Impacts of Vertical Greening System (VGS) on daylight quantity and quality in buildings

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ABSTRACT: With the efforts to reduce building energy consumptions and to improve occupant comfort, use of natural light in buildings has become inevitable. Buildings of today have large glazing on their facades to allow sunlight into building interiors. When adequately introduced, natural light provides numerous benefits ranging from energy saving to occupant comfort. However, natural light can also cause thermal and visual discomfort to occupants by uneven distributions of illuminations or extremely high luminance in occupant's field of view. Vertical greening system (VGS) on exterior building facades can be utilized to control the amount of sunlight in building interiors. Multi-angled reflective and translucent surfaces of plants reflect and diffuse direct sunlight so that appropriate amount of daylight can be introduced in buildings.

In order to verify potential daylighting benefits of VGS, physical experimentation was performed. Three different vines that are widely used in VGS were chosen and their influences on the quality and quantity of natural light were investigated. A wooden cube box was built to simulate building interior space and fitted with an acrylic panel to simulate a south-facing window. The vines are mounted on a metal trellis with a square grid of 6-inches to mimic the natural growth of the vine and installed 6inches away from the window. The model was then mounted on a Heliodon and tested for different times in the year using the Sun as a light source. Lighting characteristics such as illuminance, luminance, discomfort glare and light color temperature were measured and analyzed. The findings show that discomfort glare levels were greatly decreased with the help of the vines as vertical illuminance levels were lowered and luminance distributions became more even by reflecting and diffusing direct sun penetrations. It was also observed that illuminance level and discomfort glare reduction are not only affected by the physical characteristics of plants. They are also affected by sun positions such as altitude and azimuth angles in different times and dates of the year.

KEYWORDS: Vertical greening system, Daylighting, Vines, Discomfort glare, HDR Photography.

1.0 LITERATURE REVIEW

In a typical urban environment, buildings have a large amount of glazing on their facades. These fully or partially glazed facades allow natural light and direct views to outdoor environments. However, the transparency of the large glazed facades can cause serious visual and thermal discomfort to occupants. When discomfort is experienced, building occupants often choose to close interior blinds to block strong sunlight penetrations. This, can increase architectural lighting energy consumptions. Many exterior shading strategies have been adopted to avoid occupant discomfort and to maintain energy-saving benefit from daylight harvesting in buildings. VGS are considered as one of the potential strategies to condition sunlight for improved visual and thermal comfort while maintaining a direct view of outdoor environments. However, the impact of green screens on natural light in buildings have not been thoroughly investigated yet.

1.1. Benefits of daylighting

The largest end use of electricity by commercial buildings in the United States which constitutes to 17%, is used for lighting (CBECS 2018). This large consumption of electricity in buildings for architectural lighting can be reduced by employing a suitably designed daylighting system, which in turn can reduce the utility cost of buildings. Prior studies have found that the use of daylight in buildings also provides non-energy related benefits such as psychological and physiological impacts on occupants. Daylighting offers a better quality indoor space to building occupants as the full spectrum natural light provides the best color rendering and depth perception. These benefits are as important as savings in building energy consumption. Natural light provides a homogeneous spectral distribution of light which is critical to regulating biological functions in humans. The majority of architectural lighting used in today's buildings lacks this spectral distribution, although full-spectrum fluorescent lighting does come close (Hathaway and Others 1992). Natural light provides a balanced spectrum of color, peaking in the blue-green area of the visible spectrum which makes it highly desirable (Liberman, J. 1991). The psychological and physiological effects of the different spectrums are not easily quantifiable and hence often overlooked.

A naturally daylit space has been known to improve mood, lower workplace fatigue, reduce eye strain and enhance morale. The dynamic nature of natural light with its change in intensity, subtle changes in color provides the occupants with a sense of connection to nature and enhance their experience. Occupants in daylight and full-spectrum office buildings reported an increase in general well-being. Specific benefits in these types of office environments include better health, reduced absenteeism, increased productivity, financial savings, and preference of workers. Benefits to the office worker are so great that many countries in Europe require that workers be within 27 feet of a window (Franta and Anstead 1994).

