Comparison of Photometric Quantities and Photon Quantities of Light Sources For Interior Green Wall Illumination

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Abstract
Interior green walls which are vertical greenery systems inside buildings are gaining popularity due to their environmental, economic and social benefits. Different from exterior green facades, interior green walls usually receive limited natural light, resulting in relatively low photosynthesis rate and thus hindering the plant growth. Without violating the basic principle of sustainability, an energy efficient supplementary lighting system is required to provide the interior green wall with necessary quantity of light. Most light sources are however developed for human applications while plants have an entirely different response to light from human eyes. Light quantity for plant growth should be evaluated by photon efficiency, which is highly related to the rate of photosynthesis. This paper investigates the relationship between photometric quantities and photon quantities of various light sources with the aid of a calibrated spectrophotocolorimeter. LED lamps are recommended to be used in the supplementary lighting system for interior green walls due to their good performance in both luminous efficacy and photon efficiency.

Keywords: Interior green wall, lux, photon, photosynthesis, supplementary lighting system

Introduction

With the rapid growth of urbanization around the world, more and more areas of the human habitat have evolved from natural vegetation to concrete jungles. Building blocks are increasingly taller and densely packed to cope with the rising demand of land. After decades of urbanization, many modern cities are confronted with various environmental problems like air and noise pollutions, lack of vegetation, urban heat island effect and global warming. Many efforts are being made in a bid to mitigate the problems. The rise of environmental consciousness calls for new building designs that can provide environmentally friendly functions, e.g. reducing building energy consumption, lowering indoor ambient temperature and improving indoor environmental quality. For this purpose, various innovative solutions such as constructing greenery systems in buildings have emerged (European Commission, 2012).

Building integrated greenery systems have many benefits. With respect to the environment, plants absorb carbon dioxide and release oxygen via photosynthesis. They freshen up the air and reduce carbon emission to the atmosphere (Darlington, Dat, & Dixon, 2001). Plants also absorb short-wave radiation and reduce solar re-radiation from building surfaces (Kleerekoper, van Esch, & Salcedo, T.B. 2012). As the building surface temperature decreases, urban heat island effect is mitigated. Moreover, the ability of plants to reduce noise disturbance allows the environment to be more aurally acceptable (Wong, Kwang, Tan, Chiang, & Wong, 2010). Greenery also provides buildings with economic advantages. As plants can reduce carbon dioxide concentration and decrease the temperatures inside and outside buildings, greenery systems are particularly suitable for reducing the energy demand for ventilation and air conditioning, thus improving the energy efficiency of buildings (Perez, Coma, Martorell, & Cabeza, 2014). As for the social aspect, plants are also desirable. Since the human civilization, plants have been used to create places for recreation and rest (White & Gatersleben, 2011). Evidence shows that consistent contact with the nature has positive psychological impact, reducing stress and increasing human health and well-being (Nielsen & Hansen, 2007). Furthermore, growing plants on building structures enhances people to be aware of the importance of developing a built environment in a sustainable manner (Yuen & Hien, 2005). Whereas green roof is a useful building integrated greenery system (Wong, Cheong, Yan, Soh, Ong, & Sia, 2003), integrating vertical greenery systems into building design is another promising idea to promote sustainability, especially in the case of a densely built environment where the horizontal roof surface areas are limited.

A vertical greenery system allows plants to be grown on the wall of a building. This system can be classified into two major groups: external green facades and internal green walls (Kontoleon & Eumorfopoulou, 2010). The former consists of a vegetation covered by climbing or cascading plants rooted either at the base in the ground or in plant boxes on the outer wall of a building. An internal green wall is generally more complex. It is a layer containing a variety of plant species attached to an independent waterproof vertical structure isolated from the building inner wall. This arrangement can avoid humidity problems (Loh, 2008). There are several types of green walls; the module type is one among them. For this type of green walls, plants are filled in pockets and directly rooted in the vertical structure using a porous material that provides physical support for the plant growth and serves as a means of water distribution and irrigation uniformity (Francis & Lorimer, 2011).

