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THE EFFECT OF ORIENTATION AND PLANT TYPE ON THE THERMAL BEHAVIOUR OF LIVING WALL SYSTEMS IN BUILDINGS

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ABSTRACT

Living wall systems are the vegetated wall systems where growth layer is located behind the plant and integrated onto the wall. They started to be used widely due to their many benefits such as increasing the energy efficiency of the building. Living wall can contribute to wall's thermal performance by its shading, insulation and wind protection effects. However, there are limited studies which is done by simulation to investigate its insulation effect. In the previous studies, its shading effect is usually simulated, and evaporation and transpiration were not taken into account which are the major effect of being a live mechanism. In this study, it is aimed to see the effect of living wall's orientation and the plant types on interior thermal conditions, by using a microclimate simulation program ENVI-met. ENVI-met provides a vegetation model that simulates evapotranspiration and interaction between the outdoor microclimate with indoor climate. In this context, the temperature differences that occur between the wall layers and interior surface temperature of the living walls are compared with those of bare wall for two cities in Turkey which are representatives of hot and humid climate and temperate climate. Thus, it has been seen especially the west and south facades of the building and also the plant types according to their leaf area index (LAI) affect the efficiency of the building depending on the climate.

Keywords: *Living Wall; Performance Simulation; Vegetated Wall Systems.*

1. INTRODUCTION

Vegetated walls have been used in construction in the world for centuries due to its both functional benefits such as shielding and shading the building and aesthetic benefits. One of the first examples of using the vertical garden in construction is known to be Hanging Gardens which is one of the seven ancient wonders of the world (Manso and Castro-Gomes, 2015). Especially in countries with hot climate, covering the building envelope with vegetation is a timeless architectural precaution in order to block the undesired heat gain (Susorova, 2015). New vegetated wall systems have been developed since decades, and recently, instead of climbing plants, living wall systems have been designed and constructed more. These are vegetated wall systems where growth layer is located behind the plant and integrated onto the wall.

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The use of living wall systems is increasing day by day in the world because of their advantages. Improving air quality by working as a natural air filtration element, improving sound insulation, providing biologic diversity and habitat creation, protection of the building, adding aesthetic and economic value to the building, reduction of urban heat island effect and increasing energy efficiency are some of the advantages of living walls (Besir and Cuce, 2018; Manso and Castro-Gomes, 2015; Riley, 2017). Particularly, the increased energy efficiency provided by living walls is achieved by decreasing heating loads by being an insulation and a wind barrier mainly, and its effect on cooling loads by shadowing primarily (Besir and Cuce, 2018; Riley, 2017). Additionally, transpiration also creates small zones of cool air, between the green wall and the building envelope, and helps reducing cooling loads. For example, at the Consorcio project in Santiago, Chile, the 43% of its west façade is covered by greenings. According to the reports, the solar radiation is reduced 60%, and 48% less energy is used than other comparable buildings (Wood, Bahrami and Safarik, 2014).

In buildings with living walls, the required interior comfort conditions while using less energy can be achieved by taking the right decisions about living walls' design variables influencing energy efficiency. Specifically, as a part of building envelope the living wall system's thermal performance is affected by the characteristics of wall and insulation materials behind the greenery system, and the plant type and frequency (Susorova, 2015). However, studies which focus on the effect of plant type on thermal behaviour of the living walls, including different seasons in different climates for different orientations are very limited. In this respect, the study presented here aims to compare and discuss changing thermal responses within the wall, i.e. between building envelope layers for different plant types in different climates for different orientations based on numerical simulation results. To this end, two different cities in Turkey; Antalya and Istanbul with hot-humid and temperate climates respectively were considered to investigate the behaviour of living walls and to compare with that of bare wall (i.e. without greenery system) depending on wall orientation. In terms of plant type, their leaf sizes are considered, and two different Leaf Area Indexes (LAI) were studied. In the following sections, after a short theoretical background on living wall systems, the methodology of the study is explained. The simulation results are then presented and discussed in terms of changing behaviour in respect to aforementioned variables.