1.2. Visual discomfort

Visual discomfort is the phenomenon where there is irritation or pain in or around the eyes, usually accompanied by headache, nausea, redness or watering of eyes. Visual discomfort is caused due to lighting condition such as insufficient light for the task at hand, dramatic differences in illuminance around the task, shadows, reflections, glare and flicker (Boyce and Wilkins 2018).

Visual discomfort from natural light can be caused by direct sunlight penetrations or reflected sunlight from reflective and specular building materials. Discomfort glare can also be caused due to reflections from materials and surfaces such as glazed façade of building, water bodies and the sky. Precedent studies have proved that unsuitable levels of illumination cause strain to the eyes and reduce the productivity of occupants. Over-illumination causes fatigue, medically defined stress, anxiety and decreased sexual function in building occupants (Baum 1997, Burks 1994, Pijnenburg et al. 1991 and Knez 2001). Uneven distribution of light can make the extreme contrast in interior surfaces which cause visual discomfort.

1.3. Vertical Greening System

The vertical greening system is a structure that facilitates the growth of vegetation to spread over a building facade or interior wall. They can be installed as freestanding structures, or they can be attached to existing building facades. There are two supporting systems that are commonly used to support climbers and keep them away from facades; Cable and Wire-Rope Net and Modular Trellis Panel systems. Climbers are rooted in the ground at the bottom of these structures and it takes 3-5 years to achieve the full façade coverage (Greenscreen 2018). Vines on vertical greening system have been used for summer cooling by covering the building surfaces and pergola structure to produce shade (Stav, Y. 2008).

The metal trellis system is widely used in buildings with VGS. The trellis is made from either stainless steel or galvanized steel and coated with zinc at 380 g/m². Because of the system rigidity, it can be used for green walls that are freestanding. The thermal benefits of VGS on buildings have been extensively studied in precedent studies. However, the impacts of VGS on the quality of interior daylighting has not been quantified. Some of the notable buildings that employ VGS on their facades are, National wildlife headquarters in Virginia, The Kyocera Tanagura plant in Fukushima, Japan, The center for interactive research on sustainability in Vancouver, Canada, The Pritzker children's zoo at Lincoln Park Zoo and the Rush University Medical Centre in Chicago Illinois (Figure 1).

Figure 1: Examples of VGS on building facades (Left: Pritzker children's zoo at Lincoln Park Zoo in Chicago Illinois, Right: Rush Medical Centre in Chicago Illinois) ("Vines72.Jpg (324×432)" n.d.) ("TL_Mar-2008_Rush.Jpg (1200×900)" n.d.).

2.0 RESEARCH METHODOLOGY

To simulate and document daylighting quantity and quality influenced by VGS, physical experiments were performed in San Antonio, Texas on November 6th, 2017 under clear sky conditions. A physical model was made out of Baltic Birch wood measuring 3ft in height, width and depth (Figure 2). On one of the vertical faces, a 2ft by the 2ft window was cut out and fitted with an acrylic panel with 98% transparency to represent a window with high transmittance. The warm and light color wood material was sanded for uniform seamless grains. The vines were mounted on a metal trellis with a grid of 6-inch x 6-inch to mimic the natural growth of the vine. The 6-inch x 6-inch grid was selected as it is most widely used and provides adequate spacing between the leaves of the vines. The trellis was then installed 6 inches away from the window. The trellis is composed of a heavy duty 4 gauge (1/4") galvanized rods that were welded into a grid and are heavily galvanized with a thick zinc coating.

