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White LED Light Sources – Merging Architectural and Horticultural Lighting Applications within Interior Environments

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Abstract

Specific blue-red spectrum LED light sources have generally been used for horticultural lighting applications within interior environments. However, this small-scale qualitative pilot study comparing two plant-growth profiles reports that white LED light sources normally used for architectural lighting applications are biologically and visually more effective for horticultural lighting applications within interior environments. First profile involved three vegetable species namely, lettuce, parsley and tomato under three LED light spectrums – specific blue-red spectrum (460+630+660nm), full-range blue-red-white spectrum (380-730nm), and white full-spectrum (400-750nm). Second profile involved a collection of ornamental plant species under two colour temperatures of white LED light – warm-white (3000-kelvin) and neutral-white (4000-kelvin). Overall observations suggest that spectral properties of white LEDs, which mimic certain qualities of natural sunlight, have more advantages over blue-red LEDs such as stimulating plant metabolism for improved growth and better health, while rendering a natural appearance to plants. These observations may encourage the use of white LED light sources for both architectural and horticultural lighting applications within interior environments.

Keywords: LEDs; white light; full-spectrum; architectural lighting; horticultural lighting

1.0 INTRODUCTION

The practice of horticulture[1] – enabling cultivation of plants for food (fruits, vegetables) and ornamental use (cut flowers, potted plants, shrubs, trees and green walls) – within interior environments has been prevalent for several years. Of the many resources required for growing plants within interior environments, light is one of the most important[2] – apart from photosynthesis, it is required for several physiological processes in overall plant development such as photomorphogenesis and reproductive stage development[3]. While natural sunlight has the perfect balance of fluence and wavelengths necessary for plant growth[4]; greater control over the growth and development of plants is possible by the appropriate use of artificial light[2]. Research[5] from the Illumination for Plant Health Alliance at the Lighting Research Centre at Rensselaer Polytechnic Institute has shown that precise doses of artificial light can be used to combat the many pests and pathogens that reduce crop yields as well as increase plant health.

Agronomically, light-emitting diode (LED) technologies have the potential to cover fluence and wavelength requirements of plants, while allowing specific wavelengths to be enriched, thus supplying the light quantity and quality essential for different phases of plant growth[4,6,7]. 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 in artificial growing systems[4]: red (650-665nm) wavelengths perfectly fit with the absorption peak of chlorophylls and phytochromes[6,8]; supplemented blue (460-475nm) wavelengths allow higher photosynthetic activity by providing better excitation of different types of photoreceptors[6,9]. However, research confirms that specific blue-red spectrum LEDs used for functionalistic food production cannot be applied for the lighting of ornamental plants: the spectrum enables fast growth for market consumption usually making plants appear unnatural; whereas illumination of ornamental plants in an interior environment should help them grow at an appropriate speed, which reduces maintenance costs, and provide them with a natural appearance[10]. Additionally, plants appear purplish grey under blue-red spectrum, which makes visual assessment of plant health difficult[11].

This small-scale qualitative pilot 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 plants within interior environments. The study explores the advantages of full-spectrum (400-750nm) white LEDs over conventional blue-red combination LEDs in terms of energy and information for plant-growth, thereby ensuring better manipulation of plant metabolism. Additionally, as specific blue-red spectrum LEDs makes plants appear unnatural, the study explores how white LEDs render plants their natural visual appearance thereby making them more conducive to the people living in these environments.

2.0 MATERIALS AND METHODS

Two different potted plant-growth profiles were established for two different types of qualitative assessments. The first profile was designed to assess which of the following three different LED spectral combinations is biologically more effective for horticultural lighting applications: specific blue-red spectrum (460+630+660nm), full-range of blue-red-white spectrum (380-730nm), and neutral-white (4000-kelvin) full-spectrum (400-750nm). The second profile was designed to assess which of the following two different colour temperatures of white LED light normally used for architectural lighting applications is visually more effective for rendering a natural appearance to the plants: warm-white (3000-kelvin) and neutral-white (4000-kelvin).