2. THEORETICAL BACKGROUND

Living walls are newly developed, completely artificial wall systems where not only the plant is attached to the building façade, but also the growing medium is integrated onto the building envelope surface. This feature separates them from green facades where plants are rooted at the ground level (Bustami, et al., 2018). Living walls are divided in two main groups as (i) continuous (felt) and (ii) modular systems. Continuous systems are lighter systems where plants are rooted in, on the contrary of traditional growing medium such as soil, between two lightweight fabrics in the form of pockets which is supported by a rigid substructure system. These fabrics are usually recycled lightweight felts. Modular systems with specific dimensions, on the other hand, include the growing media (e.g. soil, coconut fiber, volcanic stones, hydro stones, stone wool). Each element is supported by a complementary structure or fixed directly on the vertical surface (Manso and Castro-Gomes, 2015).

In a living wall system, independent from the aforementioned subtypes, irrigation of the growing layer is an indispensable part of the facade system, which differs it from a traditional wall that is not intentionally exposed to water and its effects. As a result of having a wet part, i.e. regularly irrigated growing medium in the section of the wall, the whole thermal behaviour of the wall is expected to be affected. For instance, in a study that can be related to living walls and evaluates the growing layer temperatures of green roof systems mentions for achieving a cooling effect that, in order to increase the radiant heat exchange, the temperature of the back face of the green roof system has to be kept as low as possible, which could be achieved by keeping the substrate wet (Lazzarin, Castellotti and Busato, 2005). In another study on the effect of air flow in the vertical greening systems, it has been observed that the temperature differences in the mean values were 9^{0}C at various points of the wall section (Perini, et al., 2011).

Malys, Musy, and Inard (2014) explain that the most sensitive parameters are the thermal characteristics (particularly the thermal conductivity - λ) and the thickness of the growing medium which allows to calculate thermal inertia that appears in the substrate temperature evaluation. They also notice the decrease in the thermal conductivity maybe due to a drier substrate in their sample (Malys, Musy, and Inard 2014). Thus, it is expected to increase thermal conductivity relying on the water coefficient level which depends on irrigation. Consequently, the temperature on different layers for the same living wall can differ.

Apart from the limited number of studies where the effect of the growing layer of the living wall's temperature is observed, there are studies on green roofs where the growing layer has a similar effect. In the study examining the temperature values in green roof systems made by Ouldboukhitine, et al. (2011), it is observed that there are temperature differences up to 10^{0}C between outdoor air temperature and the substrate layer temperature.

In another study it is mentioned that for dry substrate where evapotranspiration is very limited, a green roof reduced the heat gain by 60% mostly due to solar reflection and absorption by the plants and the substrate. Additionally, for a wet substrate, instead of 40% entering heat flux into the building, a slight outgoing heat flux is resulted due to an increase in evapotranspiration rate is revealed. (Lazzarin, Castellotti and Busato, 2005; Raji, et al., 2015). Additionally, the water content of substrate influences the thermal performance of a green roof in each season in a different way. During hot seasons or in equatorial climates (i.e. where summer-winter temperature difference is not considerable), a wet green roof can increase the heat dissipation through evapo-transpiration cooling. Therefore, it reduces the need for indoor cooling. However, in winter, thermal resistance of a green roof improves with less water content in the substrate due to water having a higher thermal conductivity (Morau, et al., 2012; Raji, et al., 2015).

The other important component which is a part of living wall is the plant. Plant to be used at the living wall system is not only an important decision area for architects due to aesthetical reasons, but also it is another factor that may affect the thermo-physical characteristics, and in turn thermal performance of the wall system. Type, albedo and transmittance of the leaves, leaf area density (LAD) profile, leaf area Index (LAI) are some of the characteristics of plants which may affect the whole performance of the wall (Raji, et al., 2015). In terms of thermal effect of living walls, five different leaf types are present, which are; (i) fronds, (ii) conifer, (iii) angiosperm, (iv) lycophytes, and (v) sheath. Albedo of the leaf is the measure of the diffuse reflection of solar radiation out of the incident total solar radiation on leaf and measured on a scale from 0 (corresponding to a black body that absorbs all incident radiation meaning black), to 1 (a body that reflects all incident radiation meaning white) (GenScipt, 2022). Smoothness and colour of the plants are significant parameters which affect albedo. Whiteness and smooth surfaces has high albedo values compared to dark and textured surfaces (Jain, Kuriakose and Balakrishnan, 2010). LAD is the total leaf surface area per unit volume of space (m^2/m^3) (Dearuz, 2016). Transmittance of the leaf can be explained as the transmittance factor of the leaf for shortwave radiation (Bruse, 2009). LAI is a dimensionless quantity that characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area in broadleaf canopies (m^2/m^2). LAI ranges from 0 for bare ground to over 10 for dense conifer forests (Xu, 2020). Plant layers with different leaf area indexes are shown in Figure 1.