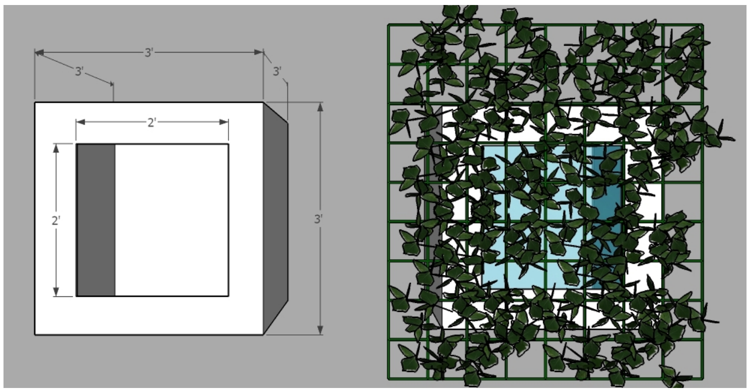


Figure 2: 3D model of the physical model and vine mounted on a metal trellis

Three different types of vines were selected for physical experiments: Carolina Jasmine, Rangoon Creeper, and Confederate Jasmine. These Vines were selected for the following three reasons: 1) they are available locally in San Antonio, 2) they are climbers that climb a metal trellis as they grow, and 3) they have different leaf sizes, shapes, leaf distribution pattern and leaf colors. The physical characteristics of each vine are listed in Figure 3. And key characteristics of the three vines such as density of foliage and leaf size are listed below.

- Vine 1(Carolina Jasmine) has the least dense foliage with small leaves of the length of 1 inch and width of 1/2 inch.
- Vine 2 (Confederate Jasmine) has medium dense foliage with medium leaves of the length of $3\frac{7}{8}$ inches and width of $1\frac{3}{4}$ inch.
- Vine 3 (Rangoon Creeper) has the highest dense foliage with large leaves of the length of 6 inches and width of 2 inches.

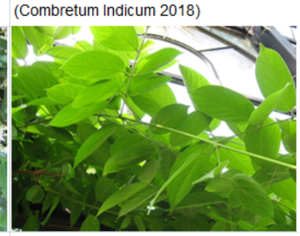
Description of Vines		
Carolina Jasmine: source: (Gelsemium Sempervirens 2018)	Confederate Jasmine: source: (Trachelospermum Jasminoides 2018)	Rangoon Creeper: source: (Combretum Indicum 2018)
		
Leaf Retention: Evergreen	Leaf Retention: Evergreen	Leaf Retention: Evergreen
Leaf Shape: Lanceolate	Leaf Shape: oval to lanceolate	Leaf Shape: elliptical
Leaf Venation: Pinnate	Leaf Venation: Opposite	Leaf Venation: Opposite
Leaf Texture: Waxy	Leaf Texture: Waxy	Leaf Texture: Waxy
Leaf Size: 1/2 inch to 1 inch long and 1/2 inch wide.	Leaf Size: ($\frac{3}{4}$–$3\frac{7}{8}$ in) long and ($\frac{3}{8}$–$1\frac{3}{4}$ in) wide.	Leaf Size: 3-7 inch long and 1-2 inch wide.

Figure 3: Physical characteristics of the three selected vines.

The physical model with each type of the vines was mounted on a Heliodon to simulate various sun positions on the summer solstice, winter solstice, and equinox. The source of light used in the experiment is the Sun. No artificial light source was utilized or introduced in this study. Various incident sun angles at 9:00 am, 12:00 pm and 3:00 pm were simulated for each of the selected days. Each vine type was tested on a total of nine different test conditions (3 days x 3 times) as shown in Figure 4. And, measured daylighting quantity and quality data were compared to a baseline case without VGS.

