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Title: **Lighting Green Walls – finding the optimum CCT and SPD of white LED light sources**

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Introduction

The concept of using green walls in built environments is a multi-disciplinary application of biophilic design, where living plant systems are integrated with non-living building systems; it dates back to the Hanging Gardens of Babylon (1–5). A 'green wall' is a descriptive term used to refer all forms of vegetated wall surfaces, which can be further subdivided into two major categories: green facades and living walls (5,6). Green façade systems are composed of climbing plants or cascading groundcovers trained to cover specially designed supporting structures (7). Living walls are composed of pre-vegetated panels, vertical modules or planted blankets fixed vertically to a structural wall or frame; there are various forms of living walls, with the main differences occurring between designs for interior and exterior built environments (7). This small-scale qualitative pilot study focuses on the optimum illumination of green living walls within interior environments using white LED light sources.

The generic objective for most green wall projects has been the aesthetic and ornamental value relating to qualitative improvement of human experience as opposed to quantitative evaluation of materials and system performance (3,8,9). Measurable improvements to the human condition in terms of health, well-being and productivity have been reported by the use of green elements such as green walls in interior environments (10–14). Robust green walls however require appropriately specified: plants for geographic location and hardiness zone; growing medium to sustain the chosen plants; irrigation levels to meet watering and nutritional needs of plants; microclimatic conditions such as humidity, light and temperature (5).

Of the many resources required for growing and maintaining robust green walls within interior environments, light is one of the most important – apart from photosynthesis, it is required for several physiological processes in overall plant development such as photomorphogenesis and reproductive stage development (15,16). Additionally, insufficient lighting can cause stoppage of water intake by the green walls resulting in excess soil-water build-up, which may lead to toxic anaerobic environments breeding soil-borne pathogens, moulds, bugs, etc. as well as root rot (17). While natural sunlight has the perfect balance of fluence and wavelengths necessary for the growth of green walls, greater control over their growth and maintenance is possible by the appropriate use of artificial light (15,18).

The amount and ratio of different wavelengths from a light source in terms of correlated colour temperature (CCT) and spectral power distribution (SPD) determine growth and maintenance patterns of green walls. Agronomically, light-emitting diode (LED) technologies have the potential to cover fluence and wavelength requirements of green walls, while allowing specific wavelengths to be enriched, thus supplying the light quantity and quality essential for different phases of plant growth (18–20). The idea that plant growth under natural sunlight could be mimicked using blue and red LEDs has generally led to blue-red combinations being used for growing green wall systems: red (650-665nm) wavelengths perfectly fit with the absorption peak of chlorophylls and phytochromes; supplemented blue (460-475nm) wavelengths allow higher photosynthetic activity by providing better excitation of different types of photoreceptors (18,19,21,22). However, research confirms that specific blue-red spectrum LEDs used for functionalistic food production cannot be applied for the illumination of green walls: the spectrum enables fast growth for market consumption usually making plants appear unnatural; whereas illumination of green walls in an interior environment should help them grow at an appropriate speed, which reduces maintenance costs, and provides them with a natural appearance (23). Additionally, green walls will appear purplish grey under blue-red spectrum, which makes visual assessment of plant health difficult thereby negating their aesthetic and ornamental value (23,24).

This study argues that white LEDs normally used for architectural lighting applications offering all the main bands of wavelengths in the photosynthetically active radiation (PAR) spectrum (390-700nm) enable plant-growth at an appropriate biological speed, while rendering a natural visual appearance to green walls within interior environments (25). Photosynthetic photon flux (PPF) derived from the total amount of PAR has the most effect on plant growth as more PPF means more photons and more power, and is a parallel to lumens. Photosynthetic photon flux density (PPFD) determines the number of incident photons and is a parallel to illuminance. While keeping the illuminance and its consequent PPFD constant, the study aims to arrive at the optimum CCT and SPD for biologically- and visually-effective illumination of green walls. Biological effectiveness is assessed in terms of growth at an appropriate speed that reduces maintenance costs. Visual effectiveness is assessed in terms of natural appearance that is visually appealing to people.