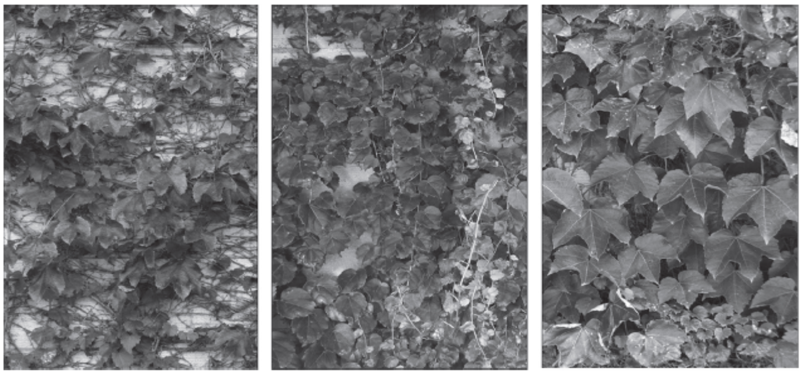


Figure 1: Plant layers with different leaf area indexes

Source: Susorova (2015)

3. METHODS AND MATERIALS

The study that aimed to investigate the effect of plant type and characteristics on interior environmental conditions in different climates was based on dynamic computer simulation performed by Envi-met software. It was consisted of five main stages, which were (i) selection of cities to be studied, (ii) determining critical dates to investigate, (iii) designing living wall and building wall, (iv) preparation of building simulation model and running simulation, and (v) assessment of the simulation results. In the following subsections these stages are detailed.

3.1 SELECTION OF CITIES

The use of living walls at buildings is not widely spread in Turkey. Istanbul, by being the most populated city of Turkey which contains ca. 11% of the buildings in the country (Tuik, 2015*)*, and by being the city where almost 20% of the total construction in Turkey is done in last 7 years, has a great potential for adopting this system. It was therefore determined to be one of the cities to be studied. Istanbul, with its temperate-humid climate, is within 2nd zone according to the mandatory Turkish Standard TS 825 Thermal insulation requirements for buildings which divides Turkey into five climate zones (TS 825 Thermal Insulation Requirements for Buildings, 2013). Knowing that the performance of livings walls varies depending on the climatic conditions, another city with a hot-humid climate, i.e. Antalya, which is located at the southern parts of Turkey were decided to be studied. According to the Turkish Standard TS 825, Antalya is in 1st climate zone with the least thermal insulation requirements among other zones.

3.2 SELECTION OF DAYS FOR INVESTIGATION

To see the effect of the exterior air temperature, two different days with high and low average temperature values with most constant solar radiation were determined from weather files (i.e. epw file) of both cities. Dates selected for each city and solar radiation and temperature values for these days are given in the Table 1.

Table 1: The outdoor air temperature and normal radiation values for selected days (*Source: Climate data for building performance simulation*, 2021)

City	Date	Direct Normal Radiation (W/m^2)		Dry Bulb Temperature (^oC)	
		Total	Maximum	Average	Maximum
Istanbul	April 9th	6987	855	10.3	14
	August 7th	6904	796	28.6	36
Antalya	February 2nd	6069	837	10	15.3
	August 14th	5954	804	29.5	31