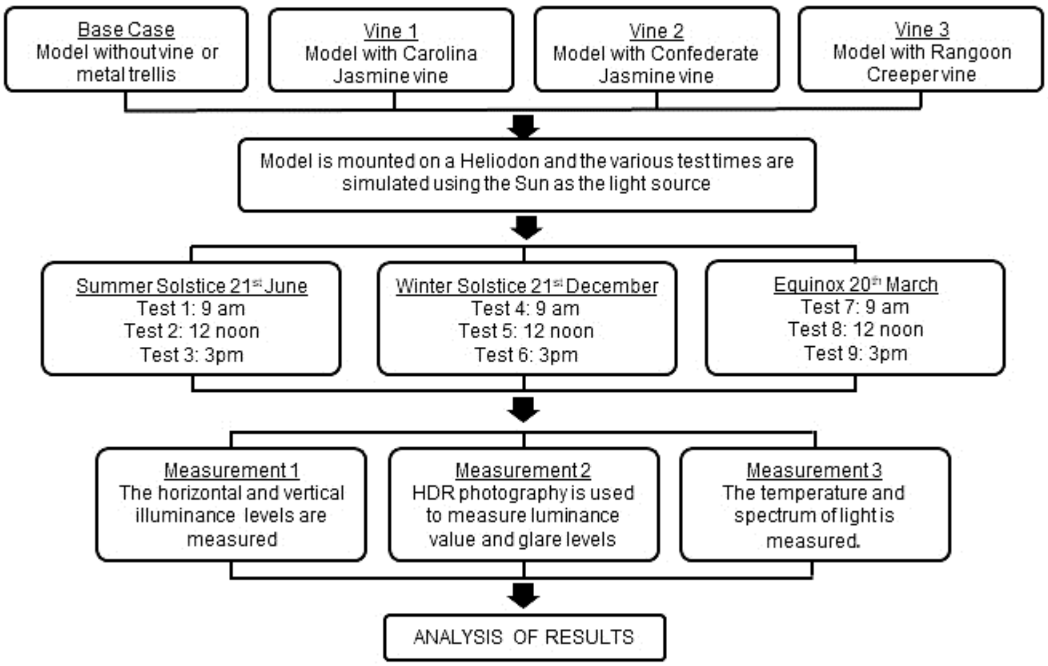


Figure 4: Physical experimentation sequence

Lighting characteristics such as illuminance, luminance, and light color temperature were measured using an illuminance meter, High Dynamic Range (HDR) photography technique and a spectrometer. Table 1 lists the different parameters and their units.

Table 1: Description and sequence of tests conducted

Sequence	Instrument	Parameter Analyzed	Metric Used
1	Illuminance Sensor	Quantity of Light	Lux
2	HDR Photography + HDR scope program	Glare	Daylight Glare Probability
3	Spectrometer	Correlated color Temperature	Kelvin
4	Spectrometer	Spectral composition of Light	Wavelengths

Li-Cor photometric sensors (Illuminance sensors) were used to simultaneously measure the quantity of natural light inside and outside the box for every case. The sensor inside the box was placed at the center of the floor of the box at the distance of 1 ft. from all the vertical faces. The sensor outside the box was placed at the center of the outward facing horizontal surface, representing the roof of the box at a distance of 1 ft. from all the edges. The indoor illuminance levels (Lux) with the three vines were compared to the illuminance levels of the base case to analyze the impacts of the vines on daylight quantity.
A spectrometer (Sekonik C-700-c) was used to analyze the light composition and color temperature of natural light inside the model after sunlight passes through the selected vines. Measured spectral composition of light and correlated color temperature values of each individual vine were compared to the base case to analyze the impacts of the vines on the quality of the light.

HDR photography was used to capture various daylit scenes with and without the selected vines. HDR images were taken inside the model with the camera fitted with a fisheye lens and facing towards the window. The camera was placed at the center of the vertical surface directly opposite to the surface with the window at a distance of 1 ft. from all its edges. Every pixel in the HDR image stores accurate luminance information that can be used to perform quantitative and qualitative light analysis. The camera was calibrated to match the luminance data from the HDR photographs to measured luminance values prior to the tests. These captured HDR images were analyzed using HDRscope to calculate the daylight glare probability (DGP) values. A DGP value below 0.35 is considered as imperceptible glare, 0.35 - 0.40 is perceptible glare, 0.40 - 0.45 is disturbing glare, and above 0.45 is intolerable glare (Wienold 2018).

3. ANALYSIS

The physical characteristics of vines such as density of foliage and leaf size play an important role in their impacts on the quantity and quality of light. Therefore, it is important to relatively compare these key characteristics amongst the three vines before analyzing the impacts of each individual vine.

3.1 Discomfort Glare Analysis

Glare analysis was first conducted with the captured HDR images. Daylight glare probability (DGP) values for each scenario were calculated and compared to the base case model (Table 2).
In the nine scenarios tested for a base case scenario without vines, five scenarios (bolded values in Table 2) show either disturbing glare or intolerable glare with DGP values ranging from 0.41 to 0.79. The calculated DGP values show that vines decrease the chances of visual discomfort, particularly in summer and winter solstices. The vines do not make any impact on DGP scores on the equinoxes as the DGP values in the base case were imperceptible to begin with.
In the five scenarios, it was noticed that:

- Vine1 (Carolina Jasmine) reduced perceptible glare to imperceptible values ranging from 0.26 to 0.35 in 3 scenarios on winter solstice.
- Vine 2 (Confederate Jasmine) reduced perceptible glare to imperceptible values ranging from 0.31 to 0.35 in 4 scenarios on winter solstice and at 3:00 pm on summer solstice.
- Vine 3 (Rangoon Creeper) reduced perceptible glare to imperceptible values ranging from 0.26 to 0.35 in all 5 scenarios on winter solstice and summer solstice.

