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Article

Lighting for Green Walls

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Abstract: This study demonstrates the possibility of growing green walls in normal commercial building environments with lighting designed primarily for aesthetic reasons, rather than the promotion of plant growth. Lighting is a key resource required for the growth and maintenance of robust green walls within interior environments. The study evaluated the appearance and growth of green walls with electric lighting used primarily for aesthetic reasons. Three identical green walls with six different plants were illuminated using three different white LED light sources for a period of five months. Plant health was monitored and documented in terms of growth patterns. One hundred and six subjects appraised the appearance of the walls using questionnaires. Findings of this study indicate that it is indeed possible to grow and maintain green walls in normal commercial building environments with lighting designed for aesthetic reasons. Further, it was observed that the selection of the correct plant species for the green walls is important to ensure plant health.

Keywords: Commercial building environments; Electric lighting; Green walls; Plant growth and health

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1. Introduction

Green walls in built environments have been used as a multi-disciplinary application of biophilic design, where non-living building systems are integrated with living plant systems, dating back to the Hanging Gardens of Babylon [1–5]. Green walls generically bring aesthetic and ornamental value in terms of qualitative improvement of human experience in buildings as opposed to quantitative evaluation of materials and system performance [3,6,7]. More and more buildings are now beginning to use green walls as a key element in the trend for biophilic design [1,2,8]. Studies [9–13] report that the use of green elements such as green walls result in measurable improvements to the human condition in terms of health, productivity and well-being. Wilkins [14] argues that the human visual system evolved in a natural environment and the modern urban environment increases the amount of neural computation necessary to process the images received. Wilkins further suggests that this may support the *biophilia hypothesis* [15]. Although Sutton [16] argues that green walls and roofs contribute to the beauty of the environment, it is acknowledged that care is needed in the design of such elements to ensure that the results of a wall are not banal, dull, trite or unfulfilled.

Light is one of the most important resources required for growing and maintaining robust green walls within buildings: it is required for several physiological processes in overall plant development such as photomorphogenesis, photoperiodism, etc. apart from photosynthesis [17,18]; apart from chlorophyll, plants contain several other photopigments that function by the absorption of light [19]. While the visible electromagnetic spectrum of light (380-780nm) is also actively used in plant photosynthesis, it is important to understand that visible 'brightness' does

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not effectively support the photosynthesis process. Optimum lighting for plants is determined in terms of the Light Recipe: intensity, schedule, and spectrum of the light [20]. The light intensity requirements for plants is measured in Photosynthetic Photon Flux Density (PPFD), which can be described as the number of photosynthetically active photons measured in terms of moles or micromoles (1 mole ≈ 6.022 x 10^{23} photons) that fall on a given surface each second. Photoperiod (or day length) is the period of time each day during which the plants receive light. The light spectrum requirement of plants is measured in Photosynthetic Active Radiation (PAR). Plant Biologically Active Radiation (PBAR) is a relatively new metric that recognizes and takes into consideration all photopigments in plants, other than chlorophyll, that are sensitive to a wider range of wavelengths (350-800nm) in the spectrum.

Figure 1 from Weir [21] describes the interaction between plants and light along with the various impacts of light on green walls. Insufficient light may lead to stoppage of water intake by the green walls, thereby leading to toxic anaerobic environments breeding soil-borne pathogens, moulds, bugs, etc. as well as root rot by the excess soil-water build-up [22].