3.3 LIVING WALL AND BARE WALL DESIGNS

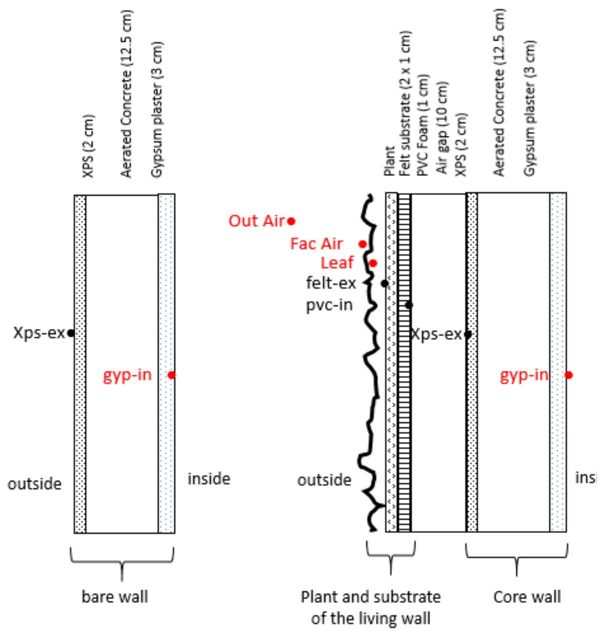
Bare wall and core wall of the living wall were designed considering the commonly used wall materials in Turkey and the thicknesses of materials were determined considering the U-value limits identified in TSE 825 for both climate zones, which are 0.66 W/m^2K and 0.57 W/m^2K for Antalya and Istanbul respectively. The schematic sections of these walls and materials' thermal conductivity values used in in the simulations are given in Figure 2. Since the simulation software allows to use only three layers in the core wall, exterior render is omitted both in bare wall and in living wall design.

In the living wall, double layer felt system is investigated as a growing medium. In the material database of the software, felt is not present. However, it allows to add new materials, and felt is introduced accordingly. Characteristics of the substrate and plant layers as used in the simulations are given in in Table 2. Since it is desired to see the effect of leaf property, two different LAI values, i.e. 1.5 and 5 m^2/m^2 are examined.

3.4 PREPARATION OF SIMULATION MODEL AND RUNNING SIMULATIONS

In the study Envi-met which is a 3D prognostic microclimate model based on computational fluid dynamics and thermodynamics was used. The software is capable of simulating exchanges of energy and mass between vegetation and its surrounding (ENVI-met 3.1 Manual Contents, 2022).

A building with 10 m width, 10 m depth and 14 m height with a flat roof was modelled for the study within a site of 26 m x 26 m. In the grid systems of both building and the site, except the first floor of the building, cell size was taken as 2 m. The program has an option to split into 5 sub-cells on the vertical axis grid for the first floor of the building. The building modelled in these respects is shown in Figure 3-a. 12 different simulations depending on location, time and wall type in terms of LAI were run as given in Figure 3.b.



	Thermal Conductivity W/(m K)
Plant	-
Felt Substrate	0.04
pvc foam	0.1
Airgap betw. substrate and wall	-
insulation XPS	0.03
Aerated concrete	0.11
Gypsium Plaster	0.58

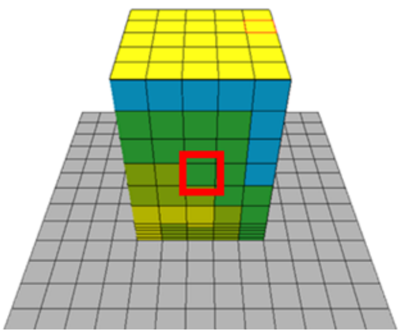
Monitoring locations

Out Air	Outside air dry bulb temperature (C°)
Fac Air	Air Temperature in front of the façade (C°)
Leaf	Leaf Temperature (C°)
Felt-Ex	Outside surface of the substrate (C°)
Pvc-In	Inside surface of the substrate(C°)(pvc-in)
Xps-ex	Outside surface temperature of the bare wall(C°)(xps-ex)
Gyp-in	Inside surface temperature (C°) (gpy-in)

Figure 2: Schematic sections of investigated bare wall and living wall, thermal conductivities used and locations of temperature monitors.

Table 2: Characteristics of Greenery system (i.e. substrate and plant)

Plant Characteristics	Value used	Substrate Characteristics	Value used
Albedo (0-1)	0.25	Albedo (0-1)	0.3
Height (cm)	2	Emissivity (-)	0.95
Leaf angle distribution (-)	0.5	Water coefficient (-)	0.5
Transmittance	0.2	Type of material	Artificial
LAI (-)	1.5 and 5	Air gap bet. sub. and wall	10 cm

a) 

b)