Table 2: Daylight glare probability (DGP) values for glare analysis.

Glare Analysis - Daylight Glare Probability (DGP)					
Day and Time	Altitude	Base case	Vine 1	Vine 2	Vine 3
Summer Solstice-9:00 am	42°	0.29	0.25	0.25	0.23
Summer Solstice-12:00 pm	80°	***0.79***	0.47	0.54	***0.37***
Summer Solstice-3:00 pm	57°	***0.41***	0.41	***0.33***	***0.28***
Winter Solstice-9:00 am	16.5°	***0.47***	***0.26***	***0.32***	***0.27***
Winter Solstice-12:00 pm	36°	***0.55***	***0.35***	***0.31***	***0.24***
Winter Solstice-3:00 pm	26°	***0.53***	***0.32***	***0.33***	***0.26***
Equinox-9:00 am	30°	0.29	0.25	0.25	0.23
Equinox-12:00 pm	60°	0.26	0.23	0.23	0.22
Equinox-3:00 pm	46°	0.23	0.22	0.22	0.21

It is observed that the reduction in discomfort glare (the calculated DGP values) is directly proportional to the density and leaf size as the higher density of leaves provided more shading. Additionally, the larger glare reduction was seen in vines during test scenarios where the altitude of the sun was low, ranging from 16.5 degrees (9:00 am on the Winter solstice) to 57 degrees (3:00 pm on the summer solstice). However, in the case of the Equinox, the low sun altitude of 30°, 60° and 46° at 9:00 am, 12:00 pm and 3:00 pm showed imperceptible glare for the base case as well as the three vines. This imperceptible glare at low sun altitudes was caused due to the low levels of illuminance in comparison to the other cases. The luminance level inside the box for 9:00 am was 2596 Lux, 12:00 pm was 1678 Lux and 3:00 pm was 974 Lux which are significantly less when compared to the cases that show perceptible glare in the base case. This illustrates that in addition to the altitude of the sun, the DGP value is directly proportional to the intensity of the light.

At 9:00 am on Winter Solstice (16.5-degree sun altitude), the calculated DGP values for the base case was 0.47, Vine 1 was 0.26, Vine 2 was 0.32 and Vine 3 was 0.27. All three vines showed a significant reduction in

discomfort glare where the intolerable glare in base case was brought to imperceptible glare with the help of the vines.
At 3:00 pm on the summer solstice, the DGP values for the base case was 0.41, Vine 1 was 0.41, Vine 2 was 0.33 and Vine 3 was 0.28. Vine 1 showed no reduction in DGP score. However, Vine 2 and Vine 3 significantly reduced the DGP scores to imperceptible glare.
The test case with the highest altitude of the sun, at 80 degrees was observed at 12:00 pm on the summer solstice. In this case, the DGP value in the base case was 0.79 which is the highest DGP value observed in the tests. The DGP value of the Vine 1 was 0.47, Vine 2 was 0.54 and Vine 3 was 0.37. Despite a significant reduction of DGP values was observed in all three venues, only Vine 3 brought the DGP value low enough to be classified as perceptible glare. From the above data, it is inferred that the glare reduction potential of all three vines is inversely proportional to the angle of altitude of the sun in the sky.