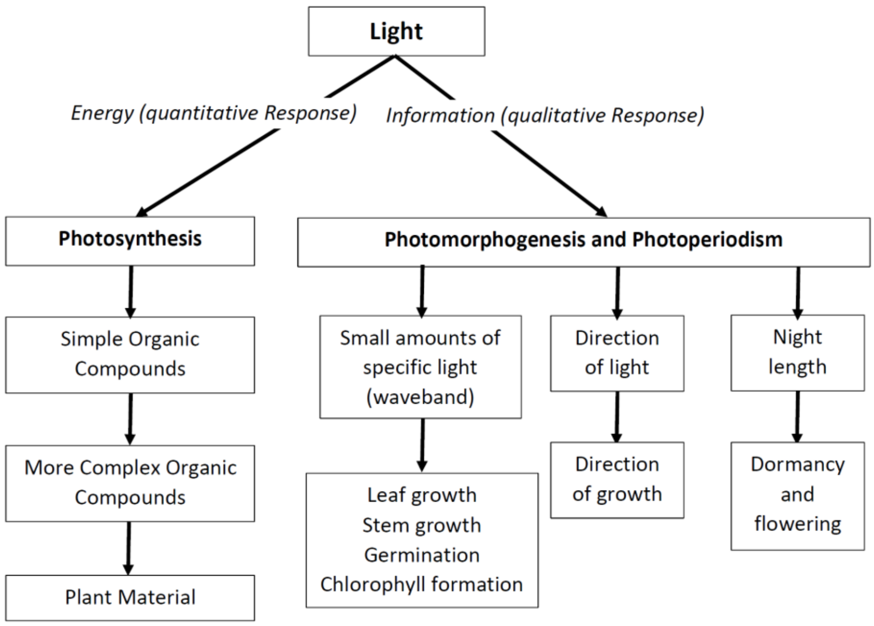

Figure 1 Plant responses to light

This study focuses on the use of green walls inside buildings where electric lighting used for aesthetic reasons is the only source of light. In spaces without daylight, well-lit green walls can contribute towards the biophilia hypothesis by making these spaces feel less gloomy. As green walls are generically categorised under ornamental plants, the electric lighting requirements have a dual function: render a natural visual appearance to green walls as well as enable plant-growth at an appropriate biological speed [23–25]. While existing literature about the use of electric light on plants has primarily focussed on plant growth for functionalistic food production, plant growth within green walls is best discouraged to reduce constant maintenance such as pruning or trimming to maintain the ornamental form of the walls [20,23]. This study builds on the argument put forward by earlier studies [24,25] that lighting designed for aesthetic reasons can perform the dual function of keeping the plants within green walls healthy as well as making the walls look good, with a more detailed reporting of the experimental results.

2. Materials and Methods

Three identical green walls, each comprising six different plant species were illuminated by three different white LED light sources and allowed to grow for a period of five months. Over 100 subjects appraised the walls so as to gain an impression of user acceptance.

2.1. The Green Walls

The three green walls supplied by Wonderwall comprised six different types of plant species. Each wall of height 2.1m and width 1.8m was based on an interlocking system of planters providing 13 rows of six irrigated planters. Each planter has a built-in reservoir with a capacity to hold 0.75 litres of water, thus providing the plants with constant access to water. Each wall contains a water storage tank at its base. A pump at the base circulates water to the top row of planters, which then cascades down through the planters and any overspill returns to the tank. During the experiment the pump was run once a week to ensure that the planters did not become dry. The green wall system is illustrated in **Figure 2**.

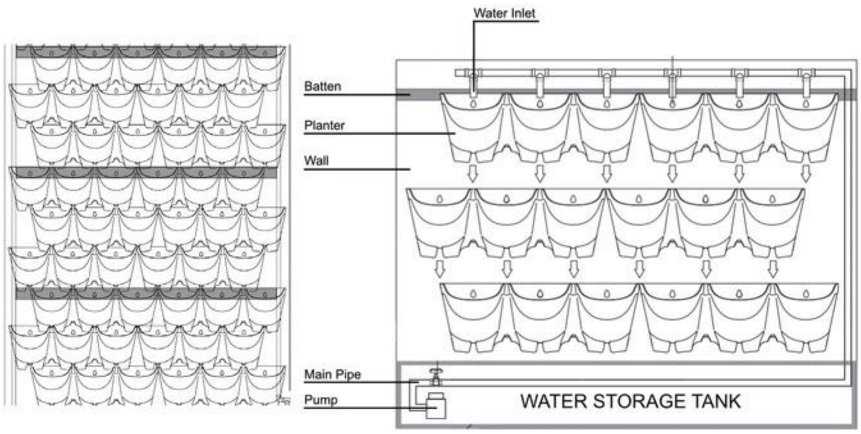

Figure 2 Green wall planter interlocking pattern and installation setup with pump, irrigation pipes and water storage tank

The six different plant species are listed in **Table 1**

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A	Aspar D Sprengeri
B	Asple Antiquum
C	Hedera He Wonder
D	Maranta Fascin
E	Nephr Ex Emina
F	Radermachera Sinica

Table 1 Varieties of plant species installed in the walls

During the growing phase of the experiment, each wall was illuminated using one of the three different light sources as described in Section 2.2. Each wall was lit with a different light source and are referred to as Walls 3000K, 4000K and 5600K for purpose of simplicity. The distribution of the different plants species in each of the planters within the walls is shown in **Table 2**. Note that a few of the planters were left empty, which are marked with an 'X'. User assessments of the walls were done after four months, while assessment of plant health was done at the end of five months of plant growth under electric light.