Apart from air and water, light is another essential element for green plants to grow well. Chlorophyll in green plants initiates photosynthesis by capturing light energy and converting it into chemical energy. In this way, plants transform water and carbon dioxide into primary nutrients. Photosynthesis does not necessarily take place in continuous light (Sysoeva, Markovshaya, & Shibaeva, 2010). An accumulated period of time with specific lighting level would similarly trigger photosynthesis. Naturally, daylight is the best light source for plants to grow. It is capable of providing plants with a high lighting level and a continuous spectrum throughout the daytime. Plants on green roofs or green facades exposed outdoors normally do not have any problem in obtaining sufficient light. Green walls in interiors, however, usually receive less or no daylight. A supplementary lighting system should then be provided for healthy plant growth. However, if the lighting system consumes too much energy, it would violate the principle of sustainability. An energy efficient supplementary lighting system which provides appropriate light quality, photoperiod and, more importantly, light quantity for the indoor plant growth (Goto, 2003) should be installed (Fernandex-Canero, Perez-Urrestarazu, & Franco-Salas, 2012). Light quality refers to the spectral composition of the light source. Not all wavelengths are equally effective for photosynthesis. Red and blue light drives photosynthetic metabolism the best as chlorophyll absorbs red and blue wavelengths most efficiently while almost all green and yellow counterparts are reflected or transmitted (Pinho, Jokinen, & Halonen, 2012). Light of the same energy but at different wavelengths emits different numbers of photons. Photoperiod is defined as the duration of plants' daily exposure to light (Mattson & Erwin, 2005). Plants can be classified into short-day and long-day in this way, where short-day plants grow well when the night length exceeds their critical photoperiod and long-day plants grow well when the night length falls below their critical photoperiod. In this paper, the light quantity in terms of the benefits to both human perception and plant growth would be studied. Common light sources used for illuminating green walls are investigated.

Photometric quantities

Light quantity is considered to be very important to the supplementary lighting system of an interior green wall. It can be evaluated using the parameter, luminous flux (Φ_v), which is defined as the total amount of light emitted in all directions from a light source. The SI unit of luminous flux is lumen (lm). Luminous flux is a photometric parameter that quantifies the light within the visible spectrum, which means the part of electromagnetic radiation visible to a human eye and ranging from 380 to 780 nm. Therefore, it gives no indication to the level of other parts of electromagnetic radiation like ultraviolet or infrared. Unlike radiation power unit, measurement of light quantity is dependent on human factors. Different wavelengths of visible electromagnetic waves of the same radiation power and beam angle do not look the same to the human eye. The parameter of light quantity has to be adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light. As a result, when radiant power is converted into luminous flux, a correction factor which is spectral luminous efficiency $V(\lambda)$ for photopic vision or $V'(\lambda)$ for scotopic vision should be added. The luminous flux output of a light source is defined by Equation (1),

$$\Phi_v = K_m \int_{380}^{780} \Phi_e(\lambda) V(\lambda) d\lambda \qquad (1)$$

where $\Phi_e(\lambda)$ is the spectral radiant power in W/nm and K_m is the maximum spectral luminous efficacy which equals 683 lm/W.

Light quantity can also be further regarded as the luminous flux incident on a surface per unit area (m^2), which is characterized by another lighting parameter, called illuminance (I). The unit of illuminance is lux (lx). This is the parameter commonly used to specify the lighting level on a reference plane in many international and local lighting codes and standards. The illuminance at a point on a surface is defined by Equation (2),

$$I = \frac{d\Phi_v}{dA} \qquad (2)$$

The light quantity received by the plants on an interior green wall decreases with the distance from the light source. The required illuminance differs among plant species as some with a high degree of shade tolerance can grow under lower illuminance than others (Niinemets, 2006). The recommended illuminance level on the typical plants growing indoors ranges from 750 to 2,000 lux (IESNA, 2011). For the purpose of defining the efficiency of a light source to convert electrical energy into lighting energy, the parameter luminous efficacy would be used. It is defined as the ratio of luminous flux output to electrical power input. The unit of is lm/W.

Electric light sources

For the supplementary lighting system of interior green walls, standard incandescent lamps, tungsten halogen lamps, metal halide lamps and LED lamps are commonly used.