Materials and Methods

Three identical green walls with six different plant species as listed in Table 1 were illuminated with three different CCTs/SPDs of white LED light sources as provided in Figure 1. The walls were illuminated for a period of 5 months from September 2019 to January 2020. Plant health in terms of leaf and stem growth patterns was monitored and documented at the end of the 5-month period. A total of 106 subjects in smaller groups of seven or eight were presented with this experimental set-up and expected to complete a questionnaire. The independent variable for this experimental setup is the SPD and CCT of the light sources. The starting point was a practical one having an SPD most commonly used in offices: 4000K. The second SPD had a warmer CCT sometimes used in offices but also hotel foyers and shopping malls: 3000K. The third SPD is less often used in these application areas, nevertheless fitting with the hypotheses that plants grow best and appear most natural under daylight: 5600K. The dependent variables are the plant-growth patterns and people's responses towards the appearance of these plants.

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

Table 1: Six different species of plants used in the green walls

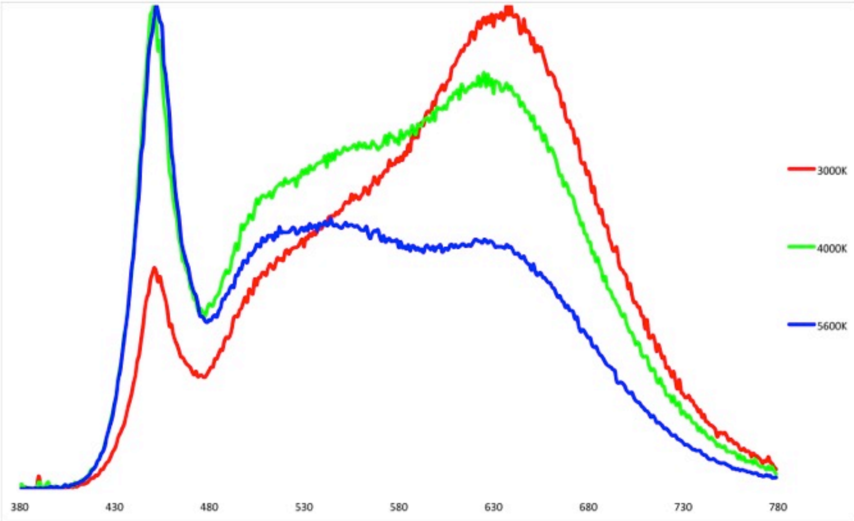

Figure 1: The three different CCTs and SPDs of LED light sources used in the experiment

The Apto family of track-mounted spotlights from LumenPulse AlphaLED as depicted in Figure 2 were specified considering the flexibility and installation requirements of the experiment. These luminaires are equipped with the Xicato Artist Series 5600K 5000lm daylight module running at 350mA, 4000K 1300lm and 3000K 1300lm modules both running at 700mA. Each luminaire consists of 60° wide-beam specular reflectors to ensure an even and smooth light distribution across the entirety of the green wall bays at an average efficacy level of 92lm/W. Two luminaires of each CCT/SPD were assigned for each of the three living walls leading to a total of eighteen luminaires.

The luminaires offer on-board dimming through DALI Pro. Mounted on three-circuit track, each luminaire was connected to a separate circuit, allowing for individual CCT/SPD grouping per green wall and seamless switching control during active demonstrations. Control was designed such that, during the visual assessments by test subjects, scenes could be recalled from a touch panel with a one-second fade-time. The scenes had all three walls being lit by each CCT/SPD, with an “All Off” scene between each for adaptation purposes. For all other times when visual assessments were not taking place, each wall was lit with a different CCT/SPD. A clock timer was used to switch on and off the lighting each day for a period of 12 hours between 7:00AM to 7:00PM.

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Figure 2: Apto track-mounted spotlight from LumenPulse AlphaLED with 60° beam angle

The SPDs were analysed according to the ANSI/IES TM-30-15 and the results are listed in Table 2, in terms of the measured CCT of the sources, their colour fidelity and colour gamut. All of the sources have very good colour properties. The number of photons, in the band 400nm to 700nm, per 1000 light source lumens was also calculated. By convention the number of photons is expressed in mols, which is the total number of photons divided by Avogadro's number. In the sources with the lower colour temperature have higher relative photon output, this was expected as lower colour temperature means more light at the longer wavelength end of the spectrum and thus lower average photon energy. The lower photon energy means there are more photons for a given radiated power.

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

Table 2: Light source properties

The green walls were installed within a confined room (3.5m by 3.2m) with no windows or external source of light at the University College London (UCL) HereEast Campus Building in London as depicted in Figure 3. The room used had been designed as a storage area with no ventilation or thermal control. Each wall was lit with a different colour of light source and for purpose of simplicity the walls are referred to as Walls 3000K, 4000K and 5600K.