Wall 3000K						Wall 4000K						Wall 5600K					
F	F	E	A	F	F	F	F	F	C	C	B	F	E	B	B	E	F
B	C	A	B	D	A	B	E	D	E	B	C	B	F	D	E	F	C
D	A	B	C	B	C	C	D	C	B	A	C	F	B	A	E	A	E
A	C	D	B	E	B	B	B	F	E	X	B	X	B	F	E	D	B
F	B	F	A	B	F	D	C	B	D	B	F	B	D	E	C	B	A
D	A	F	A	F	E	A	A	C	E	C	F	B	A	B	F	A	C
B	D	C	D	C	B	B	B	D	F	A	E	F	C	F	A	D	B
C	B	F	B	D	F	D	E	B	A	D	A	D	B	E	B	D	C
B	A	E	B	F	A	A	A	B	E	B	B	C	B	A	C	A	E
F	B	X	B	C	A	B	F	B	A	C	B	F	E	B	C	E	B
A	A	C	A	A	B	C	C	B	C	B	A	A	C	A	E	B	B
B	A	A	B	F	B	B	B	A	F	A	B	A	X	B	C	X	B
B	B	B	C	B	B	B	B	C	B	B	C	C	B	B	B	X	B

Table 2 Distribution of the different plant species in the three walls

2.2. The Light Sources

Each wall was illuminated with Apto track mounted 60° spotlights from LumenPulse AlphaLED, as shown in **Figure 3**. The spotlights were installed with three different types of light sources from Xicato namely, Artist Series 5600K 5000lm daylight module running at 350mA, 4000K 1300lm and 3000K 1300lm modules both running at 700mA. All the spotlights were installed with DALI controlled drivers, which allowed for each wall to be set to similar illuminances while providing the flexibility to change the lighting when the room was being viewed for user appraisals.

Figure 3 Apto track-mounted spotlight from Lumenpulse Alphaled with 60° beam angle

The experiment consisted of two parts: firstly, the growth of the plants; and secondly, user appraisals by the test subjects. In the first part of the experiment, two spotlights of the same colour of light source were aimed at each wall, creating illuminances of 1200 lux and 500 lux on the vertical surfaces at the top and bottom sections of each wall respectively. The lighting system was programmed to provide 12 hours each of darkness and light for the plants. Placing all the three walls in the same room led to a potential problem with inter-reflected light; a temporary dark carpet was placed on the floor to minimise this problem.

In the second part of the experiment, when the subjects were viewing the walls, additional spotlights were added to illuminate all the walls with the same colour of light at the same time. During user appraisals by the subjects, the sequence of illumination was to start with one source, and after the appraisal of all three walls, the sources were dimmed and turned off and a different set of sources was turned on and faded up. This process was repeated till the subjects had appraised all the walls

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under the three different sources. The order in which the different sources were used was randomised.

The spectra of the three different light sources are shown in **Figure 4**

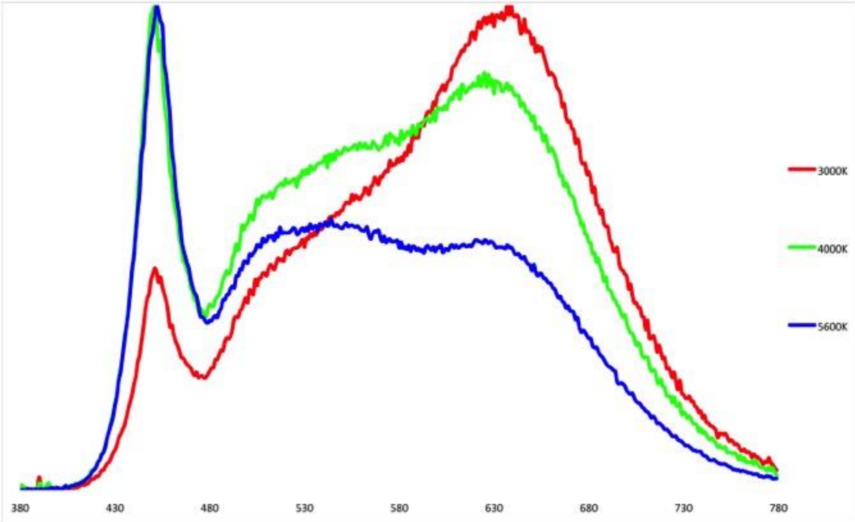

Figure 4 Spectra of the light sources

Light source properties such as correlated colour temperature, colour fidelity and colour gamut were calculated from the spectra using the methods outlined in IES TM-30-18 [26]. Additionally, the relative photon flux for each source was calculated for the range 400-700 nm. The results of the calculations are listed in **Table 3**.

Source [Nominal CCT]	**CCT [K]**	**Colour Fidelity [Rf]**	**Colour Gamut [Rg]**	**Relative Photon Output [μm/klm]**
3000K	2976	96	102	17.32
4000K	4105	94	102	16.48
5600K	5551	93	101	16.30

Table 3 Calculated light source properties

2.3. The Physical Setup

The three green walls along with the spotlights were installed in a storeroom (3.5m by 3.2m) at the University College London (UCL) HereEast Campus Building in London with no windows or ventilation as shown in the location plan in **Figure 5** and the room view in **Figure 6**. The door to the room was left open during the experiment to permit air circulation. The conditions in the room were monitored with temperature and relative humidity being logged every 5 minutes. The median temperature was 20°C and the median relative humidity was 75.6 %. The temperature in the space was typical of many office spaces, while the relative humidity was a bit higher than most offices. The high relative humidity is probably a function of the plants transpiring and so is likely to be typical for the area close to a green wall in a real installation.