Incandescent lamps are one of the oldest electric lighting technologies. By heating a tungsten filament inside a standard incandescent lamp, the atoms within the filament become excited and light energy is radiated in a full and continuous spectrum. A standard incandescent lamp is cheap in price and its disposal causes little environmental problems. However, it has the drawbacks. Most of the radiation output of a standard incandescent lamp falls in the infrared region that is not visible, resulting in that it is the least energy efficient light source with a high heat output and a low luminous efficacy (7 – 14 lm/W). Besides, with use, the tungsten slowly evaporates, eventually causing the filament to break, which leads the standard incandescent lamp to have a relatively short life, typically nominated as 1,000 hours. Due to the high energy use of standard incandescent lamps, some governments are now in the process of phasing out the use of these lamps in favour of more energy efficient lighting.

Another type of incandescent lamps is the tungsten halogen lamp, in which a small quartz capsule contains the filament and a halogen gas. The small capsule size allows the filament to operate at a higher temperature such that the full spectrum light is produced at a higher energy efficiency than the standard incandescent lamp. The luminous efficacy of tungsten halogen lamps can reach 23 lm/W. These lamps take the benefits of the halogen cycle such that the halogen gas combines with the evaporated tungsten redepositing it on the filament extends the life of the filament, keeps the lamp wall from blackening and reducing luminous output. The rated lifetime of tungsten halogen lamps can be as long as 5,000 hours. Those of reduced voltage can be smaller in size and thus allow greater accuracy of light beam control than the standard incandescent lamps.

The most common supplementary lighting system for interior green walls uses metal halide lamps, which belong to high intensity discharge lamps. They have several advantages (Egea, Perez-Urrestarazu, Gonzalez-Perez, Franco-Salas, & Fernandez-Canero, 2014). They are full spectrum light sources which produce an intense white light with blue being dominant. They have a high luminous efficacy of 60 – 98 lm/W and a long lifespan ranging from 2,000 to 10,000 hours (CIBSE, 2009). However, they have the drawbacks. A “cold” metal halide lamp cannot immediately start producing its full luminous output because the temperature and pressure in the lamp have not yet reached the full operation level. The warm-up process usually takes several minutes. The energy used during the warm-up time is therefore wasted.

Rapid advances in lighting technology provide an increasing number of options for the supplementary lighting system of an interior green wall. The use of LED lamps as a lighting system for horticulture is rapidly expanding (Morrow, 2008, Massa, Kim, Wheeler, & Mitchell, 2008, Olle & Virsile, 2013). Compared with metal halide lamps, high quality LED lamps have an even higher luminous efficacy (approaching 100 lm/W) and release less radiant heat. They have a longer lifetime of 15,000 – 60,000 hours such that they can maintain useful luminous output for years (CIBSE, 2009). Their abilities to allow luminous output adjustment and to emit a controlled spectral composition, e.g. red and blue wavelengths, for plants to undergo effective photosynthesis allow them to imitate the changes of daylight quantity and quality during the day (Yeh & Chung, 2009), which is what metal halide lamps cannot achieve.

The aforementioned four types of electric light sources can be used in indoor spaces to replace daylight or partially supplement it during the periods of low daylight availability. However, they were originally developed for human applications while plants have an entirely different response to light from the human eye. The appropriateness of the light sources for plant growth should be evaluated by photon efficiency, which is highly related to the rate of photosynthesis.

Photon quantities

For the calculation of photon efficiency, spectral radiant power is measured. Radiometric units are for measurement of electromagnetic radiation. It is different from photometric units which characterize the interaction between light and a human eye. The energy emitted from one photon can be calculated from the Planck’s constant (*h*). Equation (3) gives the energy of one photon (unit: J) in terms of the photon’s frequency (*f*) and therefore speed (*c*) and wavelength of light (λ).

$$E(\lambda) = h \times f = \frac{h \times c}{\lambda} \qquad (3)$$

where h is the Planck's constant (6.63×10^{-34} Js).