CODES	Location	LAI	Wall Type	Date
LiAn1,5Win	Antalya	1,5	Living wall (felt system)	2nd Feb
LiAn1,5Sum	Antalya	1,5	Living wall (felt system)	14th Aug
LiAn5Win	Antalya	5	Living wall (felt system)	2nd Feb
LiAn5Sum	Antalya	5	Living wall (felt system)	14th Aug
BareAnWin	Antalya	-	Bare wall	2nd Feb
BareAnSum	Antalya	-	Bare wall	14th Aug
LiIst1,5Spr	Istanbul	1,5	Living wall (felt system)	9nd April
LiIst1,5Sum	Istanbul	1,5	Living wall (felt system)	7nd July
LiIst5Spr	Istanbul	5	Living wall (felt system)	9nd April
LiIst5Sum	Istanbul	5	Living wall (felt system)	7nd July
BareIstSpr	Istanbul	-	Bare wall	9nd April
BareIstSum	Istanbul	-	Bare wall	7nd July

Figure 3: a) Grid system of the building simulated and the location of the area on the building considered for assessments; b) Simulations according to their location, wall properties and dates

In the simulations, the heating and cooling systems were accepted to be not operating in order to observe the individual effect of living wall system. In relation to this preference, in order to allow a settling time for the interior air temperature, the starting day of the simulations were determined to be two days prior to the selected day, and simulations were run for a 3-day period. The initial interior air temperature was set to be equal to outside temperature, and the balance was confirmed to be occurred within 48 hours. In the assessments, the results of the 3rd day are being evaluated.

3.5 ASSESSMENT OF THE SIMULATION RESULTS

The results of each cell specified in the grid plane are different from that of others depending on its place on the building height, amount of radiation and shade, wind direction and its effect. Therefore, for the four facades of the building, the results of the cell, which is at the midpoint of the facade, are taken into consideration, and the temperatures obtained were evaluated in terms of the effect of building orientation, LAI and environmental climate conditions by comparing with each other and with that of bare wall.

4. SIMULATION RESULTS AND DISCUSSION

The changes in the behaviour of living wall in respect to (i) change in the orientation, (ii) change in LAI, and (iii) change in exterior environmental conditions are discussed separately in the following sections considering the simulation results.

4.1 THE EFFECT OF ORIENTATION ON WALL TEMPERATURES

Temperature change in the living wall layers facing different orientations were compared with each other for the days selected. As given in Figure 4 for simulation LiAnWin1.5 as an example, the general temperature distribution pattern within the wall at a particular hour of the day was similar in all directions, but with changes in the temperature values observed. The temperature of pvc-in for instance was nearly always lower than that of other layers, while sometimes the temperature of gyp-in and sometimes the temperature of xps-ex was higher when these two were compared with each other. Experimental studies reported a similar behaviour where the temperature of substrate was lower than that of the leaves (Dearuz, 2016; Ouldboukhitine, et al., 2011).

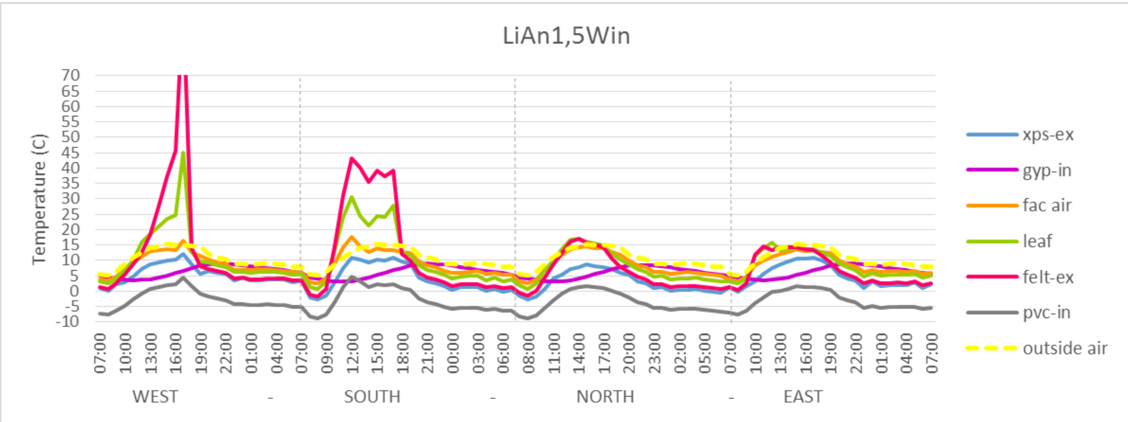


Figure 4: LiAn1,5Win - Temperature change during the day in the wall layers facing different directions.

