescoping grids were applied in vertical space, with a
237 telescoping factor of 15% and started after 10 m. Vertical greenings were set in all building envelopes to
238 maximize their microclimatic effects. Since this study focused on the thermal and human-biometeorological
239 impact of urban greenery at the pedestrian level, green roofs were not tested since Sinsel et al.[30] reported
240 that the cooling effect of green roofs has limited elevation distribution and may cease at building heights of
241 around 100 m.

242 *3.2.3. ENVI-met initialization*

243 Simulations ran for 17 hours for all test cases, starting at 01:00 h and ending at 18:00 h. To maximize
244 the microclimatic effects of urban greenery, the hourly meteorological data of the hottest summer day in
245 2019 (9th August) from the Hong Kong Observatory (HKO) were applied in the full-forcing module (listed
246 in Appendix A). The IVS (indexed view sphere) module was applied with 45° resolution. Tmrt (mean

247 radiant temperature) used the common six-directional approach. The ACRT module was turned on to
248 calculate the attenuated and scattered direct shortwave radiation within plants.

249 *3.2.4. Data analysis*

250 Eight microclimatic parameters (i.e., air temperature, specific humidity, wind speed, Tmrt, direct
251 shortwave radiation, diffuse shortwave radiation, reflected shortwave radiation, and wall surface
252 temperature) and one basic human thermal comfort indicator (PET, physiological equivalent temperature)
253 at the pedestrian level (1.5 m height) were extracted for further analysis. PET is a function of four main
254 meteorological variables of Ta, RH, WS, and Tmrt, considering human elements such as gender, height,
255 age, weight, clothing heat resistance, and metabolic heat [31, 32]. It is the most widely used indicator in
256 urban climatology [33-36] and ENVI-met greenery-related studies [5]. The simulation results of 15:00 h
257 were analyzed because it is the time when the maximum differences between the thermal comfort of open
258 and vegetated areas generally occur [5], and the differences among test cases would be considerable. In the
259 tree model tests, the analysis area was set as a rectangle of 12 m×8 m, involving the areas under the tree
260 canopy and tree shading at 15:00 h (Fig. 3(a)). In the green roof/façade model tests, the analysis focused on
261 the blocks' central area, avoiding unstable simulation results in outer block areas (Fig. 3(c)). Paired samples
262 T-test was conducted in SPSS 24 [20] (117 paired samples were used in tree-related cases. 7985 and 1906
263 paired samples were respectively for the microclimate conditions and wall surface temperature at the
264 pedestrian level in roof/façade greening cases). A 95% confidence interval percentage was applied.

265 *3.2.5. ENVI-met validation*

266 The authors' research team has previously conducted a series of urban greenery studies in hot and
267 humid high-rise, high-density cities, where the suitability of the ENVI-met simulation model for urban
268 microclimate was validated and demonstrated [13, 37-42]. A validation paper conducted by the authors'
269 team concluded that ENVI-met effectively simulated air temperature and mean radiant temperature with
270 satisfactory accuracy during summer daytime. The simulations also successfully replicated the thermal and
271 radiative characteristics of various green infrastructures, such as ground trees, green facades, and green
272 roofs [14]. Additionally, another validation study conducted by the authors' research team focused on

273 evaluating ENVI-met's performance in simulating physiological parameters (leaf surface temperature and
274 vapor flux) and thermal effects (solar radiation, air temperature, and humidity) of four commonly found
275 tree species in southern China, reported that the ENVI-met tree model is suitable for subtropical hot-humid
276 climates [13]. Based on the solid research foundation, it is accurate to apply ENVI-met as the primary
277 simulation tool in this study.

278 *3.3. Developing an ENVI-met vegetation model library*

279 After determining the microclimatic-sensitive parameters from the sensitivity tests mentioned above,
280 an ENVI-met vegetation model library was developed. It has two aspects: a tree library and a roof/façade
281 greening library. Previous field measurement studies and ENVI-met greenery studies furnished the primary
282 data sources.

283 *3.3.1. Determining plant species in the library*

284 Considering that common plant species may vary among climate regions, this study applied those in
285 subtropical South China as an example to develop an ENVI-met vegetation model library. Roadside trees,
286 public housing estate trees, and urban park trees in three typical cities in southern China, i.e., Hong Kong,
287 Macau, and Guangzhou, were comprehensively surveyed during the last twenty years [23, 43-50], providing
288 the primary data sources in this study. Frequency distributions of tree species were distilled from the
289 published tree survey reports, from which the top 20 common tree species were analyzed.

290 Regarding roof/façade greening, due to the lack of detailed surveys like trees, this study referred to the
291 *Pictorial Guide to Plant Resources for Skyrise Greenery in Hong Kong* [51]. The plant database was
292 compiled by the *Greening and Landscape Office* in the *Development Bureau of the Hong Kong Government*.
293 It could facilitate proper plant selections and encourage the installation of green roofs and vertical greening.
294 This study distilled four main categories of roof/façade greenings, i.e., climber, succulent, grass, and fern,
295 from the database. In total, 24 commonly-used plant species in roof/façade greenery were included in the
296 library development.

297 3.3.2. *Selecting data sources*

298 The library's primary data source is the literature, including previous field measurement studies and
299 ENVI-met greenery studies. The microclimate-sensitive parameters were used as keywords in literature
300 searching, but only studies in the *Cfa* climate zone were selected because plant geometry varies among
301 climate regions. Regarding ENVI-met greenery studies, the 47 studies reviewed in Section 2 were also
302 applied here. In the library, species Latin or common names followed those reported in the original literature.
303 Basic information, vegetation modeling parameters, corresponding values, data sources, and images were
304 extracted in detail.

305 **4. Results and discussion of sensitivity tests**

306 *4.1. Trees*

307 The average differences between the two tree modeling levels (between the medium level and the
308 high/low level, respectively) are displayed in Fig. 4 (detailed values listed in Appendix B). The light grey
309 dash lines represent differences of 0.01 (for radiation-related variables, they represent differences of 1 W/m²)
310 because most microclimatic studies round to two decimal places. In the data analysis in this study,
311 differences between the two levels of test cases lower than 0.01(1 for radiation) would be considered “no
312 difference at all”.

