A methodological approach for vertical greening systems modeling optimization: a case study in Athens, Greece

Triantafyllos Ampatzoglou[1*], *Francesca* Mosca[2], *Marta* Pianta[3], *Enrica* Roccotiello[3], *Vasiliki* Geropanta[1], and *Katia* Perini[2]

[1]School of Architecture, Technical University of Crete - TUC, 73100, Chania, Greece
[2]Architecture and Design Department - DAD, University of Genova, 16123, Genova, Italy
[3]Department of Earth, Environmental and Life Sciences – DISTAV, University of Genova, 16123, Genova, Italy

Abstract. Vertical greening systems (VGS) are artificial niches enriching cityscapes with ecosystem services. To accurately define these services, studying various species' performance within VGS due to differing plant variables, such as Leaf Area Index (LAI), is crucial. This study quantifies the performance of two north-oriented VGS scenarios for microclimate regulation using ENVI_met's three-dimensional CFD model in Athens, Greece. The first scenario considers a Hedera helix L. monoculture with default plant variables. The second scenario replicates real-life temporal and spatial changes of three plant species by modifying ENVI_met database variables, accounting for site specificity. For a typical Mediterranean summer day, the study evaluates the scenarios' impact on microclimatic conditions and outdoor thermal comfort, considering indices like mean radiant temperature (MRT) and universal thermal climate index (UTCI) at pedestrian level, through simulations and statistical analysis. Results show minimal impact of the second scenario on microclimatic conditions and outdoor thermal comfort compared to the default scenario. The research highlights key aspects of modeling optimization and emphasizes the necessity of thorough analysis of contextual specifics and climatic data for effective VGS incorporation and optimal microclimate performance.

1 Introduction

Developing cities that are concurrently sustainable, resilient and liveable, stands as one of the foremost challenges for humanity [1]. Rapid urbanization transforms cities into hotspots for pressing ecological and social issues, posing important challenges to ecosystems health, residents well-being, and the overall environmental quality [2, 3]. Integrating native, diverse and contextually selected plant species into urban spaces is a well-recognised adaptation strategy, essential for providing ecosystem services and further addressing future climatic stresses [3-6]. To this end, urban greening endeavors, like Nature-based Solutions (NbS), are emphasized for their ability to strengthen resilience by bridging multi-scalar biodiversity strategies while fostering inclusive, capacity-building processes aligned with sustainable development goals (SDGs) [7].

Vertical greening systems (VGS), as part of NbS, entail the potential for contributing to the socio-ecological transformation of cities [8]. VGS are artificial niches offering a plethora of ecosystem services, such as: reducing energy consumption and improving air quality in buildings [9, 10], countering the microclimate phenomenon of urban heat island (UHI) [11], providing protection and resources for urban fauna [12], among others. From this standpoint, VGS bring an alfresco breakthrough in the vacant vertical urban space [13], while additionally re-establishing beneficial human-nature relationships in cities, contributing to human well-being and support to biodiversity in a sparring and provident way [12, 14].

A significant part of the VGS virtue can be attributed to the relative amount of leaf area within its canopy, namely the Leaf Area Index (LAI) [15]. The LAI, defined as the canopy's one-sided leaf area divided by the ground unit [16], is a dynamic and dimensionless measure of leaf area in ecosystems, commonly applied across various research fields and influenced by various factors, including plant species, seasonality, orientation and so forth [15, 17, 18]. Nonetheless, within the realm of VGS, there is little evidence provided on the influence of LAI, a decisive parameter for VGS varied processes and hence, its co-benefits determination [11, 15]. LAI, along with other variables, like plant dimensions and leaf characteristics, define the relative quantity of the foliage of the vegetation layer. Maintaining an accurate determination of these variables within the modeling process is crucial for coherently accounting the effectiveness and ensuring a consistent comparison among VGS [19]. Therefore, further research into this direction and a precise assessment of the environmental effects of VGS is crucial in order to more thoroughly evaluate the benefits that are linked to it. To this effect, emphasizing the verifiable benefits of VGS is essential for determining their environmental and ecological roles and subsequently increasing their adoption potential as a viable solution, while contributing to its general civic acceptability [20].

2 Research Aims

This research paper aims to quantify the impact of vertical greening systems on microclimatic conditions and outdoor thermal comfort, considering relevant indices such as the mean radiant temperature (MRT) and the universal thermal climate index (UTCI), at the pedestrian level. The VGS analysed in this study are parametrized in terms of plant variables; indeed, the study explores the performances of a monoculture VGS and a VGS integrating different plant species.