Significant temperature variation depending on the orientation was observed especially at the exterior layers of the living wall, i.e. at the plants and the exterior side of the substrate. The temperatures of these layers were relatively similar during the whole day when north and east facing facades were compared with each other. On the other hand, the temperatures of these layers at south and west facing facades were considerably higher when there was solar exposure. Even though temperature of leaves reached up to ca. 45°C and 30°C at west and south facing facades respectively, and these were lower than that of felt-ex during these hours, the temperature of pvc-in which is the inside surface of the substrate layer is lower than that of felt-ex for all four orientation. The biggest temperature difference between leaf temperature and gyp-in is obtained at west façade. Also, it is observed in the study of Perez, et al. (2017) that the west façade is more efficient due to its contribution of the temperature difference between inside and outside, although the south façade has been exposed to higher sun radiation.

It is important to note that the interior surface temperature (i.e. gyp-int), which is an important factor in terms of providing interior thermal comfort conditions, was observed to be not changing much during the whole day depending the orientation of the façade. The maximum temperature difference between different orientations is observed to be 0.7°C.

Consequently, it has seen whereas in winter, in Antalya, using bare wall at south façade is more advantageous than the other orientations, in summer conditions living wall gives the best results for west façade orientation.

4.2 THE EFFECT OF LIVING WALL AND PLANT TYPE ON WALL TEMPERATURES

In order to understand the effect of living wall on interior conditions in general and of the plant type in particular, the interior surface temperatures of walls with plants having different LAI (i.e. 1.5 and 5) were compared with each other and with that of bare wall without any plant. These comparisons showed the followings.

High LAI creates multi layered barrier against radiation by providing a shadow. So, high LAI prevented interior surface temperature increase due to solar exposure, as expected. It created a disadvantage in winter/spring conditions but created an advantage in summer conditions by contributing to the shading (Figure 5a). In winter conditions, as the LAI rises from 1.5 to 5, gyp-in (i.e. interior wall surface) temperatures drop by an average of 0.8 °C on all facades. In summer conditions, as the LAI rises from 1.5 to 5, the gyp-in temperatures decrease on the west, east, south and north facades, by 0.9, 1.1, 1.0, 0.8 °C respectively.

Interior surface temperatures of both living walls were lower than that of bare wall. Again generating an advantageous situation in summer, while the opposite in winter. In winter conditions interior surface temperature of bare wall are higher which shows that using living wall may not be advantageous for Antalya in winter period (Figures 5a and 5b). Between 11 a.m. and 7 p.m. in Antalya, the gyp-in temperature is 7°C higher and more advantageous in the bare wall compared to that of the living wall because of the sun exposure on the western and southern fronts in winter conditions.

In winter conditions, for the case where bare wall and living wall with LAI of 1,5 are compared, the average temperature difference for gyp-in between bare wall and living wall is 4.0 ,3.5, 4.5 and 3.8 °C respectively for west, east, south and north (see Figure 5) In summer conditions on the other hand, when the average temperature differences of gyp-in between bare wall and living wall are compared, the living wall gyp-in temperatures decrease 6.0, 5.0, 5.2 and 5.5 °C on the west, east, south and north sides, respectively.