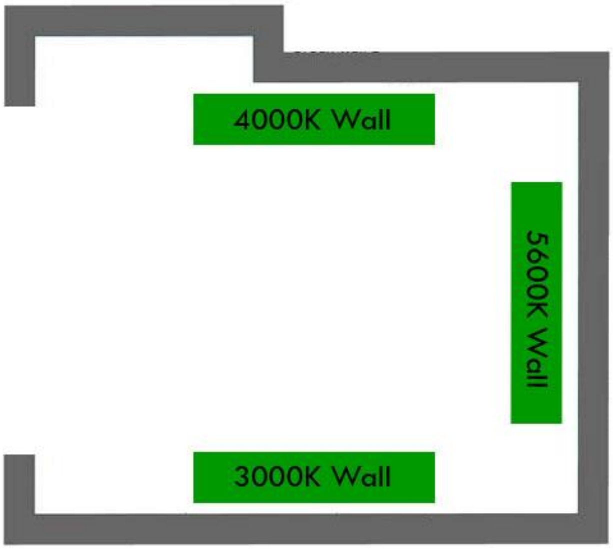

Figure 5 Layout of the three walls in the room

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Figure 6 View of the room with the three walls

2.4. The Assessment – Health of Green Walls

The health of each plant was visually assessed at the end of the study with a scoring range of 0 to 4, where "0" represented a dead plant and "4" represented a very healthy plant. The assessment of the plant health was primarily based on the noticeable condition of the leaves and stem. The authors at the end of the study performed the assessment of the health of each plant based on the scoring outlined in **Table 4**.

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Score	Plant Condition
4	Very healthy plant: no noticeable problems
3	Healthy plant: few damaged leaves
2	Unhealthy plant: many damaged, dead or missing leaves
1	Very unhealthy plant: significantly damaged, dead or missing leaves
0	Dead plant: no noticeable life

Table 4 Assessment criteria for plant health

2.5. The Assessment – Appearance of Green Walls

106 subjects were recruited to appraise the appearance of the walls in groups of different sizes from one subject up to nine subjects. The group sizes were determined randomly based on the availability of the subjects, which included 51 lighting designers, 39 architects and 16 lighting students, who had to take time off their work schedules for participating in the experiment. No personal data was collected from the subjects to ensure there were no data protection issues. Subjects were briefed about the experiment but were not provided any details about the light sources used prior to entering the room containing the green walls. Each of the subjects was then provided with a ten-page questionnaire to assist with the appraisals. The first page had boxes for the date and time of the survey together with a group name and a sequence number that could be used to identify the order that the different light sources were used in the room. The rest of the sheets were the same questionnaire with a series of questions about each wall in the room as shown in Annex A.

The questionnaire had following elements:

- Two bipolar rating scales for the pairs: unnatural – natural, and appealing – unappealing
- A free text box for the subject to describe the wall.
- A set of 10 pairs of opposite adjectives arranged in random order, where the subjects were asked to ring all adjectives that applied.

As each subject appraised each wall grown in different lighting conditions under each colour of light source, it was nominally possible to assess the influence of the colour of light both on the growing and the viewing of the walls. The following measures were designed to reveal the level of attention of the subjects while answering the questionnaire:

- the bipolar questions were arranged so as to reverse the nominal good–bad direction
- the adjectives in the block of pairs were kept away from their opposite.

These two features were used to assess the validity of the subjects' responses in a process of data cleaning. The three green walls were identified as the one on the left, the one in the centre and the one on the right. The light sources were identified by the order in which they were shown.

3. Results

This study comprises two sets of results: one set associated with the health of the plants; the other set related to the subjects' appraisal of the walls.

3.1. The Results – Plant Health

The average scores received by the different plant species installed on the three walls with different light sources are shown in **Table 5**.

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Plant species	Wall 3000K	Wall 4000K	Wall 5600K	Overall
A (Aspar D Sprengeri)	2.18	1.75	2.27	2.08
B (Asple Antiquum)	3.64	3.70	3.63	3.66
C (Hedera He Wonder)	0.00	0.13	0.00	0.06
D (Maranta Fascin)	3.57	3.29	3.83	3.55
E (Nephr Ex Emina)	1.00	1.29	1.17	1.17
F (Radermachera Sinica)	3.79	3.67	3.90	3.79
Average	**2.72**	**2.31**	**2.47**	**2.57**

Table 5 Average health scores for the different plant types in the different walls

The breakdown on plant heath by the different walls shows the impact of light source colour on plant growth. As the top of the walls received more than double the amount of light than the bottom of the walls it is also useful to breakdown the data into three zones depending on the height of the plants in the walls as shown in **Table 6**.