3 Methodology

Thermal comfort reflects a persons' satisfaction with the thermal environment [21] whereas urban microclimatic conditions influence outdoor activities, social interactions, productivity and health [22, 23]. Mean Radiant Temperature (MRT), a measure of outdoor thermal comfort, takes into account solar radiation, surrounding surfaces, and their thermal exchange - all of which are significantly influenced by vegetation, as a passive cooling technique. [24]. The UTCI is aimed at representing a persons' physiological response to the outdoor thermal physical surroundings, by taking into account meteorological variables like wind speed, air temperature, mean radiant temperature, and vapor pressure of water in the air [25].

To investigate the performance of VGS in relation to microclimate regulation, two VGS scenarios are simulated employing the three-dimensional CFD model of ENVI_met (V.5.6.1), for a case study in Athens, Greece (fig. 1).

Fig. 1. Area input for ENVI_met, location: Athens, Greece

Athens, is falling within the Köppen climate classification (Csa), which stands for characteristic Mediterranean climate with hot summers [26].

The first scenario considers a monoculture of Hedera helix L. with default plant variables, related to the existing database of ENVI_met, within the DB Manager. The second scenario through a comprehensive process incorporates three plant species, taking site specificity into account, while utilizing modified plant variables – through ENVI_met DB Manager, to replicate real-life vegetal quantity fluctuations, due to temporal and spatial peculiarities. In this context, Perini et. al., (2022) [27], pioneered advancements in enhancing the accuracy of simulations. Microclimatic models of 350 x 350 x 50 m are used in both scenarios. The simulations refer to a typical Mediterranean summer day and the related climatic data utilized for the simulations is derived from the nearest to the study area available station [28]. To identify the variances between the two scenarios, a comparative analysis was made in Leonardo, followed by a statistical test in order to determine whether the difference in the means of the examined thermal indices in the two situations is statistically significant.

3.1 Study Location

The study has been performed for the north-northwest (348°) wall – and the area adjacent to it, of a multi-storey building located at the junction of Stadiou Street, a relatively wide three-lane asphalt road, and Aiolou Street, a major pedestrian entrance to the historical center of Athens (37° 58' 56.94" N 23° 43' 45.10" E). The plot was home to a multi-storey sporting goods department store from 1970 until it was demolished in December 1980 due to extensive damage from an arson. As of now, it is an aesthetically, functionally and ecologically problematic area: a deserted and fenced spot, where invasive plant species like *Ailanthus altissima* (Mill.) Swingle. run wild.

3.2 Plant Selection Criteria

The first step in the process of plant species selection was to identify the annual sunlight exposure for the north-northwest wall in the building under investigation. After importing the areas' geometry from CADMAPPER, the 3D model was created and subsequently utilized to perform a sunlight-hours analysis using the plug-in Ladybug of Ladybug Tools suite (V.1.6) [29]. The solar access study takes into account the surrounding building stock and the orientation of the area to determine the total number of sunlight hours on the surface of interest (fig. 2). The process aids the reciprocal association of the potentially chosen plant species to match with the existing sunlight conditions, ensuring their long-term thriving.

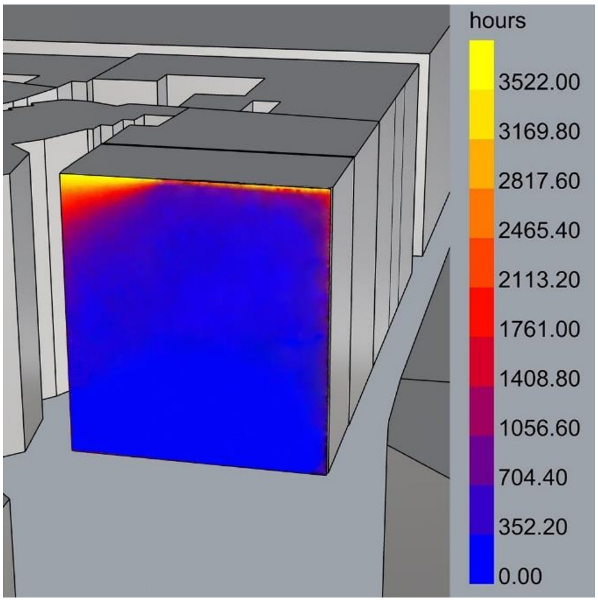

Fig. 2. Annual Sunlight Hours on the VGS viewed from the north direction

Moreover, amongst the primary aims was to encourage the uptake of native species (i.e., occurring in the geographical area according to the local climatic zone). For this aim, comprehensive and precise plant databases of Greece were used [30, 31].