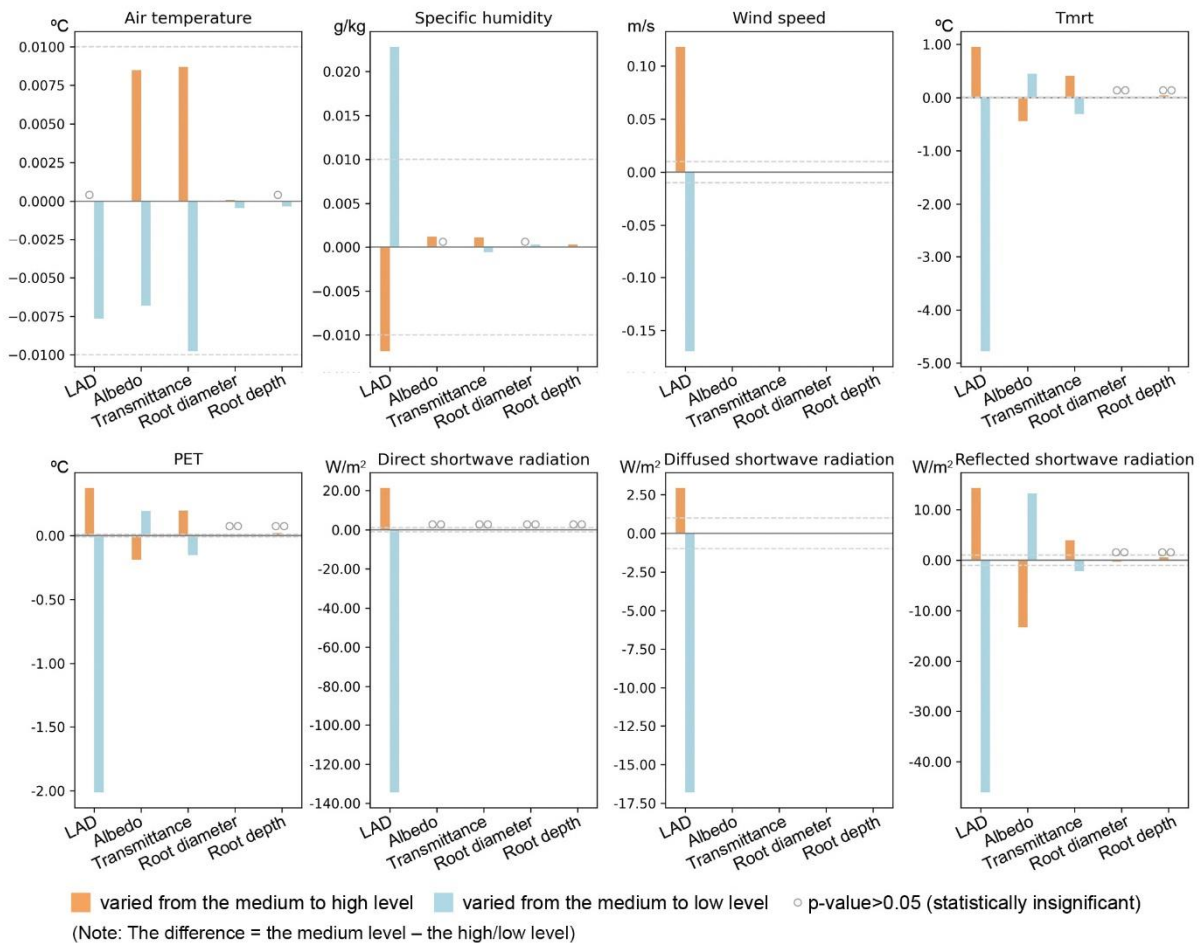
313 When LAD varied from medium to other levels, all microclimatic variables except air temperature
314 showed notable changes. Therefore, due to its high microclimatic sensitivity, LAD must be accurate in
315 ENVI-met tree modeling. In the ENVI-met ACRT module, attenuation of direct and diffuse shortwave
316 radiation through vegetation grids follows the work of Pedruzo-Bagazgoitia et al. [12, 52], using three
317 processes: 1) primary extinction of direct shortwave radiation; 2) extinction of direct shortwave radiation
318 due to scattering and creation of secondary diffuse shortwave radiation; and 3) extinction of diffuse
319 shortwave radiation. LAI_c, i.e., the sum of LAI between the grid cells, is applied to all in-canopy radiation
320 transfer calculations, revealing that LAI/LAD is an essential modeling parameter. The agglomerations of
321 leaves, given by LAD, also have crucial effects on wind speed. According to Bruse et al. [8], in the ENVI-

322 met atmospheric model, the loss of wind speed due to vegetation's drag forces is estimated by the mean
323 wind speed at the height, plant's LAD at the height and the mechanical drag coefficient. LAD is the only
324 plant parameter that affects wind speed due to the constant value of the mechanical drag coefficient (0.2).
325 In terms of air temperature, however, the p-value of 0.74 was much greater than 0.05, revealing that the
326 resulting air temperature difference is statistically insignificant when changing LAD from a medium to a
327 higher level. This phenomenon was also reported by Liu et al. [13] in an ENVI-met validation study: the
328 air temperature reduction from trees tends to be underestimated. But this is understandable since Brown et
329 al. [53] stated that "air temperature and atmospheric humidity cannot normally be significantly modified
330 by landscape elements" because "any localized changes you can make in air temperature will be quickly
331 dissipated by air movement".

332 Foliage shortwave albedo only showed notable changes in reflected shortwave radiation, Tmrt, and
333 PET. When foliage shortwave albedo varied from 0.44 (the medium level) to 0.7 (the high level), the
334 average reflected shortwave radiation, Tmrt, and PET at the pedestrian level increased by 13.31 W/m², 0.44
335 °C, and 0.19 °C, respectively. There is a positive correlation between foliage shortwave albedo and reflected
336 shortwave radiation. This result is due to the higher albedo, bringing more reflection of shortwave radiation
337 to the atmosphere. In ENVI-met, Tmrt is by default estimated by the common six-directional approach
338 since Version 5 [54], and, in the daytime, PET is affected mainly by Tmrt. This result is consistent with
339 previous findings that shortwave radiation significantly affects human absorbed radiation flux and outdoor
340 thermal comfort [55]. The foliage shortwave transmittance influences reflected shortwave radiation, Tmrt,
341 and PET, but the trend was opposite to the foliage shortwave albedo. When the foliage shortwave
342 transmittance changed from a medium level to a high level (from 0.31 to 0.52), the average reflected
343 shortwave radiation, Tmrt, and PET at the pedestrian level decreased by 3.90 W/m², 0.41 °C, and 0.19 °C,
344 respectively. For these two modeling parameters, the p-values of the direct shortwave radiation changes
345 were greater than 0.05, revealing that in varying foliage albedo or transmittance, the resulting direct
346 shortwave radiation differences were statistically insignificant. Also, there was no difference in diffuse
347 shortwave radiation, revealing that foliage shortwave albedo and transmittance did not affect diffuse

348 radiation estimation in ENVI-met simulations. These results were reasonable because, in ENVI-met, the
 349 major contributions to tree shading and radiation transfer are caused by the agglomeration of leaves, which
 350 is given by LAD [12].