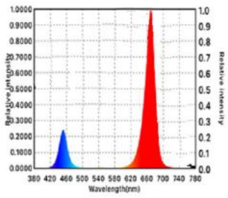
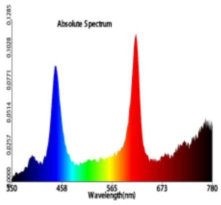
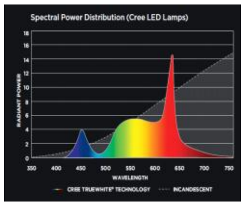
2.1 Materials and Methods – Profile-1

A service room within a residential apartment in the city of Dubai, UAE that did not have any penetration of natural sunlight was selected for this plant-growth profile. Three different vegetable species were selected namely, lettuce, parsley and tomato based on their differing requirements of photoperiodism or light hours for flowering as depicted in Table-1. Each of these types of plants were sown in pots and placed in identical canopy boxes of dimensions (60x60x60cm) as shown in Table-2: Case-A was illuminated using a 12W Essential Choice grow-light source comprising clusters of 12 LED sources (3x Red 660nm, 6x Red 630nm, 3x Blue 460nm) providing specific blue-red spectrums (460+630+660nm); Case-B was illuminated using a 28W Esbay Bulbs grow-light source comprising clusters of 28 LED sources (15x Red, 7x Blue, 1x IR, 1x UV, 2x daylight-white 5600K, 2x warm-white 3000K) providing a full-range of blue-red-white spectrums (380-730nm); Case-C was illuminated using a 20W CREE light source comprising a single LED chip providing neutral-white (4000-kelvin) full-spectrum (400-750nm). A photosynthetic photonic flux density (PPFD) of 200µmol/m^2s was maintained for each of the three cases for an average time-period of 14 hours everyday for 60 days. The 14-hour time-period was determined from the approximate light exposure time required for plants[10]. The temperature and humidity levels in the room were maintained at 25 degrees Celsius and 40 per cent respectively. The growth patterns of the different plant species were qualitatively observed and documented over this period based on two stages: germination and vegetation.

Table 1: Photoperiodism requirements of plants in Profile-1

Sr. No:	**Plant Species**	**Photoperiodism**	**Flowering**
1	***Lettuce***	Day – Long	Requires long light hours
2	***Parsley***	Day – Short	Requires short light hours
3	***Tomato***	Day – Neutral	Not related to light hours

Table 2: Experimental setup and light spectrums of the three cases in Profile-1

Case-A ***Blue-Red Spectrums (460+630+660nm)***	**Case-B** ***Blue-Red-White Spectrums (380-730nm)***	**Case-C** ***White Full-spectrum (400-750nm)***
		
		

2.2 Materials and Methods – Profile-2

A multipurpose room inside a basement office space in the city of Mumbai, India that did not have any penetration of natural sunlight was selected for this plant-growth profile. Nine different ornamental plant species as listed in Table-3 were selected based on their general popularity of use within interior environments from a preliminary market survey. Two of the most prominently used colour temperatures for architectural lighting applications within interior environments are: warm-white (3000-kelvin) and neutral-white (4000-kelvin). Two sets of 2m-long parallel tracks were mounted on the ceiling with three 30W LED track luminaires from Hazel Lighting on each track and a total of six luminaires for each set so as to bathe the space in these two colour temperatures as shown in Table-4. Two identical sets of these ornamental potted plants were placed under each of these luminaire arrangements so as to be bathed in the two different colour temperatures: Case-X in warm-white and Case-Y in neutral-white. The plants were positioned in a manner that is similar to any natural outdoor environment with a mix of small and large plants so as to study the effect of the shadow of bigger plants on the life cycles of smaller plants. An average lux level of 1000lux at a nominal height of 0.75m was maintained for both cases for an average time-period of 10 hours everyday for 90 days. The 10-hour time-period was based on the fact the office would be operational for a period of 10 hours from 8:00AM to 7:00PM. The temperature and humidity levels in the room were maintained at 25 degrees Celsius and 40 per cent respectively.