Accordingly, the selection criteria encompassed leaf size, minimal water and maintenance requirements, resistance to pollutants and pathogens as well as the prevention of ecosystem disservices (e.g., allergies, poisonous species, etc.). Based on these criteria the species selected were Hedera helix L. (Araliaceae), Carex divulsa Stokes in With. (Cyperaceae) and Cistus parviflorus Lam. (Cistaceae); these species have been previously utilized in VGS projects within the Mediterranean context [32, 33].

3.3 Microclimatic Model and Simulations

Microclimatic models of 350 x 350 x 50 m are set for both scenarios (fig. 1) on the ENVI_met Spaces module. The size of grid cells is set to 1.00 x 1.00 x 1.00 m. The simulations refer to a typical Mediterranean summer day, in particular the 8th of August 1996, at 15:00 h. The related climatic data utilized for the simulations derived from the nearest to the study area available station (37° 54' 0.43" N, 23° 43' 34.38" E), in the form of EnergyPlus Weather file (EPW) format. The weather input data for the 8th of August 1996 at 15:00 h are stated in table 1.

Table 1. Meteorological input data for the 8th August, 15:00 h.

Weather variables, 8 August 1996, 15:00 h	
Dry Bulb Temperature (°C)	33.1
Dew Point Temperature (°C)	17
Relative Humidity (%)	38
Atmospheric Pressure (Pa)	100800
Global Horizontal Radiation (W/m^2)	810
Direct Normal Radiation (W/m^2)	844
Direct Horizontal Radiation (W/m^2)	699
Diffuse Horizontal Radiation (W/m^2)	111
Longwave/Infrared Horizontal Radiation (W/m^2)	416
Wind Speed (m/s)	4.6 (forced to 1.5)
Wind Direction (°)	170
Precipitation (mm)	0

Regarding the simulations' weather configuration, within the ENVI_met - ENVI-Guide module, the option of full-forcing was chosen for the parameters - precipitation, relative humidity, radiation/clouds, air temperature and wind direction, except that of the wind speed (at inflow border), which was set at 1.5 m/s from 4.6 m/s to reduce simulations' time.

For the planting parameters, the first scenario considers only a *H. helix* with default plant variables. The second scenario involves a thorough site-specific environmental and ecological analysis, incorporating three plant species and utilizing adjusted plant variables to replicate real-life temporal and spatial plant changes; it does so by modifying the systems plant properties specifically by adjusting plant thickness and LAI from the Greening Properties within the ENVI_met - Database (DB) Manager module. The plant variables for the two scenarios are reported in table 2, while their arrangement within the VGS is depicted in figure 3.

Table 2. Depiction of the utilized plant variables in scenario 1 (default) and scenario 2 (re-parametrized)

Scenario 1 – Default plant variables		
Hedera helix Ivy [0200IV]	LAI (m^2/m^2)	1.5
	Plant Thickness (m)	0.3
Scenario 2 – Re-parametrised plant variables		
Hedera helix	LAI (m^2/m^2)	4
	Plant Thickness (m)	0.5
Carex divulsa	LAI (m^2/m^2)	4
	Plant Thickness (m)	0.5
Cistus parviflorus	LAI (m^2/m^2)	6
	Plant Thickness (m)	0.6

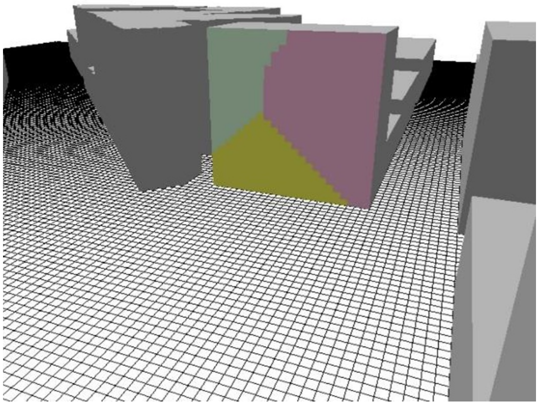

Fig. 3. Configuration of *H. helix* (yellow), *C. divulsa* (green) and *C. parviflorus* (magenta), in the scenario 2 – re-parametrised plant variables, in ENVI_met - Spaces module.