351 Tree root depth and diameter did not significantly affect the microclimate at the pedestrian level. In
 352 varying the modeling levels, no statistically significant differences existed between the simulation results
 353 of Tmrt, PET, and all shortwave radiation-related variables (p-values were greater than 0.05). When
 354 changing root diameter, the average air temperature differences were statistically significant, but the
 355 difference value was quite low (about 0.0005 °C), which can be considered no difference. But it should be
 356 noted that all tree samples in sensitivity tests were planted on loamy soil, providing well water availability
 357 for trees. The results may change if a pavement profile with drier materials is chosen.



358

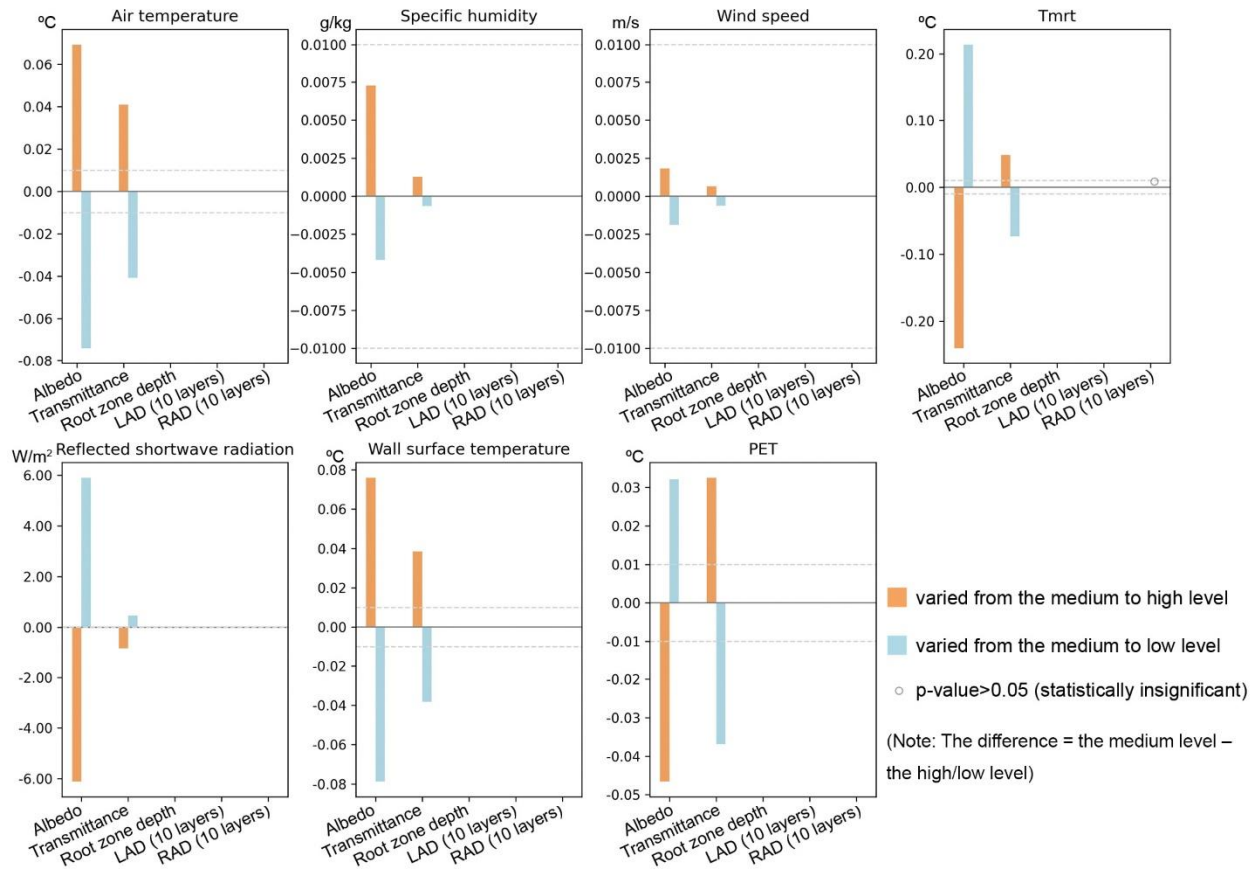
359

Fig 4. Mean microclimatic differences between two tree modeling levels.

360 4.2. Façade greening

361 The average differences between the two *simple plant* modeling levels are displayed in Fig. 5 (detailed
362 values listed in Appendix C). Direct and diffuse shortwave radiation at the pedestrian level was not included
363 in the diagram since there were no changes in all test cases. Due to the similar results, only façade greening
364 in 60 m height buildings is discussed here in detail. The results of 20 m height buildings can be found in
365 Appendix D.

366 Regarding the *simple plants* in a green roof/façade module, only plant albedo and transmittance (as
367 well as C3/C4 CO₂ fixation type, not shown in this study) were involved in calculations. When changing
368 transmittance to a lower level, the pedestrian level's air and wall surface temperature increased by 0.04 °C.
369 It is because the lower the transmittance, the higher the absorption (the albedo was set consistently),
370 resulting in more absorbed heat of plants and a higher surrounding temperature through convection. Plant
371 albedo and transmittance were not sensitive to specific humidity and wind speed, as shown by the very
372 small variation of two parameters (ranging from 0.0006 to 0.007 g/kg in specific humidity, and from 0.0006
373 to 0.002 m/s in wind speed). This is because albedo and transmittance are radiation-related parameters and
374 would not directly affect humidity and wind speed in ENVI-met. Due to the radiation budget changes within
375 and behind the canopy, some tiny changes in specific humidity and wind speed could eventually be
376 observed. Regarding root zone depth, LAD, and RAD, there was no difference in varying their modeling
377 levels because these three parameters are not involved in simulation when *simple plants* have been placed
378 in a green roof/façade module.