Table 3: Plant species in the Profile-2

Dracena	Scindapsus	Syngonium
Zamioculcus	Aglaonema	Calathea
Spathiphyllum	Sansevieria	Bird Nest

Table 4: Experimental setup of the two cases in Profile-2

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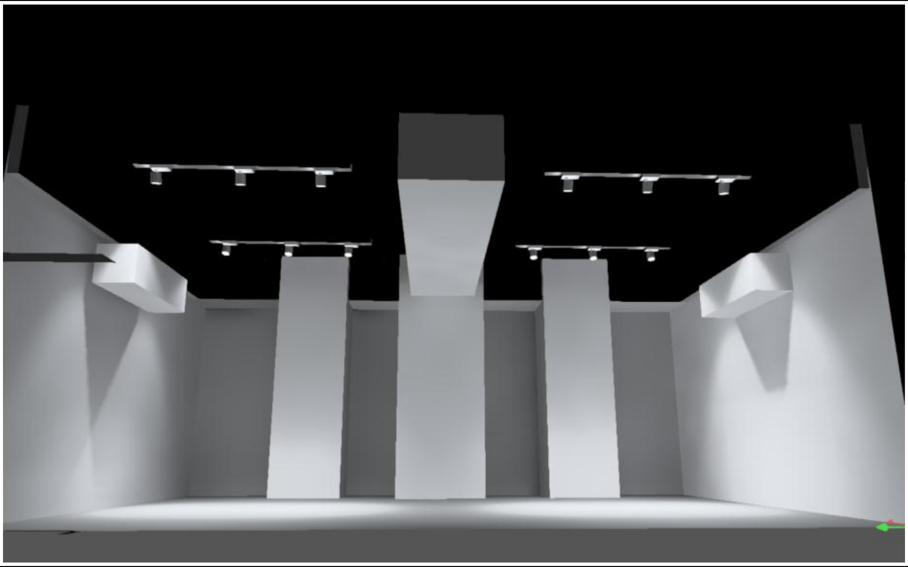
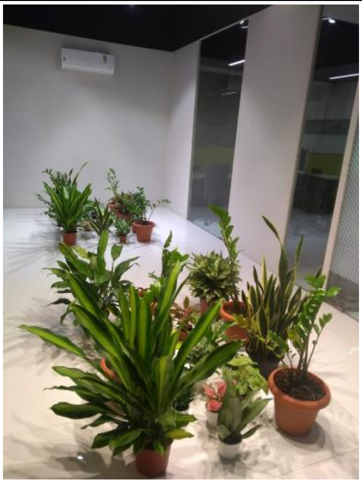
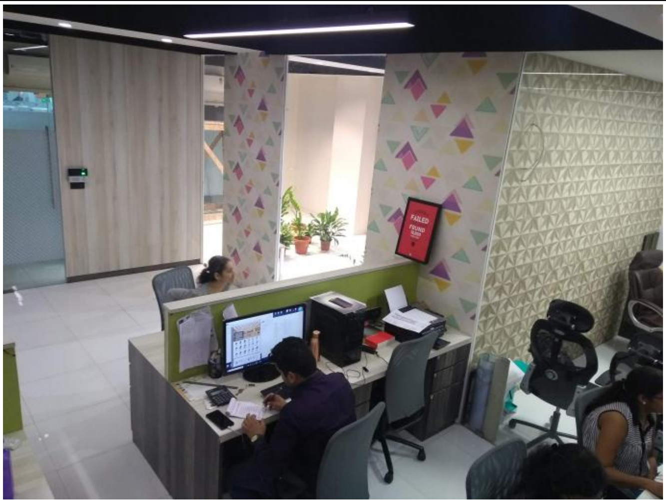
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Design of the multipurpose room with two parallel sets of track lighting for the two cases</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Case-X: Plants in warm-white (3000K) light</td><td>Case-Y: Plants in neutral-white (4000K) light</td></tr>
</table>