In addition to the calculated DGP scores, examples of the captured HDR images for the base case, Vine1, Vine 2 and Vine 3 shown in Figure 5. At 12:00 pm on the winter solstice, all the vines were able to bring down the DGP values to imperceptible glare levels (0.33-0.38) from intolerable levels (0.53). A very large sunlight patch was projected on the floor of the room through the window. It is possible to assume that intolerable glare in the base case is caused by the reflected sunlight on the floor rather than the sky through the window. All three vines cast shadows on the floor as they block and filter direct sunlight. Compared to Vine 1 and 2, Vine 3 shows the densest shadows on the floor, which lowers discomfort glare levels to imperceptible glare sensation. At 12:00 pm on the summer solstice, all four scenarios have a small direct sunlight penetration right in front of the window. It is understood that the bright sky outside the windows causes an intolerable glare sensation and the three different types of the vines help to reduce the luminance of the sky as they filter direct sunlight. The luminance outside the box was observed to be 129500Lux, the luminance inside the box for vine 1 was 4407 Lux, Vine 2 was4193 Lux and vine 3 was 3088 lux. This demonstrates that Vine 3 showed a reduction of about 25% when compared to vine 1 and 2. However, the luminance of the windows is still in the range of causing an intolerable glare sensation in the Vines 1 and 2. Vine 3 with the large leaf size greatly reduced discomfort glare levels of intolerable glare to perceptible glare. From this it is evident that reduction of luminance values inside the box also reduces the DGP values.

	High dynamic range photographs showing the light distribution patterns			
Date	Base Case	Vine 1	vine 2	vine 3
Winter Solstice 12 Noon (21 December) Azimuth: 170* Elevation:36*				
Daylight Glare Probability (dgp)	0.55	0.35	0.31	0.24
Summer Solstice 12 noon (21 June) Azimuth: 125* Elevation:80*				
Daylight Glare Probability (dgp)	0.79	0.47	0.54	0.37

Figure 5: HDR images showing the light distribution patterns and daylight glare probability values

3.2 Correlated Color temperature

The impact of the vines on light color temperature was analyzed. Out of 24 measurements of light color temperature, 62% (15 cases) showed a significant decrease in light color temperature value in comparison to the base case. Corresponding to the color spectrum, making the light "cooler/whiter" or increase the value in Kelvin. For the cases where the vines made the light "warmer/redder" or decreased the value in Kelvin, a relation to the sun altitude angle was explored. However, no relation between the angle of altitude of the sun and the temperature of the light could be established.
Careful observation of the measured color temperature data revealed a relationship between the horizontal angles of the sun from the true North orientation, also known as the Azimuth angle. The three cases in which the Azimuth angle ranging from 130 degrees to 180 degrees, the vines decreased the Kelvin value compared to the base case making the light "warmer/ redder". This phenomenon can be attributed to the fact that the sunlight was not directly incident on the face of the model containing the window, the light that was entering the window was reflected from the immediate environment. The higher amounts of red in the reflected light can be explained by the Rayleigh scattering phenomenon where the short wavelength blue light gets scattered easily compared to the red light of longer wavelengths. The typical light distribution graph of both the cases, where the vines condition the light to appear "cooler/whiter" and "warmer/ redder can be observed in Figure

6. The data from the test, simulating the equinox at 3:00 pm was omitted as the light nearing sunset would be warmer in nature and provide misleading results.

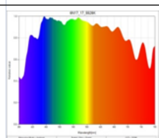
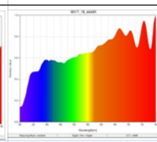
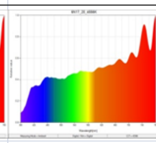
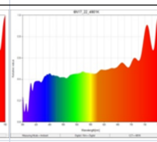
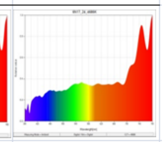
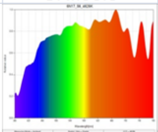
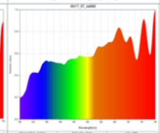
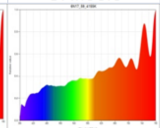
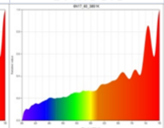
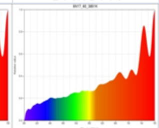
		Color Temperature(CCT) and Color Rendring Index values(CRI)			
Date	Exterior	Base Case	Vine 1	vine 2	vine 3
3pm Summer Solstice (21 June) Azimuth: 268' Elevation:57'	 CCT: 5526K CRI:98.5	 CCT:4440K CRI:96.6	 CCT:4556K CRI:95.6	 CCT:4901K CRI:95.6	 CCT:4686K CRI:97.1
12 noon Equinox (20 March) Azimuth: 160' Elevation:60'	 CCT:4626K CRI:98.6	 CCT:4466K CRI:92.6	 CCT:4155K CRI:93.5	 CCT:3851K CRI:93	 CCT:4092K CRI:97.9