379

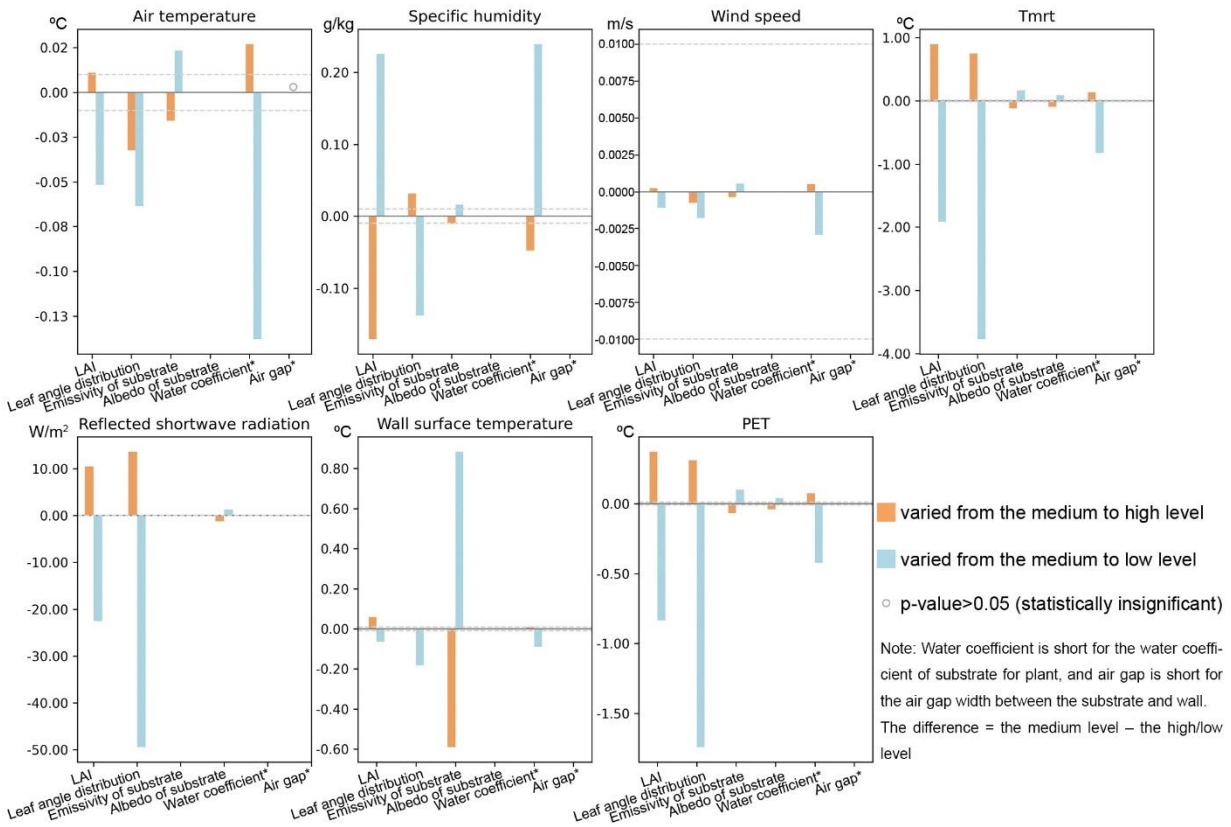
380 Fig 5. Mean microclimatic differences between two *simple plant* modeling levels in green façades.

381 Regarding modeling parameters in the green roof/façade module, the mean microclimatic differences
 382 between the two modeling levels are displayed in Fig. 6 (detailed values listed in Appendix E). Wind speed
 383 was not sensitive to all modeling parameters because it is mainly affected by urban morphology, such as
 384 building layouts and tree planting configuration. The plant thickness was only 0.3 m in this study, so,
 385 understandably, it has limited influence on street canyon air ventilation. In varying the greening properties
 386 (i.e., LAI and leaf angle distribution), all the microclimatic variables (except wind speed) showed
 387 significant differences. Particularly, PET was greatly influenced by these two modeling parameters
 388 (changes ranging from 0.37 to 0.84 °C and 0.31 to 1.74 °C for LAI and leaf angle distribution, respectively).
 389 The analysis would be conducted from the perspective of radiation transfer since most microclimatic
 390 variables here are relevant to radiation (e.g., reflected shortwave radiation, Tmrt, PET), particularly in the
 391 shortwave radiation domain.

392 In the ENVI-met green/façade module, a given fraction of the incoming shortwave radiation will not
393 enter the façade greening system. Still, it will be scattered and reflected in the environment. The shortwave
394 radiation released into the atmosphere contains three categories: 1) reflected direct shortwave radiation; 2)
395 reflected diffuse shortwave radiation; and 3) transmitted shortwave radiation from the vegetation layer
396 (radiation reflects from the wall or substrate layer and transmits through the vegetation layer to release back
397 into the atmosphere). The reflected shortwave radiation in the direct and diffuse components are estimated
398 by incoming direct/diffuse shortwave radiation, the vegetation layer's direct/diffuse absorption coefficient
399 and albedo. The direct/diffuse absorption coefficient is related to leaf angle distribution, LAD (estimated
400 from LAI and plant thickness), and the optical thickness of the vegetation layer for the direct/diffuse
401 component (related to the vegetation thickness). Estimating the transmitted shortwave radiation from the
402 vegetation layer involves leaf transmittance, leaf angle distribution, vegetation thickness, and LAD. The
403 abovementioned analysis elaborates on the significance of simple plant-radiation properties (plant albedo
404 and transmittance) and plant structural properties (LAI and leaf angle distribution) in ENVI-met radiation
405 estimation. For leaf angle distribution, this phenomenon is in line with previous studies: leaf angle
406 distribution plays a crucial role in intra- and inter-canopy microclimate, controlling energy and mass
407 balance in the soil-vegetation-atmosphere-transfer system [56].

408 Regarding substrate properties, the substrate emissivity greatly impacted wall surface temperature
409 (ranging from 0.59 °C to 0.88 °C upon changing to a higher or lower level). This result is understandable
410 since the higher the substrate emissivity, the more energy would emit to the surroundings, resulting in a
411 higher wall surface temperature. Substrate albedo is involved in the substrate-reflected shortwave radiation
412 estimation. But its effect was relatively slight (only about 1.27 W/m² differences when changing to a higher
413 or lower level) because most shortwave radiation transfer occurs between the vegetation layer and the
414 atmosphere. Changing the substrate's water coefficient level brought relatively considerable shifts in air
415 temperature and specific humidity (ranging from 0.03 to 0.14 °C and 0.05 to 0.24 g/kg, respectively). Since
416 the substrate layer can be seen as soil materials, the turbulent fluxes of heat and vapor in the substrate layer
417 can be estimated according to Ref. [8]. Neglecting horizontal transfers, the soil can be treated as a horizontal

418 column with heat and soil volumetric moisture content distributions and can interact with the atmosphere.
 419 The air gap width had no notable effect on microclimate at the pedestrian level since almost all interactions
 420 occur among air, vegetation layer, and a substrate layer. Also, the substrate blocks all the radiation (both
 421 shortwave and longwave domains) and cannot reach the wall surface.