Using a calibrated spectrophotocolorimeter, the spectral radiant power ($\Phi_e(\lambda)$) (unit: W) emitted by a light source can be measured. The number of photons (N_λ) emitted at a particular wavelength per unit time can then be calculated by dividing the spectral radiant power by $E(\lambda)$, as expressed in Equation (4),

$$N_\lambda = \frac{\Phi_e(\lambda)}{E(\lambda)} = \frac{\Phi_e(\lambda)\times\lambda}{h\times c} \tag{4}$$

The total number of photons emitted per unit time from the light source can be calculated by integration over the visible spectrum. The unit for the number of photons can be changed to moles using the Avogadro's number (6.02×10^{23}). As a result, photon efficiency can be found by dividing the rate of photon emission with electrical power input (P). Equation (5) shows the calculation,

$$\text{Photon efficiency (mol/J)} = \frac{\sum_{\lambda=380}^{780} N_\lambda}{6.02\times10^{23}\times P} \tag{5}$$

The fundamental objective of an interior green wall is to promote sustainability in buildings. The supplementary lighting system should be designed in a way that the light sources would not consume excessive energy but give high photon efficiency for facilitating the photosynthesis process of the plants. However, few lamp manufacturers provide this technical information. This paper investigates the relationship between photometric quantities and photon quantities of various light sources that are commonly found being used for interior green wall illumination with the aid of a calibrated spectrophotocolorimeter.

Experimental results

A total of 13 different types of light sources were purchased from the market and investigated in this study. They included one standard incandescent lamp, one tungsten halogen lamp, two metal halide lamps, three LED bulbs, two LED MR16 lamps, two LED floodlights and two LED strip lights. Measurements were conducted for their electrical and photometric characteristics in a calibrated spectrophotocolorimeter. The integrating sphere of the meter is located in the lighting laboratory of Department of Building Services Engineering, The Hong Kong Polytechnic University. The basic properties of these light sources are tabulated in Table 1.

Table 1: Basic properties of the light sources being investigated in this study

Lamp type	Brand	Electrical power input (W)	Correlated colour temperature (K)	Luminous output (lm)	Luminous efficacy (lm/W)
Standard incandescent	A	52.3	2580	366.2	7.00
Tungsten halogen	A	48.1	2825	560.1	11.64
Metal halide 1	A	152.5	5085	10348.1	67.86
Metal halide 2	A	277.7	5891	20034.1	72.14
LED bulb 1	A	6.9	6402	593.4	86.00
LED bulb 2	A	7.3	3059	637.7	87.36
LED bulb 3	A	9.9	6759	998.6	100.87
LED MR16 1	A	7.7	2720	341.1	44.30
LED MR16 2	A	7.9	4026	423.2	53.57
LED floodlight 1	B	12.0	3061	822.6	68.55
LED floodlight 2	B	11.9	4371	666.0	55.97
LED strip light 1	A	5.4	3359	185.0	34.26
LED strip light 2	A	5.0	4499	151.5	30.30

A standard incandescent lamp, due to its operating principle, approximates an ideal blackbody radiator. The colour temperature of the standard incandescent lamp investigated in this study was measured to be about 2,600K. This lamp had the nominal rating of 60W, which echoed the measured electrical power consumption of 52.3W. Among the 13 light sources studied, despite consuming a moderate amount of power, the measured luminous output of the standard incandescent lamp was not high. Its lighting performance was the worst and its measured luminous efficacy was the lowest which was only 7 lm/W.

The electrical and photometric characteristics of the tungsten halogen lamp investigated in this study were in general similar to those of the standard incandescent lamp previously discussed. The colour temperature of the tungsten halogen lamp was measured to be about 2,800K. The nominal rating of the lamp was 50W while the measured electrical power consumption was 48.1W. Despite similar amount of power consumption, the luminous output of the tungsten halogen lamp was measured to be 560 lm, about 50% more than that of the standard incandescent lamp, leading its measured luminous efficacy to reach 11 lm/W.

Two metal halide lamps were purchased for investigation in this study. The brand of these two lamps was the same, but their nominal ratings were respectively 150W and 250W, which were consistent with the electrical power input measured (i.e. 152.5W and 277.7W). The correlated colour temperatures of the two metal halide lamps were high towards bluish white, between 5,000K and 6,000K. Although it required a large amount of power for these metal halide lamps to give full luminous outputs, because their luminous outputs were also high, their luminous efficacies were abundantly higher than those of the incandescent lamps, reaching about 70 lm/W.

Since LED lamps were reported to become popular light sources for growing plants, 10 LED lamps of four types were examined for their electrical and photometric properties. In general, LED lamps have a higher luminous efficacy than the other types of lamps investigated in this study, but the value of this parameter varies a lot among the 10 LED lamps. The 3 LED bulbs of three different nominal ratings (7W, 7.5W and 10.5W) and two different levels of correlated colour temperatures (about 3,000K and about 6,500K) had the highest luminous efficacy ranging from 86 lm/W to over 100 lm/W. For the LED MR16 lamps of the same nominal rating (6.5W) but having different correlated colour temperatures (about 2,700K and about 4,000K), their measured luminous efficacies were only around 50 lm/W.