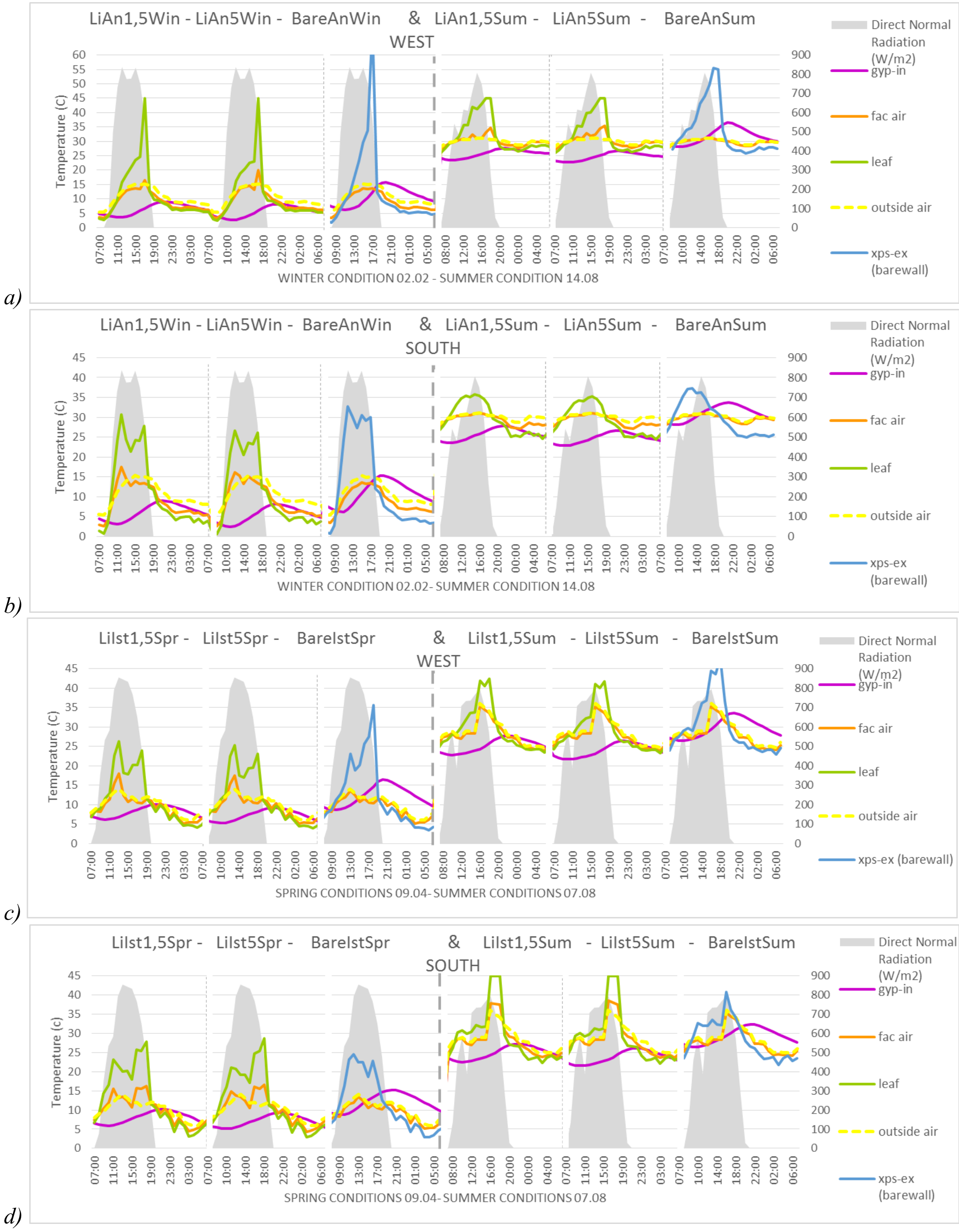


Figure 5: Temperature variations (a and b) in Antalya for west and south facades respectively, and (c and d) in Istanbul for west and south facades respectively for the selected days and investigated LAIs

Moreover, the bare wall xps-ex temperatures reaches 48^{0}C in summer conditions for west façade, whereas living wall with LAI of 1.5 reaches 42^{0}C for the same day (Figure 5a). For winter the xps-ex temperature difference between the bare wall and living wall with LAI of 1.5 is also higher around 10^{0}C in Istanbul. Another study also shows that the bare wall's outside surface temperatures can reach to 58^{0}C while the living wall's exterior surface temperature stays maximum at 35^{o}C (Chen, et al., 2013).