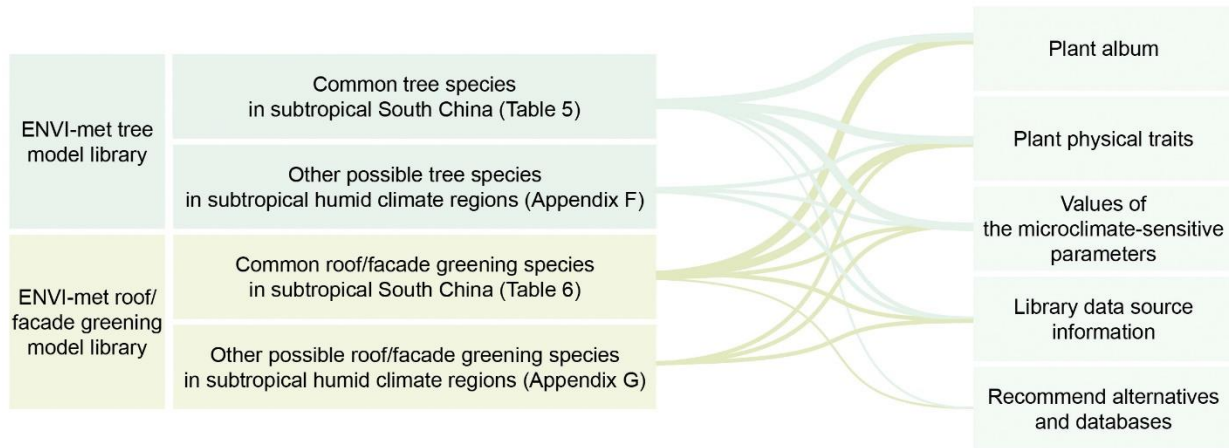


422

423 Fig 6. Mean microclimatic differences between two green façade modeling levels.

424 **5. ENVI-met vegetation model library**

425 The structure of the proposed ENVI-met vegetation model library is displayed in Fig. 7.



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Fig. 7. The structure of the proposed ENVI-met vegetation model library.

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5.1. Tree model library

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Based on the tree survey reports in the last 20 years [23, 43-50], the main characteristics of the top 20 common tree species in subtropical South China were distilled (Table 4). The dominant tree species were *Acacia confusa*, *Ficus microcarpa*, and *Bauhinia x blakeana*, with frequencies considerably greater than other tree species (64,550, 37,867, and 34,488 trees, respectively). 75% of these common tree species were evergreen trees, so there is no need to edit the seasonal scale factor in *Tree Calendar* for these trees in ENVI-met *Albero*. The average and large tree sizes were extracted from Ref. [22, 57], with the values representing tree dimensions in current and future scenarios, respectively. However, their appropriateness in future studies should be carefully assessed since the data sources were the tree surveys in Hong Kong's public housing estates [22, 57].

Table 4. Main characteristics of the common tree species planted in subtropical South China cities.

Rank	Tree species	Family	Foliage retention	Frequency	Average size		Large size	
					Height	Crown width	Height	Crown width
1	<i>Acacia confusa</i>	Mimosaceae	Evergreen	64,550	9.8	8.2	15.9	17.7
2	<i>Ficus microcarpa</i>	Moraceae	Evergreen	37,867	8.3	9.6	16.1	22.7
3	<i>Bauhinia x blakeana</i>	Caesalpiniaceae	Evergreen	34,488	7.4	6.5	13.6	12.5
4	<i>Melaleuca cajuputi</i> <i>subsp. cumingiana</i>	Myrtaceae	Evergreen	28,530	10.5	5.1	-	-

5	<i>Macaranga tanarius</i>	Euphorbiaceae	Evergreen	26,950	6.1	7.1	10.9	14.4
6	<i>Casuarina equisetifolia</i>	Casuarinaceae	Evergreen	25,099	15.0	8.4	-	-
7	<i>Livistona chinensis</i>	Arecaceae	Evergreen	24,572	-	-	25.6	19.4
8	<i>Aleurites moluccana</i>	Euphorbiaceae	Evergreen	23,345	10.2	7.4	17.3	14.3
9	<i>Ficus virens</i>	Moraceae	Deciduous	17,947	10.2	10.9	18.7	22.6
10	<i>Schefflera heptaphylla</i>	Araliaceae	Evergreen	17,323	-	-	11.4	10.5
11	<i>Lagerstroemia speciosa</i>	Lythraceae	Deciduous	17,145	5.4	5.3	10.9	9.3
12	<i>Celtis sinensis</i>	Ulmaceae	Deciduous	16,780	8.4	8.0	16.3	16.1
13	<i>Bauhinia variegata</i>	Caesalpiniaceae	Deciduous	16,585	7.5	6.4	13.9	11.9
14	<i>Sterculia lanceolata</i>	Sterculiaceae	Evergreen	15,171	-	-	11.2	12.3
15	<i>Cinnamomum camphora</i>	Lauraceae	Evergreen	14,276	9.1	7.8	15.6	17.5
16	<i>Delonix regia</i>	Caesalpiniaceae	Deciduous	13,268	8.9	11.0	16.7	22.0
17	<i>Lophostemon confertus</i>	Myrtaceae	Evergreen	10,967	-	-	14.4	12.3
18	<i>Melaleuca leucadendra</i>	Myrtaceae	Evergreen	10,203	-	-	-	-
19	<i>Eucalyptus spp.</i>	Myrtaceae	Evergreen	9,849	-	-	23.1	15.4
20	<i>Mallotus paniculatus</i>	Euphorbiaceae	Evergreen	9,779	-	-	14.2	12.7

439

440 The ENVI-met tree model library for the common tree species is displayed in Table 5. Due to the lack
441 of relevant literature, five tree species (*Schefflera heptaphylla*, *Celtis sinensis*, *Bauhinia variegata*,
442 *Eucalyptus spp.*, and *Mallotus paniculatus*) were not included in the current library. Except for the top 20
443 common tree species, modeling information of other possible tree species mentioned in the reviewed
444 literature was also recorded for users' reference (Appendix F).

445 The first step in applying the library is choosing the most appropriate information. Since there could
446 be several pieces of modeling information for a given tree species, users must select the most appropriate
447 one based on their needs. This library provided detailed tree physical traits, tree albums, and data source
448 information. Also, if the crown diameter and bole height information are not included in that piece, tree
449 photographs in the original literature or the tree album included in this study (Fig. 8) can be used as ballpark
450 references. Users can roughly estimate them from the proportions of the tree shape. The source of tree

451 images is the *Plant Photo Bank of China* (<http://ppbc.iplant.cn/>). Here, to provide readers with a relatively
 452 accurate visual reference of tree form, photographs of individual mature trees were selected, minimizing
 453 the influence of surrounding buildings and other plants on the tree's shape. However, this study encourages
 454 readers to conduct extensive research and gain knowledge about the morphology of the specific tree species
 455 before modeling.