Although manufacturers claim that LED floodlights usually have a very high luminous efficacy (over 80 lm/W), the two LED floodlights that were purchased for this study could only have the measured luminous efficacies of about 60 lm/W, regardless of their correlated colour temperatures. These LED floodlights produced exceptionally low luminous efficacies probably because they almost demanded the least electrical power input among the similar types of lighting products in the market. It is believed that LED floodlights of a higher nominal rating would have a luminous efficacy approaching 100 lm/W.

LED strip lights are rather new lighting products. Their applications range from decoration to general illumination. LED strip lights have the advantage that their length is adjustable allowing them to be convenient in use. The two LED strip lights (with length of 0.5 m) that were investigated in this study demanded about 5W similarly, but had different correlated colour temperatures, which were about 3,000K and 4,500K respectively. Both of these lights had a measured luminous efficacy of about 30 lm/W. Despite a low value at present, the photometric characteristics of LED strip lights are undergoing development. It is believed that they could have a much higher luminous efficacy in the near future.

Among the above mentioned four types of light sources measured by the calibrated spectrophotocolorimeter, LED lamps were found to be the most energy efficient light sources with the higher value of luminous efficacy in general. However, this parameter was derived with the basis on human perception such that the rate of photosynthesis promoted by the light sources was not implied. Photon efficiency was therefore calculated using Equation (5), which is reported to be the most suitable parameter to quantify the efficiency for plant growth due to light (Nelson & Bugbee, 2014). The calculated photon efficiency of the 13 types of light sources investigated in this study was tabulated in Table 2.

Table 2: Calculated photon efficiency of the light sources (from best to worst)

Lamp type	Photon efficiency (μmol/J)
LED bulb 3	1.51
LED bulb 1	1.31
LED bulb 2	1.24
Metal halide 1	1.23
LED floodlight 1	1.03
Metal halide 2	0.99
LED floodlight 2	0.81
MR16 LED 2	0.78
MR16 LED 1	0.70
LED strip light 1	0.52
LED strip light 2	0.48
Tungsten halogen 1	0.48
Incandescent 1	0.31

Comparing Table 1 and Table 2, it could be found that although for most of the light sources investigated in this study, the higher the luminous efficacy, it was likely that the photon efficiency would usually be higher as well, there were exceptional cases. Metal halide 1 had a lower luminous efficacy than metal halide 2, but it had a higher photon efficiency. Similarly, LED bulb 1 had a lower luminous efficacy than LED bulb 2, but it had a higher photon efficiency. The findings therefore mean that luminous efficacy has no direct relationship with photon efficiency, which is affected by the spectrum of the light emitted from the light source.

With the advanced development of lighting technology, LED lamps are now dimmable. Apart from their relatively high luminous efficacy, more lighting energy could potentially be saved by the dimmable function. Hence, there is a need to study how the reduced luminous output of dimmable LED lamps would influence the photon efficiency. Consequently, a dimmable LED lamp was purchased for the experiment.

The nominal rating of the dimmable LED lamp was 12W. The spectral radiation was measured by the calibrated spectrophotocolorimeter at its full luminous output as well as five different dimming levels, each of which consumed power at 2.1W, 4.0W, 6.1W, 8.4W and 10.1W. Figure 1 shows the values of photon efficiency at different electrical power input values of the dimmable LED lamp.