Plant species	Top 4 Rows	Middle 5 Rows	Bottom 4 Rows
A (Aspar D Sprengeri)	2.50	1.94	2.00
B (Asple Antiquum)	3.58	3.79	3.61
C (Hedera He Wonder)	0.18	0.00	0.00
D (Maranta Fascin)	3.57	3.54	n/a
E (Nephr Ex Emina)	1.55	0.89	0.67
F (Radermachera Sinica)	3.86	3.79	3.60
Average	**2.66**	**2.59**	**2.46**

Table 6 Average health scores for the different plant types in the levels of the walls

3.2. Results – Subjective assessment of the walls

The completed questionnaires of the subjects were used to fill a data-table of results, with a new record for each subject-wall-light source colour combination and the fields in the record containing the data from a single questionnaire page as shown in Annex A. After data cleaning the records were used to create a data summary and then used for further analysis.

3.2.1 Data cleaning

The purpose of data cleaning is to remove data where it was assumed that the subject was not paying full attention to the task of assessing the green walls. The following series of rules were developed: firstly, if a record did not have either of the bipolar semantic questions about naturalness or appeal then the record was not processed; secondly, if more than two contradicting adjectives pairs were found in the records associated with a given subject, then the data for that subject was removed; thirdly, if the subject always contradicted themselves on the natural and appealing questions, the subject was eliminated. 953 records were collected from 106 subjects prior to cleaning, which then resulted in 752 records from 87 subjects after cleaning. Additionally, it was difficult to work with the descriptions of the walls given by the subjects in a systematic way. After an initial reading of the free text descriptions, a series of key words and themes were developed. Out of the total 590 descriptions provided by the subjects it was possible to assign key words to only 401, which resulted in 537 key words being assigned. Two main problems arose while working with the descriptions: firstly, the transcription of the hand written text to typed text, as the original handwritten text descriptions provided by 50 cases was not legible; secondly, several comments were irrelevant to the study, for example five descriptions discussed the smell of the walls.

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3.2.2 Natural and Appealing scores

The results of the natural and appealing bipolar semantic questions are shown in **Figure 7**.

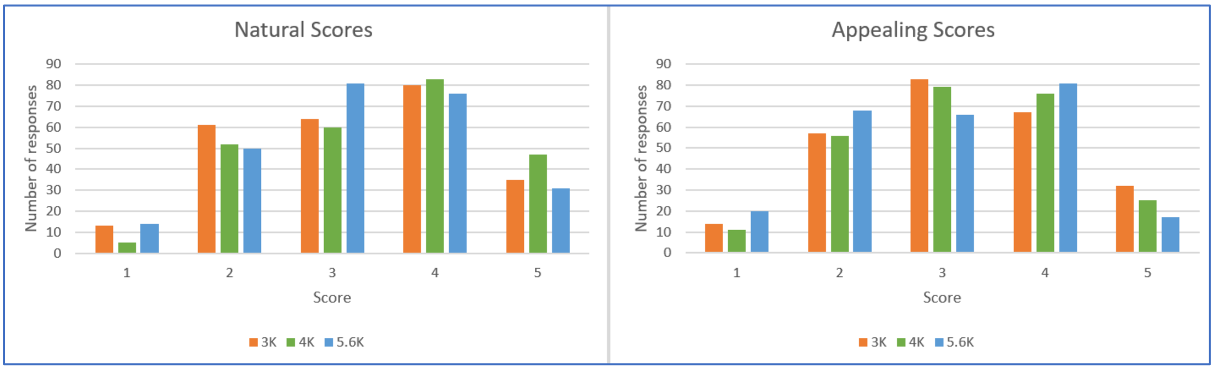

Figure 7 Number for responses for natural and appealing scores. Note: the scale for appealing is reversed from the questionnaire; in the plot high scores indicate that the subject thought the wall was more appealing.

Overall the results show that the colour of light only had a marginal impact on how subjects appraised the walls.

3.2.3 Adjective counts

The use of the different adjectives were counted and distributed based on light source colour when viewing the walls. The results of this process are shown in **Table 7**.