Fig. 8 Tree album for the common tree species planted in subtropical South China cities.

Based on the abovementioned sensitivity tests, LAD, foliage shortwave albedo, and transmittance are microclimate-sensitive. In the library, tree height and LAI values were ascertained. It is because although LAD is the most essential modeling parameter, it is difficult to measure precisely. Thus, it is usually estimated by an empirical formula using LAI and tree heights [58]. Very few studies reported foliage shortwave albedo and transmittance. It is understandable because leaf albedo was generally measured from spectrophotometers [13] or two albedometers [59, 60], which are expensive and relatively inaccessible to some extent. Approximations from ENVI-met built-in library or literature findings from other climate regions (included in Appendix F) could provide alternatives, but their appropriateness needs to be carefully assessed before use. The influence of approximation can refer to the sensitivity test results mentioned above. Some researchers used a smartphone application called *Albedo: a Reflectance App* to measure material

468 albedo in situ [61]. However, whether this application suits foliage albedo measurement is still unclear. In
469 terms of foliage shortwave transmittance, it is sometimes confused with “tree canopy transmissivity” in
470 some studies. Defined by the radiative transmissivity of a single leaf, an approximation of 0.3 is offered by
471 ENVI-met as a default setting based on previous measurement studies [62, 63].

472 It should be noticed that in ENVI-met tree modeling, “deciduous leaves” should be chosen in the
473 “Basic Plant Physiology” panel in *Albero*, whether it is an evergreen or deciduous tree in Table 4. In ENVI-
474 met, the leaf type (grass leaves, deciduous leaves, and conifer leaves) is used for a specific aerodynamic
475 resistance calculation, in which different leaf types have different plant-specific constants and leaf
476 diameters (leaf diameters 0.15 m for deciduous trees and 0.02 m for conifers and grass) [11, 64]. Plant
477 aerodynamic resistance is essential since it would be used for all sensible heat flux, latent heat flux, and
478 evapotranspiration calculations.

479 Some useful data sources are recommended, offering researchers a direction to obtain modeling data.
480 LAI and tree maximum height, tree form, and other basic tree information can be found on the Singapore
481 Flora&Fauna Web (<https://www.nparks.gov.sg/florafaunaweb>). The LAI values in that database are for
482 Green Plot Ratio calculation, which can provide a practical data source for ENVI-met modeling for tropical
483 climates. For the common tree species in residential areas in Guangzhou, China (*Michelia alba*, *Mangifera*
484 *indica*, *Ficus microcarpa*, and *Bauhinia x blakeana*), detailed modeling information such as tree size, leaf
485 albedo, LAI, LAD profile, even root depth and width can be found in Ref. [13].

Table 5. An ENVI-met tree model library for the top 20 common tree species planted in subtropical South China cities.

No.	Tree species	Tree physical trait				Microclimate-sensitive modeling parameter			Tree photo in original literature	Data source				Note	
		Height (m)	Crown diameter (m)	Bole height (m)	DBH (cm)	LAI (m ² /m ²)	LAD at each layer (m ² /m ³)	Foliage shortwave albedo		Data source category*	ENVI-met version (if any)	City	Country		Ref.
1		12.5	-	-	-	2.5	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
2		12.3	-	-	-	2.5	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
3	<i>Acacia confusa</i>	10.0	16.0	1.8	60	2.40	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
4		8.92	6.00	-	24	3.0	-	-	✓ Front	LIT	-	Hong Kong	China	[67]	LAI in the intermediate canopy
5		10	-	-	-	3	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
6		9.6	-	-	-	3.14	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
8		7.8	18.0	1.8	78	2.81	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
9		8.1	11.0	1.3	-	-	Listed	0.31	✓ Front	FM	-	Guangzhou	China	[55]	-
10		8.1	11.0	1.3	-	3.88	Listed	0.31	✓ Front	EN-fm	4.2	Guangzhou	China	[13]	-
11		7 – 15	-	-	-	1.26 4.44	-	-	-	EN-fm	≥4	Guangzhou	China	[68]	-
12	<i>Ficus microcarpa</i>	7 – 15	-	-	-	1.26 4.44	-	-	-	EN-fm	4.4.4	Guangzhou	China	[69]	-
13		10	9	-	-	2	-	-	-	EN-set	4.4.4	Guangzhou	China	[69]	-
14		5.50	6	2	18.98	3.43	Listed	0.31	✓ Front	EN-mix	4.2	Guangzhou	China	[26]	From the regression model of measurement
15		8 – 13	7 – 15	-	-	3.45 (summer) 3.21 (autumn) 3.02 (winter)	-	-	-	EN-fm	4.3.2	Shenzhen	China	[70]	-
16		10	9	-	-	2	-	-	-	EN-mix	4.3.2	Shenzhen	China	[70]	-
17		7.5	-	-	-	3	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
18		7.3	-	-	-	2.84	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
19		7.2	6.0	2.0	24	3.55	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
20	<i>Bauhinia × blakeana</i>	4.9	5.8	-	-	3.55	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	-
21		14.4	9.4	1.6	-	-	Listed	0.31	✓ Front	FM	-	Guangzhou	China	[55]	-
22		8.8	9.1	1.8	-	4.27	Listed	0.31	✓ Front	EN-fm	4.2	Guangzhou	China	[13]	-

23		14.4	9.4	1.6	-	4.17	Listed	0.31	✓ Front	EN-fm	4.2	Guangzhou	China	[13]	-
24		6.82	6	2	14.87	3.02	Listed	0.31	✓ Front	EN-mix	4.2	Guangzhou	China	[26]	From the regression model of measurement
25		7	6	2	-	3.55	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
26		10	-	-	-	2	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
27	<i>Melaleuca cajuputi</i> subsp. <i>cumingiana</i>	11.7	-	-	-	2.14	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
28		8.65	3.79	-	24	3.0	-	-	✓ Front	LIT	-	Hong Kong	China	[67]	LAI in the intermediate canopy
29		4.2	8.0	1.2	25	3.02	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
30	<i>Macaranga tanarius</i>	5.2	8.0	-	-	3.02	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	Named as <i>Macaranga tanarius</i> var. <i>tomentosa</i> in the original literature
31		4	8	1	-	3.02	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
32		11.2	6.0	6.2	20	2.11	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
33	<i>Livistona chinensis</i>	9.0	5.6	-	-	2.11	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	-
34		11	6	6	-	2.11	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
35		15	-	-	-	2	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
36		15.6	-	-	-	1.93	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
37	<i>Casuarina equisetifolia</i>	13.0	4.0	4.4	23	1.52	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
38		8.0	7.2	-	-	1.52	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	-
39		14.0 ± 5.9	-	-	45 ± 24	1.7 ± 0.5	-	-	-	FM	-	Greater Sydney	Australia	[73]	Sample size = 58
40		14	7	4	-	1.52	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
41		10	-	-	-	2.5	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
42		10.8	-	-	-	2.46	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
43		9.0	7.0	2.6	20	2.77	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
44	<i>Aleurites moluccana</i>	6.0	6.8	-	-	2.77	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	-
45		10	7	3	-	3.10	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
46		9	7	3	-	2.77	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-
47		9	7	3	-	2.77	-	-	-	EN-set	4.3	Hong Kong	China	[74]	-