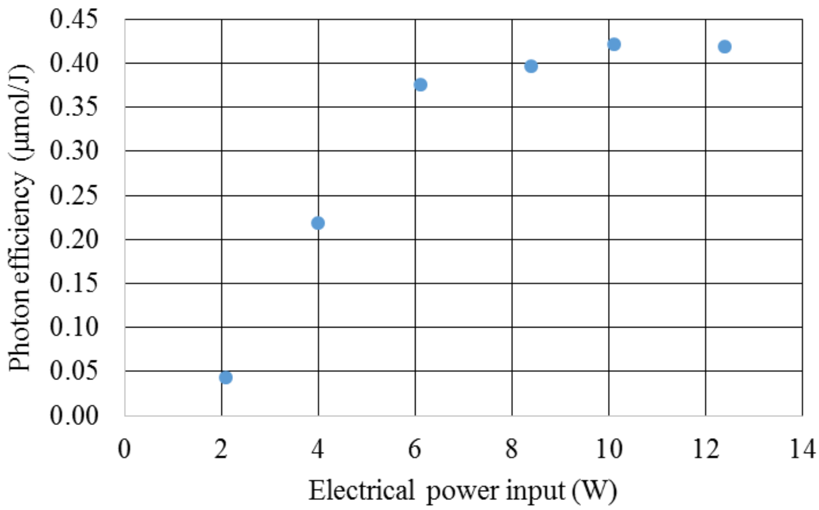

Figure 1: Relationship between photon efficiency and electrical power input of the dimmable LED lamp investigated in this study

Figure 1 reveals that the relationship between the photon efficiency and the electrical power input of the dimmable LED lamp was nonlinear. Nevertheless, the trend was unlike that of the metal halide lamps whose photon efficiency was reported in other researches to drop significantly when they are dimmed (Bubenheim, Sargis, & Wilson, 1995). For the LED lamp, the photon efficiency remained almost constant with the power reduced to half value. Therefore, with the advantages of high luminous efficacy and high photon efficiency despite half-dimmed, it is recommended to use dimmable LED as the light source of the supplementary lighting system of interior green walls.

Discussion

There are a few remarks for this study. First, it is technically required for LED lamps to be physically attached to the luminaires which allow heat dissipation by the heat sink. The reflectors, diffusers and other parts of the luminaire would absorb both the light and photon output. Meanwhile, for the other light sources, the lamps can be separated from the luminaires, so that the luminous output and photon output are correctly measured. Second, the number of tested lighting products was not adequate. There were two major reasons: (i) it was not an easy task to purchase various types of high output LED lamps; and (ii) even if a high output LED lamp was obtained, it was difficult to measure its electrical and photometric characteristics using the standard integrating sphere of the spectrophotocolorimeter due to its large physical size. For the latter reason, it was a difficult task to accurately measure the spectrum radiation output of large LED lamps as significant errors would arise.

Conclusion

Plants and greenery provide numerous benefits for urban areas and environment. Interior green walls enable the distribution of vegetation across the interior wall surfaces of a building. Due to the difficulty to obtain sufficient daylight energy for producing nutrients, an interior green wall usually requires a supplementary lighting system that is both energy efficient for not violating the basic principle of sustainability and can provide adequate light quantity for maintaining plant growth in a healthy manner. Since most lighting products were developed for human applications, light quantity was expressed in the photometric unit based on the luminous sensitivity of a human eye. Plants however have an entirely different response to light from the human eye. For the study of plant growth, light should be quantified by the number of photons which is highly related to the rate of photosynthesis. However, few lamp manufacturers provide sufficient technical information in this aspect.

Various light sources are commonly found being used for interior green wall illumination. They are namely standard incandescent lamps, tungsten halogen lamps, metal halides and LED lamps. Experiments in a controlled laboratory environment were conducted to investigate the relationship between the photometric quantities and photon quantities of 13 types of these light sources with the use of a calibrated spectrophotocolorimeter. Electrical and photometric characteristics of the light sources were measured. Luminous efficacy were obtained and photon efficiency was calculated for all the light sources under investigation. The findings of this study indicated that there is no direct relationship between luminous efficacy and photon efficiency of a light source. Photon efficiency is influenced by the spectrum of the light emitted from the light source and separate calculation for photon efficiency is required for choosing the appropriate light source for plant growth. Besides, since LED lamps are now dimmable, the change of photon efficiency due to the dimming function was examined. It was found that the photon efficiency decreased in a limited way when the electrical power input was reduced. In view of the merits of high luminous efficacy and high photon efficiency, this study therefore recommends to use dimmable LED lamps as the light sources for interior green wall illumination.

References

Bubenheim, D. L., Sargis, R., & Wilson, D. (1995). Spectral changes in metal halide and high-pressure sodium lamps equipped with electronic dimming. *HortScience* 30, 1086-1089.

CIBSE (2009). *The SLL Lighting Handbook*. Geneva: Chartered Institute of Building Services Engineers.