Aside from these modifications to the plant variables, no other changes were made to the DB Manager's variables between the two scenarios. In both scenarios, the sites' ground surface material configuration is set to concrete pavement used/dirty (albedo: 0.25, emissivity: 0.9).

Within the ENVI_met - BIO-met module, the post-processing tool for computing human thermal comfort indices from model output files, the setting of "Default Female, Summer Clothing" was used as the personal factors for both UTCI, and MRT indices.

3.4 Data Analysis

A comparison between the two VGS scenarios - the first scenario (S.1) and second scenario (S.2), was performed to highlight the variances and verify the differences at the pedestrian level, i.e. at 1.5 m height. The visualization analysis of the outputs from the two scenarios was performed in Leonardo by creating two-dimensional maps, from which the thermal comfort parameters were extracted as Excel sheets from grid points.

Subsequently, for each scenario the MRT and UTCI mean values were calculated gradually from 1 to 5 meters, as well as, the difference ΔMRT and ΔUTCI between the two scenarios from 1 to 15 meters.

Then, a two-sample t-test was conducted with R studio (V. 2024.4 Chocolate Cosmos) [34] to compare whether the means of the thermal indices between the two scenarios are significantly different ($p < 0.05$).

4 Results

4.1 Temperature Distribution Maps

The outputs of the microclimatic simulations show minimal differences between the two scenarios' outdoor thermal comfort. Figure 4, shows the mean radiant temperature MRT for both scenarios S.1 and S.2. In both scenarios the MRT minimum temperature is 21.61 °C, and the maximum 74.38 °C. Figure 5 shows that the universal thermal climate index does not change between scenarios, with common minimum temperature 24.45 °C and maximum 43.63 °C.

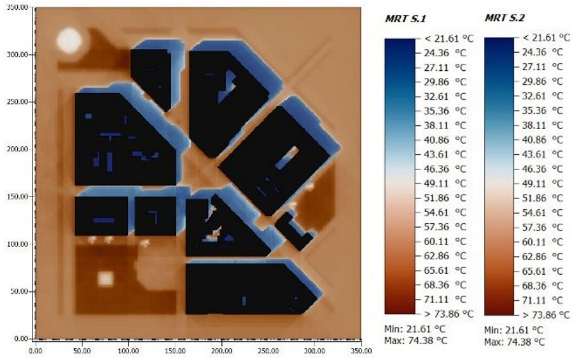

Fig. 4. Mean Radiant Temperature (MRT) for S.1 and for S. 2

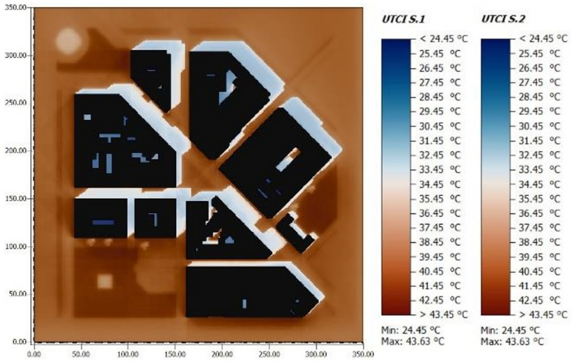

Fig. 5. Universal Thermal Climate Index (UTCI) for S.1 and for S. 2

Similarly, bringing into focus the study area - in front of the VGS, and by juxtaposing the legend charts of the bioclimatic indices reveals fractional variations between the two scenarios. In figure 6, the differences in MRT legends bring out a difference of 0.06 °C regarding the minimum temperature - MRT S.1 min: 29.10 °C, MRT S.2 min: 29.16 °C, and a difference of 0.04 °C for the maximum temperature - MRT S.1 max: 63.44 °C, MRT S.2 min: 63.48 °C. In figure 7, the differences in UTCI legends bring out a difference of 0.02 °C regarding their minimum temperature - UTCI S.1 min: 31.88 °C, UTCI S.2 min: 31.86 °C, and a difference of 0.01 °C for their maximum temperature - UTCI S.1 max: 40.83 °C, UTCI S.2 max: 40.82 °C.