48	<i>Ficus virens</i>	5 – 6	3 – 4	-	-	2.36 (summer) 1.32 (autumn) 0.78 (winter)	-	-	-	EN-fm	4.3.2	Shenzhen	China	[70]	-
49	<i>Lagerstroemia</i>	7.5	-	-	-	3	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
50	<i>speciosa</i>	6.5	-	-	-	2.98	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
51	<i>Sterculia lanceolata</i>	8 – 10	-	-	-	1.16 1.72	-	-	-	EN-fm	4.4.4	Guangzhou	China	[69]	-
52		10	-	-	-	3	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
53		8.8	-	-	-	3.05	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
54		10 – 20	-	-	-	1.77 3.03	-	-	-	EN-fm	≥4	Guangzhou	China	[68]	-
55	<i>Cinnamomum camphora</i>	10 – 20	-	-	-	1.77 3.03	-	-	-	EN-fm	4.4.4	Guangzhou	China	[69]	-
56		13.3 ± 2.7	-	-	72 ± 20	1.9 ± 0.5	-	-	-	FM	-	Greater Sydney	Australia	[73]	Sample size =48 Named as Camphor laurel in the original literature
57		8	7	-	-	3.80	-	-	-	EN-fm	4	Wuhan	China	[75]	-
58		15	8	-	-	-	1.80	-	-	EN-fm	4	Changsha	China	[16]	-
59		10	-	-	-	2.5	-	-	-	EN-fm	4	Hong Kong	China	[65]	-
60		9.7	-	-	-	2.52	-	-	-	FM	-	Hong Kong	China	[65]	Raw data from measurement
61		4.4	12.0	2.0	35	1.91	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
62	<i>Delonix regia</i>	6.7	9.4	-	-	1.91	-	-	✓ Front	LIT	-	Hong Kong	China	[71]	-
63		8.86	6.21	-	28	2.5	-	-	✓ Front	LIT	-	Hong Kong	China	[67]	LAI in Open canopy
64		5 – 20	-	-	-	0.41 1.09	-	-	-	EN-fm	≥4	Guangzhou	China	[68]	-
65		5 – 20	-	-	-	0.41 1.09	-	-	-	EN-fm	4.4.4	Guangzhou	China	[69]	-
66	<i>Lophostemon confertus</i>	12.5 ± 6.9	-	-	35 ± 33	2.1 ± 0.4	-	-	✓ Front	FM	-	Greater Sydney	Australia	[73]	Sample size =49
67	<i>Melaleuca leucadendron</i>	10.6	6.0	3.2	43	3.42	-	-	✓ Hemispheric	FM	-	Hong Kong	China	[66]	-
68		11	6	3	-	3.42	-	-	✓ Hemispheric	EN-fm	4	Hong Kong	China	[37, 72]	-

487 Note: In the data source category, *FM* means direct measurements, *EN* means ENVI-met studies, and *LIT* means from previous literature or external databases. *Fm*, *lit*, *set*, and *mix*,
488 respectively, means the data sources of the original ENVI-met study of field measurements, literature, and values set based on study foci and mixed sources. *No* means that data
489 sources are not explicitly mentioned.

490

491 5.2. Green roof/façade model library

492 An ENVI-met green roof/façade model library for the common roof/façade greenings recommended
493 by the *Hong Kong Greening and Landscape Office* is displayed in Table 6. The plant album is shown in
494 Fig. 9, and the photo source is *Pictorial Guide to Plant Resources for Skyrise Greenery in Hong Kong*.
495 Based on the sensitivity tests, LAI, leaf angle distribution, albedo, and transmittance values were
496 microclimate-sensitive and should be included in the library. LAI values were ascertained due to its wide
497 acquisition and use in greenery and microclimate studies. Very few studies reported leaf angle distribution,
498 and only three records were found for *Funkia sp.* (Hosta) (0.5) [76] and *Hedera helix* (0.7) [77, 78]. Despite
499 the fundamental importance of leaf angle distribution, Wang et al. [56] stated that its field measurements
500 are laborious, requiring repeated determinations as the canopy develops. Muller-Linow et al. [79] found
501 that no single method could meet all the requirements of leaf angle distribution measurement, such as easy
502 applications under field conditions, the ability to measure changing canopies moved by wind, and the
503 delivery of large sample size and high spatial resolution. Consequently, measuring a limited sample size by
504 labor-intensive manual methods (such as using an inclinometer) under laboratory conditions may offer a
505 possible solution. Otherwise, datasets or literature from other climate zones could be adopted as alternatives,
506 but their appropriateness should be carefully reconsidered. For example, an Australian dataset includes
507 measured leaf angle distribution of some climbers and ferns [56].

508 Regarding leaf albedo and transmittance, their values were relatively less well-documented. Only one
509 study reported leaf transmittance (0.3, *Funkia sp.* (Hosta) [76] (listed in Appendix G). Some studies
510 measured the collective reflectivity and transmissivity of plant leaves of the whole green façade rather than
511 individual leaves. For example, a green façade reflectivity of 0.13, 0.22, and 0.26 were reported by [80-82].
512 However, due to the gaps among leaves, the albedo of a single leaf should be relatively larger than a group
513 of plant leaves. Moreover, the leaf properties may vary at different phenological stages [83], so using such
514 data in the literature demands careful consideration.

515 Since roof/façade greening properties are relatively less documented, only one-third of the plant
516 species recommended by the *Hong Kong Greening and Landscape Office* are listed in the proposed library.

517 Therefore, users can consult information from other climate regions or consider other plant species in the
 518 subtropical humid climate region (*Cfa*). The alternative library is listed in Appendix G.



519

520 Fig. 9 Roof/façade greening album for the common species planted in subtropical South China.

521 Table 6. An ENVI-met roof/façade greening model library for the common plant species planted in
 522 subtropical South China.