	Light Source					Light Source		
	3000K	4000K	5600K			3000K	4000K	5600K
Ugly	4	10	13		**Beautiful**	29	21	20
Sad	27	26	24		**Happy**	33	29	20
Sick	17	14	18		**Healthy**	53	55	50
Dull	41	52	51		**Colourful**	52	30	27
Artificial	43	38	67		**Natural**	54	72	58
Tiring	21	23	18		**Refreshing**	32	34	34
Dim	37	35	30		**Bright**	28	25	68
Subdued	18	37	34		**Vivid**	40	28	41
Boring	21	15	29		**Interesting**	50	42	39
Calming	38	38	20		**Stimulating**	20	27	27

Table 7 Number of times each adjective was used under the different light sources

3.2.4 Description keywords

15 sets of keywords were used in the assessment of the free text descriptions of the walls. **Table 8** shows the number of times each keyword was assigned to the free text description when the walls were viewed under the different light sources.

	Light Source		
Keywords/Phrases	**3000K**	**4000K**	**5600K**
Vivid/Vibrant/Colourful	11	6	12
Glossy/Shiny/Waxy/Reflective	6	7	12
Healthy/Alive/Lush	9	13	10
Unhealthy/sick/Withered/Dead	22	20	13
Artificial/Plastic	18	12	21
Warm/Warmer	25	7	1
Cold/Cooler	1	7	9
Natural	22	25	21
Unnatural	12	6	11
Bright	5	10	13
Dim/Dark	12	12	19
Shadow	14	11	15
Unappealing	3	5	5
Appealing	6	4	2
Dull	19	18	25

Table 8 Frequency of keywords for describing the walls when viewed under different light sources

4. Analysis and Discussion

This study was conducted to better understand the issues associated with installing green walls in a normal commercial building. The key investigations for the study were to understand how the plants responded to the environment and the people's satisfaction with the appearance of the walls.

4.1 Plant health

The plants installed in the walls of this study received no other care apart from being irrigated for a period of 5 months. In real-life installation however, it is likely that the plants in a commercial building

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will be maintained on a regular basis with excess growth being pruned, dead leaves removed and the plants being nurtured.

The general objective of horticultural lighting studies is to promote plant growth, crop size or flowering rate. In such studies an objective measure of plant development is possible. However, the objective of this study was to keep the plants looking healthy which required a more subjective means of assessing the plants. Thus the scoring system described in **Table 4** was developed, which made it easy to apply to most plants, with only a few plants being borderline cases where difficult choices were necessary.

The first finding is that plant health varied widely for different plant species: Radermachera Sinica (F), Asple Antiquum (B) and Radermachera Sinica (F) were all generally in good condition at the end of the study with each averaging a score over 3.5 out of 4 (see **Table 5**). However nearly all the Hedera He Wonder (C) died during the course of the study. The colour of light under which the plants were grown and the position in the wall had a relatively minor impact on plant health. **Figure 8** shows average plant heath scores for the six different plant types used (see **Table 1**) broken down by light source colour and position in the wall. It shows that the average health score is mainly associated with plant type, while light source colour and position in the wall only have a minor impact on plant health.

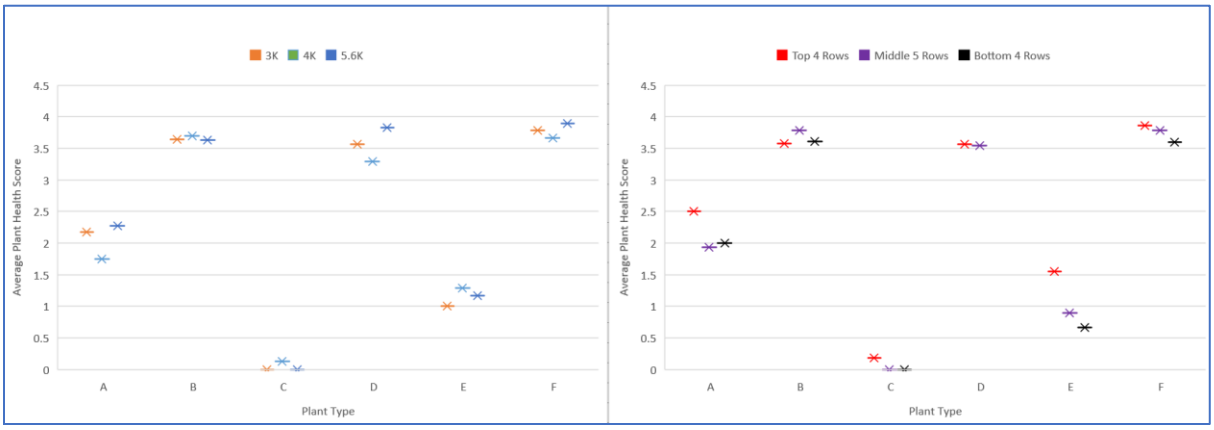

Figure 8 Plots of Tables 6 and 7 showing the variation of plant health score with light source colour (left) and position in the wall (right)

In addition to monitoring the individual health of each plant species, a subjective assessment was made of the walls. It appeared that the stems of the plants grown under the 3000K light sources were longer and thinner, and the stems of the plants grown under the 5600K sources were shorter and sturdier. The stems of the plants grown under the 4000K sources were somewhere between the other two sources. However, due to unforeseen access restrictions (arising from COVID-19) it was not possible to follow up this observation with a set of objective measurements. It is assumed that such an analysis would reveal that there was excessive leggy growth in the plants under the 3000K source, which may lead to the conclusion that 3000K is not ideal for this application [25].