A qualitative survey interview questionnaire was designed to assess how the installation of illuminated ornamental plants impacted the overall views of the multipurpose room as depicted in Table-5. A total of 25 users (13 from the office, 5 from the neighbouring offices and 7 regular office visitors) were interviewed twice: once before, and once 45 days after the installation. The first interview documented their aspirations about the installation with questions pertaining to: whether they would like such an installation in their office, if yes why, what kind of plants, and in what spatial arrangement; whether they will sacrifice some of their workable office space to accommodate such an installation. The second interview documented their experience after the installation with questions pertaining to: whether the installation met their aspirations in terms of the kind of plants and spatial arrangements; whether they will sacrifice some of their workable office space to accommodate such an installation; whether the installation provided any improvement in their health, productivity and wellbeing; and finally their preference for which of the two colour temperatures for lighting the installation.

Table 5: Office users' views of Profile-2

	
View in the multipurpose room	**View of the multipurpose room from the office**

3.0 RESULTS AND DISCUSSION

The plant-growth results listed in this section are purely on the basis of qualitative observations and literature references. Considering the pilot nature of this small-scale study, no other forms of scientific analysis or assessment has been done.

3.1 Results and Discussion – Profile-1

The results of the germination stage for the first profile are outlined in Table-6. Case-A reported the fastest germination time for lettuce and parsley due to the high content of red spectrum, which speeds the process. Case-B reported the slowest germination time for lettuce due to the low content of red spectrum, which slows the process. Case-C reported an average germination time for lettuce due to the combined presence of red and far-red spectrums, where red spectrum speeds the process and far-red spectrum slows the process. There was no difference in germination time between all the three cases for tomato.

Table 6: Germination stage results of Profile-1

Case	**Germination**	**Lettuce**	**Parsley**	**Tomato**
A *Blue-Red Spectrums (460+630+660nm)*	*Time*	2 Days	8 Days	5 Days
	Reasoning	Fastest germination time for lettuce and parsley – high content of red spectrum speeds germination process		
B *Blue-Red-White Spectrums (380-730nm)*	*Time*	3 Days	9 Days	5 Days
	Reasoning	Slowest germination time for lettuce and parsley – low content of red spectrum slows germination process		
C *White Full-spectrum (400-750nm)*	*Time*	2.5 Days	9 Days	5 Days
	Reasoning	Average germination time for lettuce – combined presence of red and far-reds spectrums balances germination process		

The results of the vegetation stage divided under seedling growth, leaf and plant growth, and growth till blooming for the first profile are outlined in Table-7. Case-A reported a seedling growth that is slowest for lettuce and parsley, and fastest for tomato; unhealthiest leaf and plant growth for all three vegetables; and fastest blooming time for tomato. This can be attributed to the fact that the specific blue-red spectrum (460+630+660nm) light source has low content of blue spectrum that diminishes vegetative growth for leafy vegetables like lettuce and parsley; and high content of red spectrum that leads to elongated and weak stems, increases the inter-nodal distance, and aids blooming for tomatoes[12]. Case-B reported a seedling growth that is average for lettuce and parsley, and slowest for tomato; leaf and plan growth that is healthy for lettuce and parsley and unhealthy for tomato; and no blooming for tomato. This can be attributed to the fact that the full-range blue-red-white spectrum (380-730nm) light source has higher content of blue spectrum that aids vegetative growth for leafy vegetables like lettuce and parsley; and lower content of red spectrum that diminishes blooming for tomatoes[12]. Case-C reported a seedling growth that is fastest for lettuce and parsley, and average for tomato; healthiest leaf and plant growth for all three vegetables; and average blooming time for tomato. This can be attributed to the fact that the full-spectrum (400-750nm) light source has a slightly better balanced content of all the spectrums than the other cases, which aid vegetative growth thereby leading to overall healthy plants[10]. However the overall growth for lettuce in all the three cases was much less compared to naturally grown lettuce. This can be attributed to the fact that all three light sources have a low content of green spectrum (500-600 nm), which enhances the growth of lettuce plants[11].