No.	Plant growth form	Plant species	Plant height (m)	LAI (m ² /m ²)	Tree photo in the original literature	Measured city	Measured country	Ref.	Note
1	Climber	<i>Epipremnum aureum</i>	0.25-0.35	2.27	✓	Wuhan	China	[84]	-
2			-	0.24	-	Hong Kong	China	[85]	-
3	Climber	<i>Lonicera japonica</i>	-	0.69	-	Hong Kong	China	[86]	-
4			-	0.70	-	Hong Kong	China	[87]	LAI 0.695 in the original literature
5	Climber	<i>Pyrostegia venusta</i>	-	4.51 ± 0.033 (3-day mean)	✓	Guangzhou	China	[81]	-
6	Climber	<i>Wisteria sinensis</i>	-	0.95	-	Hong Kong	China	[88]	LAI 0.945 in the original literature
7			0.07	4.6	-	Guangzhou	China	[89]	Rooftop greening
8			0.1 (summer) 0.02 (winter)	3.7 (summer) 0.2 (winter)	-	Shanghai	China	[90]	Rooftop greening
9	Succulent	<i>Sedum lineare</i>	0.1 both	4.1 (with aquifer)	✓	Nanning	China	[91]	Rooftop greening
10					2.9	-	Chongqing	China	[92]
11			0.08 (mean)	2.6	-	Nanjing	China	[93]	Rooftop greening
12			0.08 (mean)	2.6	-	Nanjing	China	[94]	Rooftop greening
13			-	0.88	-	Shenzhen	China	[95]	Rooftop greening

				4.45 ± 1.72					Seasonal variations in LAI
14	Grass	<i>Cynodon dactylon</i>	-	(the whole growing season)	-	-	China	[96]	listed in the original literature
15			-	2.21±0.16	-	-	Japan	[97]	Rooftop greening
16	Grass	<i>Zoysia japonica</i>	-	1.55 ± 0.20	-	Kinkazan	Japan	[98]	<i>Zoysia japonica</i> was the only dominant, but several other species occurred, all with small to tiny plants
17	Fern	<i>Nephrolepis auriculata</i>	-	2.88 ± 0.63 (40% fern cover) 3.05 ± 0.50 (80% fern cover)	-	Hong Kong	China	[99]	-

523 **Note:** The default data source in this library is actual measurements. Data extracted from previous ENVI-met studies are noted.

524 **6. Conclusion**

525 This study aimed to formulate strategies for ENVI-met vegetation modeling to boost modeling data
526 quality, simulation veracity, and rigor of ENVI-met studies. A series of sensitivity tests were conducted to
527 investigate the microclimate-sensitive parameters and their influence on microclimate at the pedestrian
528 level. For the microclimate-sensitive parameters in tree and roof/façade greening modeling, an ENVI-met
529 vegetation model library focusing on species commonly planted in cities in subtropical South China was
530 offered for users' reference. The main conclusions and modeling strategies are given below.

531 In ENVI-met tree modeling, LAD is the most significant parameter. It has a much greater impact on
532 almost all microclimate variables at the pedestrian level (except air temperature) than foliage shortwave
533 albedo and transmittance. Since LAD is commonly estimated by tree height and LAI, using accurate tree
534 physical traits and LAI values would be strongly recommended to improve simulation accuracy. Some
535 compromises on roof properties' input accuracy could be tolerant since they would not considerably hamper
536 the overall simulation quality at the pedestrian level. When relevant literature and professional instruments
537 are lacking, ENVI-met default values can be used as roof properties.

538 Three strands of information demand attention in ENVI-met green roof/façade modeling. First, as a
539 green roof/façade entity, only the simple plants' albedo, transmittance, and CO₂ fixation type significantly
540 influence the simulation processes. The values of root zone depth, LAD profile, and RAD profile are
541 neglected. Second, regarding roof/façade greening properties, LAI and leaf angle distribution are significant
542 and should be accurately input to ensure simulation quality. Third, substrate properties affect the
543 microclimate but are less influential than vegetation properties. Substrate emissivity greatly impacts
544 building wall surface temperature, and an accurate value should be used in relevant studies. The sensitivity
545 test results can be used as references in data analysis for the impact of modeling approximations. It should
546 be noted that the results are based on hot and humid meteorological conditions, and their appropriateness
547 should be carefully assessed before applying in other climate regions.

548 A seminal ENVI-met vegetation model library was developed, including a tree model part and a green
549 roof/façade model part. In the library, data on fundamental plant physical traits, plant albums, and the
550 essential parameter LAI were ascertained so that users could build a basic model. The vegetation model
551 library can augment the microclimate research tools. It can be regarded as a helpful and actionable package
552 through which researchers can quickly obtain accurate tree models without needing professional knowledge
553 or instruments. It can also be beneficial for a more accurate understanding of the cooling role of greening
554 in a local urban environment. Although this study only focused on commonly-used plant species in
555 subtropical South China, it furnished an innovative and systematic workflow of vegetation model library
556 development (Fig. 2) reproducible for implementation in other climate regions.

557 The current vegetation model library is in its preliminary stage of development and has some
558 limitations. For instance, only the availability of data on LAI in the library can be ensured. However, in the
559 case of foliage shortwave albedo or leaf angle distribution, which are also sensitive to microclimate, precise
560 reference values for all plant species cannot be offered currently due to insufficient literature data.
561 Addressing this limitation will be one of the future directions for developing the database.

562 Regarding reporting modeling information in manuscripts, this study suggested reporting values and
563 corresponding data sources as detailed as possible. The essential information such as modeling settings,

564 values, and data sources are valuable for future researchers, reuse, repurposing, and meta-analysis.
565 Considering the word limit in journals, this study proposed at least reporting information on the essential
566 plant physical traits and the microclimate-sensitive parameters comprehensively. Showing photographs of
567 sample trees in a perspective view is recommended, supplementing details at the pedestrian level and
568 providing a visual reference to readers. Evaluating the tree images can also help researchers judge whether
569 the models in previous studies are applicable and suitable to their work.

570 For future studies, collaborating with experts and professional research teams in botany and
571 dendrology can provide an optimal direction and more accurate measured values for library improvement.
572 Tree albums that focus on trees' 3D shape (for example, a library of *Lindenmayer-System* trees) can be
573 another feasible direction for library improvement. Substrate properties also deserve more future studies.
574 Due to the considerable diversity of green roof/façade substrate materials and time limitations, the proposed
575 model library mainly focused on plant-related parameters with little information on substrate properties.
576 The substrate's microclimatic effects have been verified in the sensitivity tests. Therefore, its properties can
577 provide a valuable direction for future library development studies.

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581

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