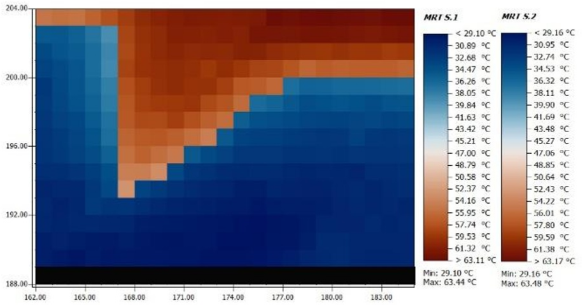

Fig. 6. Detail, Mean Radiant Temperature (MRT) for S.1 and for S. 2 at the study area

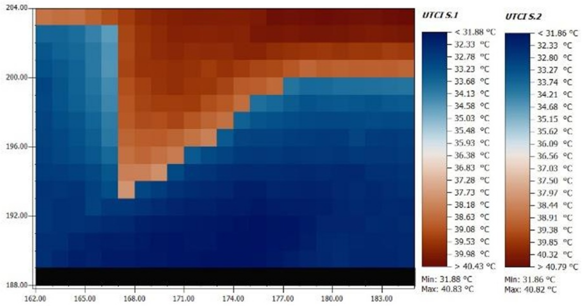

Fig. 7. Detail, Universal Thermal Climate Index (UTCI) for S.1 and for S. 2 at the study area

4.2 Line Charts

Figure 8 depicts the two scenarios MRT average values, while figure 9 shows the two scenarios UTCI average values.

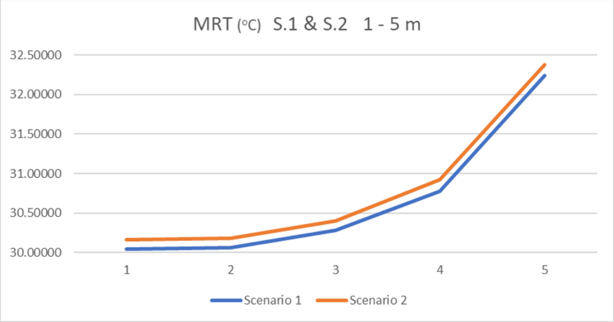

Fig. 8.

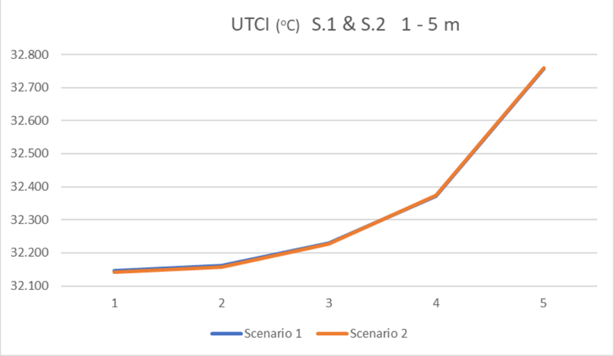

Fig. 9.

In a similar way, figure 10 depicts the difference ΔMRT and ΔUTCI between the two scenarios S.1 – observation, and S.2 – reference, from 1 to 15 m distance from the VGS.

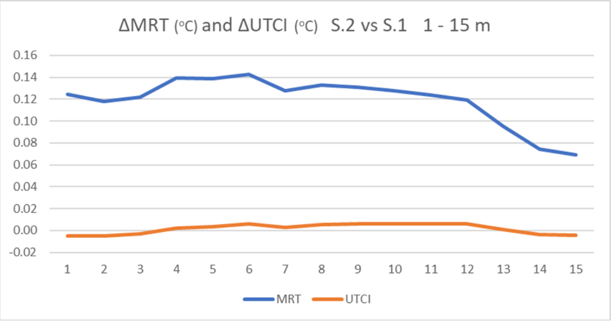

Fig. 10. ΔMRT °C and ΔUTCI °C, S2 - S1, 1 to 15 m from the VGS

4.3 Two Sample *t-test*

Table 3. Two sample t-test for the two VGS scenarios (S.1 – default, and S.2 – re-parametrised) thermal comfort parameters' mean values; Air Temperature (Ta), Mean Radiant Temperature (MRT), Universal Thermal Climate Index (UTCI), Wind Speed (WS), and Relative Humidity (RH), are extracted from grid coordinates at 1.5 m height.