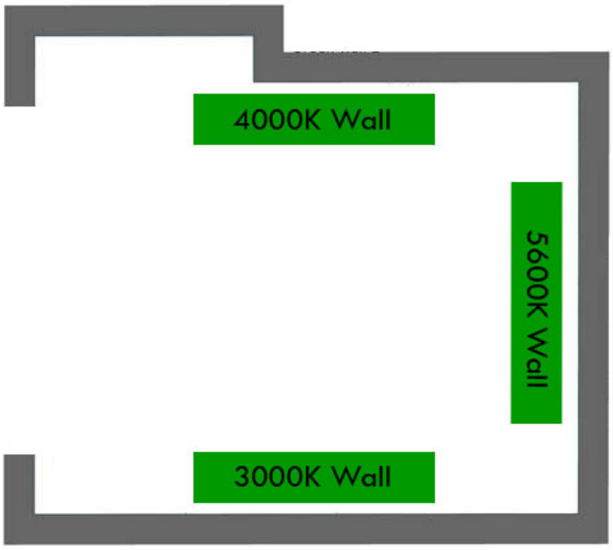

Figure 3: Schematic layout of the three green walls arrangement in a confined room at UCL Here East

To allow the plants to grow, in a way expected in an interior, each of the walls was lit using a set of two track-mounted lights. The lights were mounted at a height of 2.5m and 1m away from the face of the wall as shown in Figure 4. The lights were aimed to create an illuminance of approximately 1200 lux on the vertical at the top of the wall and about 500 lux at the bottom of the wall. In this part of the experiment it was important that each wall only received light from a single set of light sources. To reduce the amount of inter-reflected light in the test room the floor was covered with dark carpet tiles. The worst problem with spill light was at the bottom of the walls; switching of the lights for a given wall and measuring the illuminance of the wall due to spill light from the other two tested this. After the mitigation, measures had been put in place the illuminance at the base of the wall due to inter-reflected light was 20 lux.

During this part of the experiment, the luminaires were run at full power for 12 hours per day and the room was in darkness for the other 12 hours. An additional display set up was used for the walls when the subjects were invited to appraise the walls. In this set up one set of two luminaires of each colour was aimed at each wall. During appraisals the colour of the light on each of the walls was the same and was achieved using the DALI controller to turn on the next scene.

Figure 4: Luminaire arrangement in the ceiling for lighting the three green walls

The intention of this experiment was to obtain feedback from subjects with appropriate educational and professional backgrounds in designing built environments so as to comprehensively review and comment on the naturalness and visual appeal of the green wall. Therefore it was decided to involve subjects with a design background such as architects, landscape architects, lighting professionals and students in the experiment. A selective sampling method was used where specific invitations were prepared and sent to a selected number of architects, lighting professionals and students. Additionally, by ensuring that all the 106 subjects who agreed to participate in the experiment given an identical treatment, the influence of any form of individual characteristics was eliminated. The experiments were conducted over a period of six specific days from 03 December 2019 to 29 January 2020 based on the availability of the subjects.

Figure 5: Subjects' appraisals of green walls using a survey questionnaire

The subjects were asked to respond to each wall and lighting condition by completing a questionnaire as shown in Figure 5. A trial experiment of showing the walls to some subjects who did not take part in the main study and asking their opinions about the walls in a semi-structured interview further developed the questionnaire. The key issues found were naturalness and the appealing nature of the walls in the environment. There were a number of other terms that were also raised by the trial pool of subjects. Thus the questionnaire started with two questions set as bipolar semantics on a 5-point scale asking about naturalness and visual appeal of the walls. The other issues were addressed by the use of ten pairs of opposed adjectives. The adjective pairs used in the experiment are listed in Table 3. To reduce the possibility of bias the 20 words were arranged in a random block and subjects were asked to ring all of the adjectives that applied.

On arrival at the test site subjects were greeted with refreshments and brief introduction to the use of green walls. During the introduction the presenters spoke only in general terms and were careful not to give any details of the experiment to the subjects. The subjects visited the test room in groups of varying size from one person on their own to nine people at the same time. Before the subjects entered the test room the lighting on all walls was set to the first colour temperature for the test. When all of the subjects had appraised all three walls, the lighting was dimmed and turned off for about 15 seconds, after which lighting with the next colour temperature was dimmed up. The appraisal of the walls was carried out again and the lighting changed again and then the final appraisal was carried out. The order in which the light sources were used was randomised.

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

Table 3: Pairs of opposed adjectives

Results and Analysis

The results are broadly classified under biological effectiveness in terms of plant health, and visual effectiveness in terms of peoples' responses towards the lighting of the green walls. Out of the 106 participants surveyed for this experiment, 39 are practicing architecture professionals, 51 are practicing lighting professionals, and 16 are students. Age and gender of the subjects were not recorded, as these were not considered as criteria for assessment.