Figure 6: Color temperature, color rendering index values, and light composition spectrum

3.3 Illuminance level analysis:

Illuminance levels inside and outside the box were simultaneously measured for each scenario as shown in Table 3. The illuminance levels inside the physical model for the base case were compared to the three vines. In comparison with the light levels outside the box, the average reduction in light levels inside the model for the base case was 93.6%. In comparison to the light levels inside the model at the base case, the average reduction in Vine 1 was 34%, Vine 2 was 44% and Vine 3 was 55%. As expected, the percentage of reduction in illuminance levels was proportional to the density of the foliage and leaf size in the vines. In addition to the physical characteristics of the vines, the altitude of the sun also influenced the percentage of reduction in the individual cases.

The maximum reduction of illuminance levels was observed at 9:00 am on winter solstice, when the altitude angle is lowest among the cases. The reduction percentage in Vine 1 was 63%, Vine 2 was 60% and Vine 3 was 70 %. In the case of highest sun angle of 80 degrees at 12:00 pm on the summer solstice, the reduction percentage in illuminance levels were 37% in Vine 1, 40% in Vine 2 and 55% in Vine 3. This result also relates to the reduction in daylight glare probability of the individual vines.

Table 3: Light level reduction of the three vines compared to the base case

Test Conditions				Illuminance-Interior (Lux) and Percentage of reduction			
Date and Time	Azimuth (Degree)	Elevation (Degree)	Illuminance-Exterior	Base Case	Vine 1	Vine 2	Vine 3
21 June 9:00 am	84°	42°	90,980 lux	1564 lux	1116 lux 28%	1221 lux 22%	1022 lux 34%
21 June 12:00 pm	125°	80°	12,9500 lux	6934 lux	4407 lux 37%	4193 lux 40%	3088 lux 55%
21 June 3:00 pm	268°	57°	84,170 lux	2482 lux	1705 lux 31%	1092 lux 56%	1131 lux 54%
21 December 9:00 am	130°	16.5°	44,980 lux	6480 lux	2366 lux 63%	2586 lux 60%	1917 lux 70%
21 December 12:00 pm	170°	36°	66,720 lux	4810 lux	3382 lux 30%	2400 lux 50%	2555 lux 47%
21 December 3:00 pm	217°	26°	32,140 lux	3895 lux	1462 lux 62%	1783 lux 54%	1399 lux 64%
20 March 9:00 am	109°	30°	55,670 lux	2596 lux	1745 lux 33%	1706 lux 34%	982 lux 61%
20 March 12:00 pm	160°	60°	43,740 lux	1678 lux	1116 lux 33%	919 lux 45%	651 lux 61%
20 March 3:00 pm	235°	46°	20,310 lux	974 lux	722 lux 25%	622 lux 36%	451 lux 54%

4.0. CONCLUSION

The objective was to gain a better understanding of the potential influence of vertical greening system on daylight quantity and quality inside buildings. The findings show that physical characteristics of plants such as density of foliage, leaf size, and distribution have a significant impact on the quality and quantity of daylight into the building. The captured HDR images also show that the leaf size and density blocks outdoor view but casts more shadows, especially at low sun angles. Discomfort glare levels were greatly decreased with the help of the vines as both illuminance and luminance levels were lowered by blocking and diffusing direct sun penetrations. The study also reveals that illuminance level and discomfort glare reduction is not only affected by the physical characteristics of plants, but also affected by the intensity of sunlight, sun positions such as altitude and azimuth angles in different times and dates of the year. Consideration of both plants and sun position is required to make a successful integration of vertical greening system in buildings. No strong correlation was found between light color temperature changes in relation to the types of vines. However, vertical greening system can ensure the benefits of daylighting by significantly reducing glare and reducing the excessive amount of light levels.

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