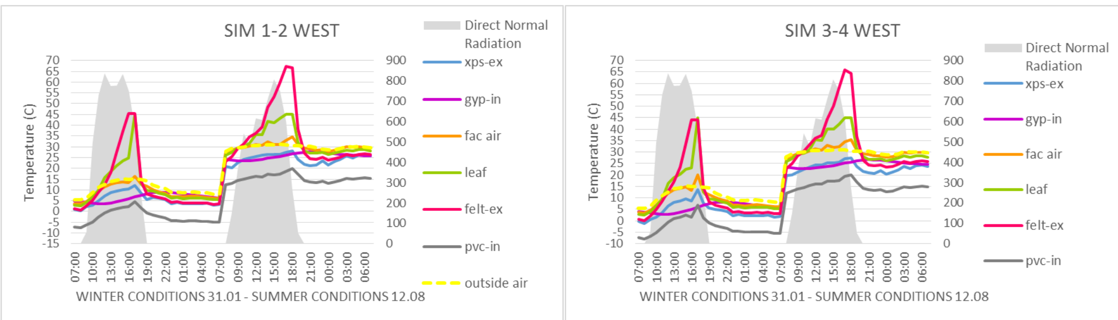
4.3 THE EFFECT OF CLIMATIC CONDITIONS

The comparison of outside air temperature and interior surface temperatures observed in different seasons showed that the difference between them was higher on the west and south side in summer conditions than winter/spring conditions for both cities as can be seen in Figure 5a and 5c. Additionally, bare wall is observed to be affected from outside air temperature especially in the summer conditions. Thus, the gap between indoor surface temperature (gyp-in) and outside air temperature is lower than that of living walls during summer time in İstanbul and Antalya.

In winter and in summer conditions in Antalya, even though the leaf temperature in the afternoon depends on the outside air temperature, due to the effect of having same amount of radiation during the daytime, the leaf temperature reaches to the same peak temperature which is 45°C on the west facade (Figure 5a-5c). However, on the east façade, the leaf surface temperature is parallel to the outside air temperature. The reason behind it can be predicted as the accumulated radiation in the morning. The comparison of outside air temperature and interior surface temperatures observed in different hours during the day shows in Antalya that, for the first half of the day from 8:00 am to 8:00 pm (during the daytime), the gyp-in (wall inside surface temperature) is lower than the outside air temperature, whereas in the evening the outside air temperature is almost equal to gyp-in. Thus, in summer, especially during the daytime living wall is more advantageous.

For the same conditions, in summer, in Antalya, during the daytime, bare wall gyp-in is slightly lower than the outside temperature compared to the living wall and in the evening, gyp-in is higher than the outside temperature. The reason behind it can be shadow effect of living wall or the studied bare wall's heat capacity with the appropriate U value according to the standard may not be enough for summer conditions in Antalya. However, living wall's performance is better in terms of heat storage and it releases unwanted heat gain slowly and it keeps its gyp-in temperature constant (Figure 5a-5c).

Substrate layer's outer surface (felt-ex) temperature reaches to high temperatures in comparison to that of other monitoring points in all green wall types and in all cities, especially on the western facade and later on the south, as exampled in Figure 6 for Antalya.



a) b)

Figure 6: Winter and summer conditions for 1,5 LAI and 5 LAI Living wall systems in Antalya

Its reason can be explained with the wet substrates increased heat storage capacity; thus high solar exposures cause a dramatical temperature increase for felt-ex (i.e. front face of the substrate layer). The temperature of Pvc-in on the other hand is more stable, without a peak like that of felt-ex, which can be associated with the wet substrate.

5. CONCLUSION

In this study, where the effect of plant type, orientation and climatic conditions on living walls thermal behaviour is examined, two different LAI values as 1.5 and 5, four different orientations (i.e. cardinal directions) and two different climates (i.e. hot humid and temperate climates) are studied to see their effect on living walls compared to bare walls without any vegetation.

The results of the study can be summarized as follows;

- The living wall systems provide benefit in summer conditions both in Antalya and Istanbul, while they negatively affect indoor environment in winter conditions, when their effect on interior surface temperatures are considered.
- Both in Istanbul and Antalya, the increase in the value of LAI contributes to the interior surface temperature in a positive way for all façade directions in summer, while in the winter it has a negative effect.
- The use of the living wall system causes significant variations in the temperature values within the wall. Because of the irrigation requirements of the plants and the lack of sun exposure on the back surface of the growing layer, the wall's interior surface temperature decreases both in winter and summer conditions.
- In order to have an effective result in the living wall design, the façade direction that it must be applied is west and then south to see the difference on wall section. This is because the wall is exposed to solar radiation with a horizontal angle.

According to the results obtained, it was observed that the properties of the substrate layer may have effect on the indoor temperature as much as the plant. For this reason, in further studies, it is desired to see the effect of the irrigation frequency and thermal conductivity value of the substrate layer and the air gap on wall layer's temperatures.

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