4.2 Appraisal of the walls by the subjects

Figure 7 summarises the responses to bipolar questions on the two adjectives: natural and appealing. The results are distributed based on the light source used to illuminate the walls during viewing. Summary of average scores of this appraisal are shown in **Table 9**.

	Light source colour for viewing		
	3000K	4000K	5600K
Natural	3.249	3.466	3.238
Appealing	3.182	3.194	3.028

Table 9 Average scores for natural and appealing broken down by light source used during viewing

The scores are similar for all the three sources, with the 4000K sources scoring marginally higher. It is also possible to distribute the scores for the adjectives based on the light source that the wall was grown under, as shown in **Table 10**. Again the scores are similar, with the 3000K sources scoring marginally higher.

	Light source colour used for wall while growing		
	3000K	4000K	5600K
Natural	3.460	3.206	3.285
Appealing	3.228	3.150	3.024

Table 10 Average scores for natural and appealing broken down by light source used when the walls were allowed to grow

It is possible to calculate the net scores for the adjectives selected by subtracting the number of times an adjective was used and subtracting the number of times the opposite of that adjective was used. For example the net use of *Beautiful* is the number of times *Beautiful* is used minus the number of times *Ugly* is used. The net scores for all of the adjective pairs are shown in **Figure 9**. The results show there are some clear differences in the perception of the plants under the different light sources. The 3000K source has the maximum net use of Beautiful, Colourful and Vivid, the 4000K source has the maximum net use of Natural and the 5600K source has the maximum net use of Bright and Stimulating.

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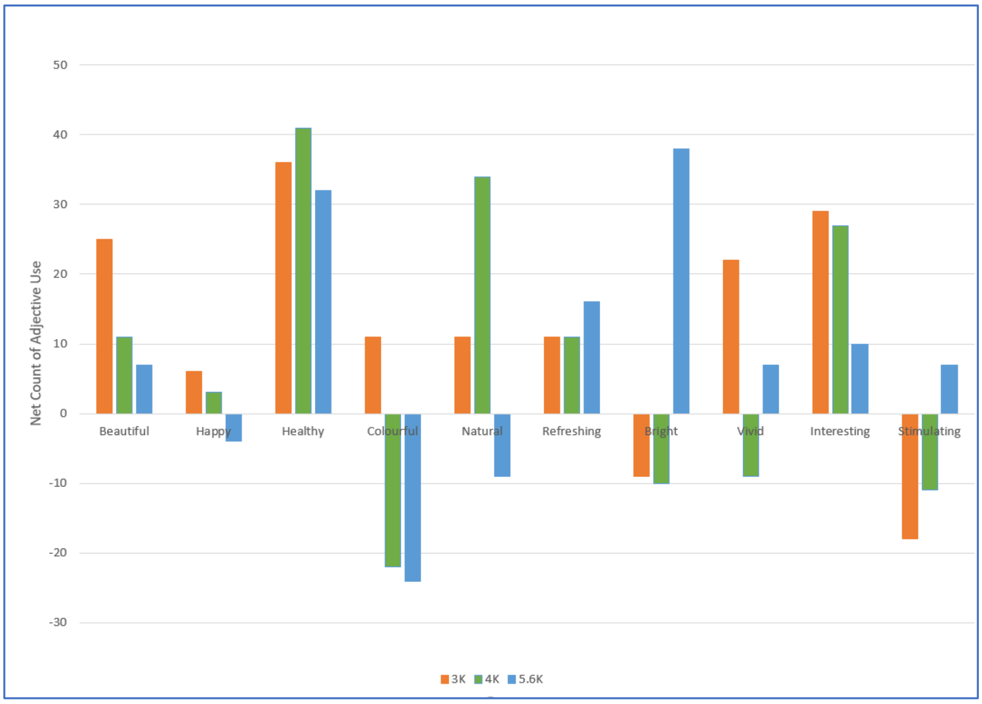

Figure 9 Net uses of adjectives broken down by light source colour used to view the plants

It is also possible to distribute the adjective use by colour of the light source used to grow the wall as shown in **Figure 10**. This shows that for many of the adjectives used, the wall grown under the 3000K light source scored the highest while wall grown under the 5600K light source scored the lowest scores. However, before placing too much weight on this finding it should be noted that the layout of the walls was fixed during the experiment as shown in the location plan in **Figure 5** and the room view in **Figure 6**. Moreover the sequence of appraisal in the questionnaire started with the left (4000K) wall then the centre (5600K) wall and finally the right (3000K) wall. Both the layout and the order of appraisal may have biased these results.