3.2 Results and Discussion – Profile-2

All plants reported good growth and health over the entire 90-day period. All 25 participants (100%) in the survey interview before the installation expressed their preference plants in the office space. However, only 10 participants (40%) were willing to sacrifice their space for plants and 20 participants (80%) refused to take any responsibility for taking care of these plants. In the survey interview after the installation, 22 participants (88%) were willing to sacrifice their space to accommodate plants as well as personally take care of these plants. All 25 participants (100%) confirmed that having plants in their surroundings provided improvements in their health, productivity and wellbeing. This can be attributed to biophilia, meaning the beneficial characteristics of the natural world to improve human health, productivity and wellbeing, in relation specifically to interior ornamental plants[13]. All 25 participants (100%) confirmed that lighting in terms of lux level was comfortable, and they preferred neutral-white (4000K) light for the plant installation. This can be attributed to the fact that neutral-white has the closest property to daylight, which renders a natural appearance to plants[10].

Table 7: Vegetation stage results of Profile-1

Case	Vegetation	Lettuce	Parsley	Tomato
A ***Blue-Red Spectrums (460+630+660nm)***	*Seedlings Growth*	Slowest growth ≤ 6mm per day	Slowest growth ≤ 3mm per day	Fastest growth ≤ 18mm per day
	Leaf & Plant Growth	Slowest but improper formation of leaves	Tallest but weakest with slender and elongated stem leaning towards the light source	Tallest but weak with slender and elongated stem leaning towards the light source, and highest inter-nodal distance
	Growth till Blooming	NA	NA	Fastest blooming ≤ 5 weeks
	Reasoning	Low content of blue spectrum diminishes vegetative growth especially for leafy vegetables like lettuce and parsley. High content of red spectrum leads to an elongated and slender stem, increases the inter-nodal distance, and aids blooming especially for tomatoes.		

B **_Blue-Red-White Spectrums (380-730nm)_**	*Seedlings Growth*	Average growth ≤ 9mm per day	Average growth ≤ 6mm per day	Slowest growth ≤ 10mm per day
	Leaf & Plant Growth	Fastest with proper formation of leaves	Shortest but healthy with thick and sturdy stem, and large leaves	Shortest and weakest with thinnest stem, unable stay upright without support
	Growth till Blooming	NA	NA	No blooming
	Reasoning	High content of blue spectrum aids vegetative growth especially for leafy vegetables like lettuce and parsley. Low content of red spectrum diminishes blooming for tomatoes.		
C **_White Full-spectrum (400-750nm)_**	*Seedlings Growth*	Fastest growth ≤ 12mm per day	Fastest growth ≤ 9mm per day	Average growth ≤ 12mm per day
	Leaf & Plant Growth	Average but formation of largest and healthiest leaves	Average but healthiest with thickest and sturdiest stem, and largest leaves	Average but healthiest with thick and sturdy stem, and largest leaves
	Growth till Blooming	NA	NA	Average blooming ≤ 6 weeks
	Reasoning	Continuous spectrum with appropriate blue content aids vegetative growth for leafy vegetables like lettuce and parsley, red content aids blooming for tomatoes, and other spectral contents such a green ensures better overall health of all three plants.		

4.0 CONCLUSION

The overall observations of both plant-growth profiles reveals that plants can be installed and maintained in interior environments with white LED light sources used for architectural lighting applications. However, the horticulture industry seems to have overlooked the use of white light because it was believed that plant illumination should emit mostly blue and red light as it is assumed they provide the most effective photosynthesis reaction. But precise and independent measurements of photosynthetic activity under different wavelengths have demonstrated that the green spectrum (500-600nm) is nearly as effective as blue spectrum for a considerable number of plant species[12]. Additionally, the green light would make the plant leaves appear green and normal, similar to a natural setting under white light, thereby offering psychological benefits for humans[11]. Therefore for plants grown purely under artificial lighting, which can impact their visual appearance and biological function, it is advisable to consider the characteristics of broad-spectrum solar radiation via LED lighting technology[10]. As the optical characteristics of luminaires used for humans and plants in this small-scale pilot study are similar, it is possible to design lighting for both architectural and horticultural applications.

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