	Average Leaf Health		
	Wall 3000K	**Wall 4000K**	**Wall 5600K**
A (Aspar D Sprengeri)	2.00	1.75	2.27
B (Asple Antiquum)	3.67	3.70	3.63
C (Hedera He Wonder)	0.00	0.13	0.00
D (Maranta Fascin)	3.40	3.29	3.83
E (Nephr Ex Emina)	1.00	1.29	1.17
F (Radermachera Sinica)	3.79	3.67	3.90
Average	**2.31**	**2.31**	**2.47**

Table 4: Average leaf health of the six plant species after five months of experimentation

Biological effectiveness was assessed both in terms of leaf and stem health. Leaf health was assessed based on a comparative qualitative rating scale of 0 to 4: 0 correlated to a plant with completely dry leaves; 4 correlated to a plant with green leaves. Each of the plant species was assessed individually based on this rating scale and then the rating was averaged for each species on mounted on each wall. The average leaf health of all the six plant species for each of the three walls after five months of experimentation is listed in Table 4. Species B, D and F reported the greenest leaves, while species C reported the driest leaves across all the three walls. Almost all the plants of species C had withered. On an average, Wall 5600K reported the greenest leaves across all species.

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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Table 5: Comparative growth patterns of the green walls before and after the five-month experimentation period

		Average Stem Health
Wall 3000K	*Rating*	**1** – Longest stems but elongated and slender
	Reasoning	High content of red spectrum leads to elongated and weak stems
Wall 4000K	*Rating*	**2** – Long stems but thicker and sturdier
	Reasoning	Balanced content of all spectrums leads to long yet strong stems
Wall 5600K	*Rating*	**3** – Shortest stems but thickest and sturdiest
	Reasoning	Low content of red spectrum leads to shortest and strongest stems

Table 6: Average stem health of the three walls after five months of experimentation

Stem health was also assessed based on a comparative rating scale of 1 to 3: 1 correlated to the plant wall with the longest and unhealthiest stems; 3 correlated to the plant wall with the shortest and healthiest stems. Instead of measuring each individual plants, it was decided to measure the overall plants overhangs for each wall from four different heights i.e. 350mm, 700mm, 1050mm and 1400mm from the base of the wall. These three lengths were then averaged and the wall the shortest overhang was assigned 3, while the wall with the longest overhang was assigned 1. Wall 5600K reported the shortest and strongest stems, while Wall 3000K reported the longest and weakest stems. The comparative growth patterns of the green walls before and after the five-month period of experimentation are depicted in Table 5. The average stems health of the green walls before and after the five-month experimentation period is depicted in Table 6.

Visual effectiveness was primarily assessed based on the naturalness and appealing nature of the green walls. Figure 6 and Figure 7 represent the distribution patterns of the participants' responses for naturalness and visual appeal respectively on a scale of 1 to 5. Participants demonstrated an inclination towards 4000K for both naturalness and visual appeal, as the green wall illuminated with 4000K received the highest scores as shown in Table 7. A lexical analysis of the adjectives used to describe the lighting of the green walls are listed in Table 8, which again demonstrates an inclination towards 4000K for a healthy and natural appearance of the plant walls.

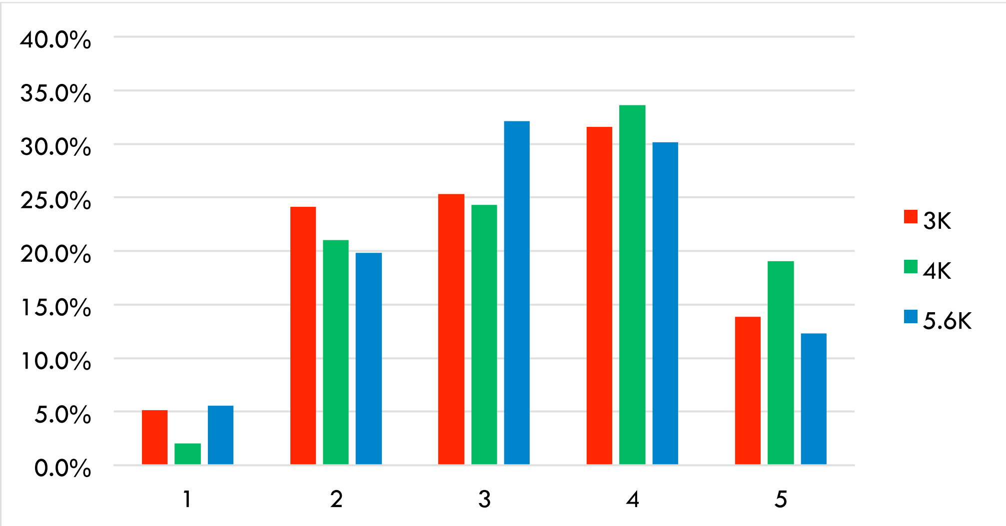

Figure 6: Naturalness distribution of participants' responses for the three walls