m		Ta	MRT	UTCI	WS	RH
1	S.1	33.09	30.04	32.15	0.09	39.41
	S.2	33.03	30.17	32.14	0.09	39.57
	p	*< 0.05*	*0.53*	*0.93*	*0.99*	*< 0.05*
2	S.1	33.09	30.06	32.16	0.11	39.39
	S.2	33.04	30.18	32.16	0.10	39.54
	p	*< 0.05*	*0.55*	*0.93*	*0.99*	*< 0.05*
3	S.1	33.10	30.28	32.23	0.13	39.36
	S.2	33.05	30.40	32.23	0.12	39.51
	p	*< 0.05*	*0.55*	*0.96*	*0.92*	*< 0.05*
4	S.1	33.10	30.78	32.37	0.14	39.34
	S.2	33.05	30.92	32.37	0.14	39.48
	p	*< 0.05*	*0.54*	*0.97*	*1.00*	*< 0.05*
5	S.1	33.11	32.24	32.76	0.16	39.31
	S.2	33.06	32.38	32.76	0.16	39.44
	p	*< 0.05*	*0.92*	*0.99*	*1.00*	*< 0.05*

The re-parametrized scenario (S.2) has about 0.16 % lower Ta within 5 m of the VGS than the default scenario (S.1); similarly, the re-parametrized scenario (S.2) has about 0.37 % rise in RH with 5 m of the VGS than the default scenario (S.1).

5 Discussion

The comparative performance assessment indicates that among the considered variables Ta and RH differed significantly; as a consequence, the two scenarios do not overlap, despite the increased plant density of the re-parametrized VGS scenario – consequential of the increased LAI and plant thickness variables, compared to the default scenario. The two sample t-test indicate that air temperature (Ta) and relative humidity (RH) are the variables with significant differences in mean values between the two scenarios. Additionally, the examined north-northwest wall was found to have a diminished presence of annual sunlight - with the exception of a small, higher section. Thus, the attempted optimization process was shown to have minimum impact on the area's microclimatic conditions. Considering this intriguing outcome, a suggested conclusion is that it is up to the stakeholder to decide whether to uptake such a methodological optimization process for modeling VGS, depending on the contextual peculiarities. In addition to these, some additional considerations are brought up for discourse.

Regarding the present study, the results advocate the importance of a building's orientation and subsequently its solar exposure - along with climate and location, in VGS performance investigations [35]. Research on VGS in the Mediterranean region showed that shortage of sunlight renders northern orientations to be less effective in terms of reducing energy consumption, compared to other orientations [36]; additionally, north-oriented VGS provide less cooling compared to other orientations in the northern hemisphere [37]. In similar contexts, it is shown the effectiveness of greenery in combination with light pavements (higher albedo surfaces) in ameliorating thermal comfort indices in urban environments [27]. Also, studies emphasize the significance of the air gap size between the VGS and building's façade - although this study does not specifically address this aspect (setting the air gap in both scenarios to 20 cm), as a feature that can improve a building's efficiency by reducing ventilation requirements [37, 38]. A noteworthy remark about the plant variables in the study presented is that no measurement was carried out for their determination. Nevertheless, various non-destructive and destructive monitoring sampling techniques are well described as well as, guidelines are suggested for a more standardized determination and reporting of LAI values in VGS [15], contributing, thus, to the discourse by providing well-informed observations. In this regard, the green building sector suggests incorporating an array of environmental performance evaluations and subsequent tools and indicators into greening initiatives, enabling or facilitating in this way several assessment procedures, like life-cycle assessment (LCA) studies - among others, developed from internationally recognized methodologies and standards [39].

Finally, creative engineering and ecologically-oriented urban design strategies are needed to technically adapt NbS to local contexts [40] while multidisciplinary cooperation and community engagement [41, 42] as well as, innovative policy-making [43] are needed for their successful implementation.

6 Conclusions

Implementing NbS and in particular VGS, for thermal comfort amelioration in urban areas presents challenges, highlighting the importance of a quantitative performance assessment in such initiatives. Consecutively, using the three-dimensional CFD model of ENVI_met, a comparative analysis between two VGS scenarios was presented for a case study in Athens, Greece. Considering site specificity, the study measured the performance of two north-oriented VGS in relation to microclimate regulation by setting forth the methodological process for utilizing local plant species and consequently re-parametrizing the chosen plants' variables of LAI and plant thickness, within the ENVI_met - Database (DB) Manager module. The mean radiant temperature (MRT) and the universal thermal climate index (UTCI) at the pedestrian level were two pertinent indices that were considered for outdoor thermal comfort. The comparative study featured minimal differences between the thermal comfort parameters at play, highlighting important aspects of the modeling optimization process and emphasizing in this way the necessity of a thorough analysis to effectively incorporate VGS for optimal microclimate performance.

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