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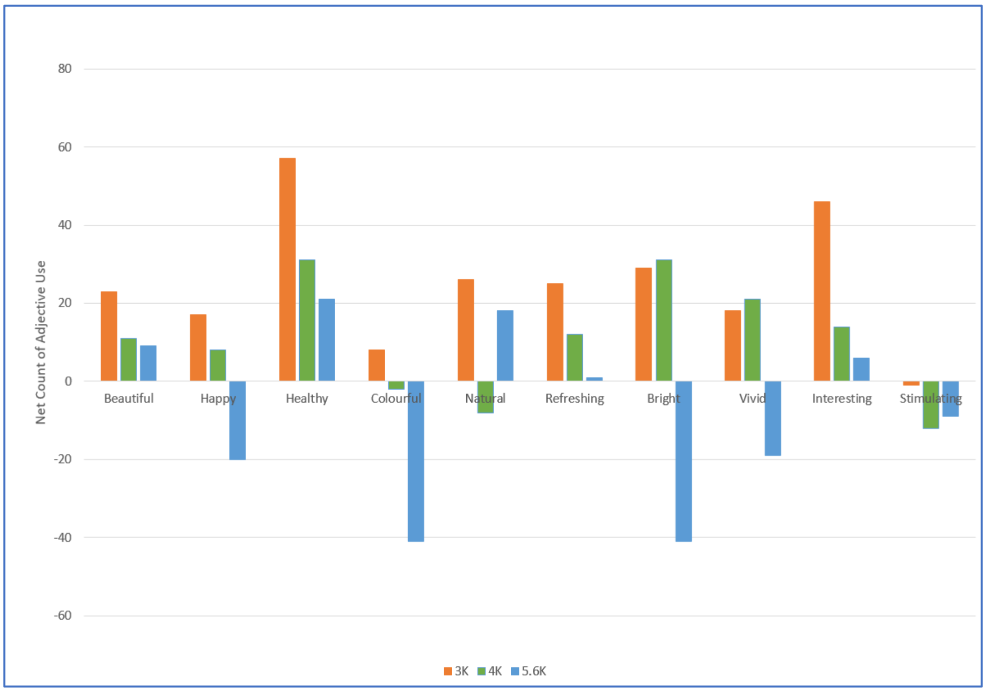

Figure 10 Net uses of adjectives broken down by light source colour used to grow the wall

5. Conclusions

This study has demonstrated that it is possible to grow green walls in the environment of a normal commercial building with lighting that is designed for aesthetic reasons, rather than the promotion of plant growth [24]. However, the selection of the correct species of plant is important to ensure plant health. **Figure 8** shows that the colour of the light source only has a marginal impact on plant health and that the position in the wall, and hence the illuminance received by the plants, had a similar limited impact on plant health. However, there are some misgivings associated with the 3000K source (see Section 4.1).

Assessing the appearance using the bipolar scales of unnatural/natural and unappealing /appealing revealed only minor differences in scores between the appearances of the walls under different light sources. Assessing the appearance based on the adjectives selected and key words allocated to the free text descriptions of the wall revealed the complexity involved in any aesthetic judgement. For

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example under the 3000K source the plants were assessed to be colourful, and under the 5600K source the plants were deemed to be bright. However, it may well be that many subjects decided that the walls were too colourful and bright, and so the walls under the 3000K and 5600K light sources did not do as well as the wall under the 4000K light source when it came to the use of the adjective Natural. **Table 11** illustrates the comparative growth patterns of the green walls before and after the 5-month experimentation period.

Table 11 Comparative growth patterns of the green walls before and after the five-month experimentation period

Time Period	3000K Wall	4000K Wall	5600K Wall
Green walls ***before*** the five-month experimentation period			
Green walls ***after*** the five-month experimentation period			

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Annex A

(Page from Survey Questionnaire)

Scene	*SS*	Wall	*WW*

Please assess the wall:

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	1	2	3	4	5	
Unnatural						Natural
Appealing						Unappealing

Please describe the appearance of the plant wall?

Please ring any adjectives that you think apply to this wall

Happy	Tiring	Beautiful	Bright	Sad
Subdued	Vivid	Dull	Dim	Colourful
Interesting	Refreshing	Healthy	Boring	Stimulating
Ugly	Calming	Artificial	Natural	Sick

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