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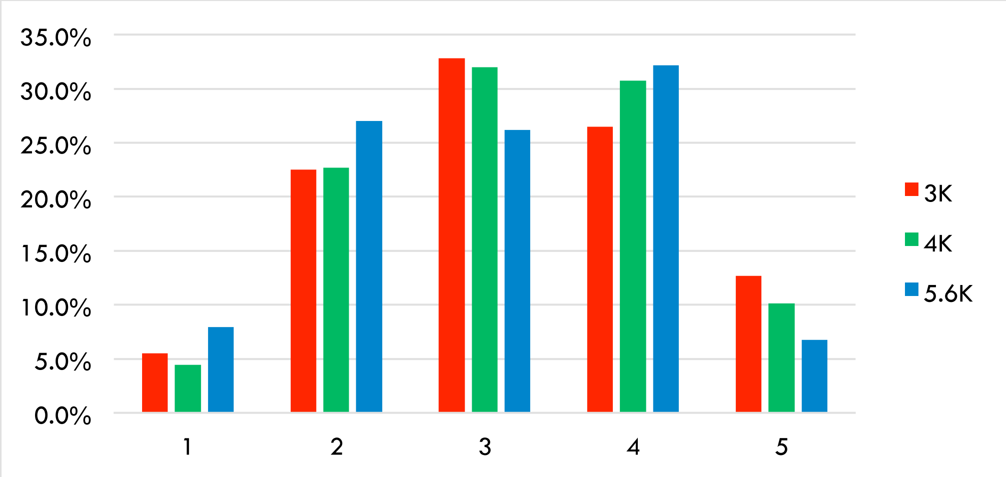

Figure 7: Visual Appeal distribution of participants' responses for the three walls

	Average Score		
	Wall 3000K	**Wall 4000K**	**Wall 5600K**
Un/Natural	3.20	3.48	3.29
Un/Appealing	3.10	3.18	3.04

Table 7: Average score on naturalness and visual appeal for the three walls

	Number of Counts		
	Wall 3000K	**Wall 4000K**	**Wall 5600K**
Alive/Healthy	11	18	13
Artificial/Plastic	18	12	20
Colourful/Vibrant/Vivid	24	18	19
Glossy/Shiny/Waxy	7	10	14

Table 8: Lexical analysis of the adjective use counts for the three walls

Discussion

Growth and health of green walls in controlled artificial environments to a large extent is dependent on the types of plant species used in the green wall design. Out of the six plant species monitored under identical experimental conditions, three (B, D, F) demonstrated good growth, two (A, E) demonstrated average growth, while one (C) demonstrated bad growth. Popular belief that high illuminance levels e.g. 5,000-10,000lux ensure growth and health of green walls can be questioned as reasonably well plant growth patterns were observed in this study under average illuminance levels of 1100lux. Warmer CCT and red spectrum cause unhealthy stem elongation, which is more prominent in the green wall illuminated with 3000K. In general for green walls, 5600K is most suitable for controlled growth and health, while 4000K is most preferred by people for naturalness and visual appeal. Therefore the main discussion point drawn from this pilot study involves a blend of 4000K and 5600K to achieve a biologically - and visually - effective illumination of green walls. Blending could imply various options ranging from the development of a dedicated single output LED module, time based SPD changes via a tunable white module or a blended lighting design using two different light sources, 4000K and 5600K.

Next Steps

The obvious next steps for this study are to firstly, experiment with just such a blended solution as is discussed above, and possibly a timed approach with tunable white solutions. With controls and tunable light sources playing a major role in all future solutions, it might be worthwhile to test such tunable solutions to achieve biologically- and visually-effective illumination of green walls. And secondly, to experiment on a larger scale with a more focussed species of plant types that are more robust for interior green wall applications. Additionally, a larger group of survey participants from the general public need to be involved so as to obtain feedback representing a broader cross-section of the general public.

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