Darlington, A. B., Dat, J. F., & Dixon, M. A. (2001). The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. *Environmental Science and Technology*, 35, 240-246.

Egea, G., Perez-Urrestarazu, L., Gonzalez-Perez, J., Franco-Salas, A., & Fernandez-Canero, R. (2014). Lighting systems evaluation for indoor living walls. *Urban Forestry and Urban Greening*, 13, 475-483.

European Commission (2012). The Multifunctionality of Green Infrastructure. Directorate-General for the Environment. European Commission.

Fernandex-Canero, R., Perez-Urrestarazu, L., & Franco-Salas, A. (2012). Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate. *Indoor and Built Environment*, 21, 642-650.

Francis, R. A., & Lorimer, J. (2011). Urban reconciliation ecology: the potential of living roofs and walls. *Journal of Environmental Management*, 92, 1429-1437.

Goto, E. (2003). Effects of light quality on growth of crop plants under artificial lighting. *Environmental Control in Biology*, 41, 121-132.

IESNA (2011). *The IESNA lighting handbook: Reference and Application*, 10th Edition. New York: Illuminating Engineering Society of North America.

Kleerekoper, L., van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resource Conservation and Recycling*, 64, 30-38.

Kontoleon, K. J., & Eumorfopoulou, E. A. (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment*, 45, 1287-1303.

Loh, S. (2008). Living Walls: a way to green the built environment. *BEDP Environment Design Guide of Australia*. Retrieved from www.environmentdesignguide.net.au.

Massa, G. D., Kim, H. H., Wheeler, R. M., & Mitchell, C. A. (2008). Plant productivity in response to LED lighting. *HortScience*, 43, 1951-1956.

Mattson, N. S., & Erwin, J. E. (2005). The impact of photoperiod and irradiance on flowering of several herbaceous ornamentals. *Scientia Horticulturae*, 25, 331-334.

Morrow, R. C. (2008). LED lighting in horticulture. *HortScience*, 43, 1947-1950.

Nelson, J. A., & Bugbee, B. (2014). Economic analysis of greenhouse lighting: Lighting emitting diodes vs High intensity discharge fixtures. *PLoS ONE, 9*(6), E99010.

Nielsen, T. S., & Hansen, K. B. (2007). Do green areas affect health? Results from a Danish survey on the use of green areas and health indicators. *Health and Place*, 13, 839-850.

Niinemets, U. (2006). The controversy over traits conferring shade-tolerance in trees: ontogenetic changes revisited. *Journal of Ecology*, 94, 464-470.

Olle, M., & Virsile, A. (2013). The effects of light-emitting diode lighting on greenhouse plant growth and quality. *Agriculture and Food Science*, 22, 223-234.

Perez, G., Coma, J., Martorell, I., & Cabeza, L. F. (2014). Vertical greenery systems (VGS) for energy saving in buildings: a review. *Renewable and Sustainable Energy Reviews*, 39, 139-165.

Pinho, P., Jokinen, K., & Halonen, L. (2012). Horticultural lighting – present and future challenges. *Lighting Research and Technology*, 44, 427-437.

Sysoeva, M. I., Markovshaya, E. F., & Shibaeva, T. G. (2010). Plants under continuous light: a review. *Plant Stress*, 4, 5-17.

White, E. V., & Gatersleben, B. (2011). Greenery on residential buildings: does it affect preferences and perceptions of beauty? *Journal of Environmental Psychology*, 31, 89-98.

Wong, N. H., Cheong, D. K. W., Yan, H., Soh, J., Ong, C. L., & Sia, A. (2003). The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and Building*, 35, 353-364.

Wong, N. H., Kwang, T. A. Y., Tan, P. Y., Chiang, K., & Wong, N. C. (2010). Acoustics evaluation of vertical greenery systems for building walls. *Building and Environment*, 45, 411-420.

Yeh, N., & Chung, J. (2009). High-brightness LEDs – energy efficient lighting sources and their potential in indoor plant cultivation. *Renewable and Sustainable Energy Reviews*, 13, 2175-2180.

Yuen, B., & Hien, W. N. (2005). Resident perceptions and expectations of rooftop gardens in Singapore. *Landscape and Urban Planning*, 73, 263-276.

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