Urban Forestry & Urban Greening 13 (2014) 475–483

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Lighting systems evaluation for indoor living walls

Gregorio Egea[a,*], Luis Pérez-Urrestarazu[a], Julio González-Pérez[a], Antonio Franco-Salas[a], Rafael Fernández-Cañero[b]

[a] Area of Agro-Forestry Engineering, Universidad de Sevilla, ETSIA Ctra, Utrera km.1, 41013 Seville, Spain
[b] Department of Agro-Forestry Sciences, Universidad de Sevilla, ETSIA Ctra, Utrera km.1, 41013 Seville, Spain

ARTICLE INFO

Keywords:
Biowall
Evapotranspiration
Ornamental
Plant growth
Plant microclimate
Urban greening

ABSTRACT

Living walls (LW) are vertical greening systems that are becoming popular due to their multiple social and environmental benefits. When LW are installed indoors, a lightening system is often required to ensure an appropriate plant development. This work assesses the performance of three artificial lighting systems on six indoor LW [0.7 m (wide) × 0.7 m (high)] placed at two distances from the light source. The plant species selected for the tests were *Soleirolia soleirolii* and *Spathiphyllum wallisii*, which are frequently used in indoor LW. Three different lamps were used in the experiment: incandescent (IL), fluorescent (FL) and metal halide (MHL) lamps, all of them with an input electric power of ≈250 W. Differences in plant growth were only observed when the LW were close to the light source (about 1 m) but not at greater distances (≈1.5 m). IL had the poorest performance. Despite the lower photosynthetic photon flux density efficiency of FL compared with MHL, FL light enabled plants placed in the upper LW (closer to light source) reached similar size to those grown under MHL. Plant quality attributes were generally not affected by light type or the distance to light source. IL and FL generated higher total water losses (i.e. transpiration plus evaporation) than MHL on a LW basis. When expressed per unit of LW area covered by vegetation, FL and MHL reduced water consumption by 34% and 56%, respectively, as compared to IL. Overall, our results indicate that both FL and MHL outperform IL and have a similar ornamental performance, whereas MHL are more advantageous than FL in terms of water consumption and annual cost.

Introduction

Vertical greening systems, also known as green wall technologies, enable the distribution of vegetation across the wall surface. For that purpose, they use vertical structures attached to a building facade or to an interior wall (Francis and Lorimer, 2011). These systems can be divided into two mayor groups: green facades and living walls (Kontoleon and Eumorfopoulou, 2010). The former consists of a vegetation cover of climbing or cascading plants rooted either at the base in the ground or in plant boxes. Living walls (LW) are generally more complex systems in which a great variety of plant species are used (Loh, 2008). LW are isolated from the building wall via a waterproof layer that avoids humidity problems. Vegetation is directly rooted in a supporting vertical structure using a porous material that provides physical support for plant growth and a suitable means for water distribution and irrigation uniformity (Francis and Lorimer, 2011).

When vegetation receives little or no natural light, as frequently occurs with indoor living walls, a supplementary light source must be provided to ensure adequate plant growth and development (Fernández-Cañero et al., 2012). Successful artificial lighting for indoor plant growth must balance quality, intensity and photoperiod (Thiel et al., 1996; Goto, 2003). Light quality refers to the spectral composition of the light source. Not all wavelengths are equally effective for plant photosynthesis, as blue and red represent the majority of wavelengths absorbed by chlorophylls (Hopkins, 1999; Pinho et al., 2012). Light intensity refers to the amount of light received by plants which decreases with the distance to the source. Light requirements differ among plant species (Niinemets, 2006), as some (shade tolerant) can grow under lower irradiances, than others. These requirements reflect the natural habitat of the species. Photoperiod, defined as the duration of plants daily exposure to light, is also an important factor for plant growth as it influences several development processes, e.g. flowering (Mortensen and Grimstad, 1990; Mortensen and Gislerød, 1999; Mattson and Erwin, 2005).

* Corresponding author. Tel.: +34 954482004.
E-mail addresses: gegea@us.es (G. Egea), lperez@us.es (L. Pérez-Urrestarazu), juliogonzper@gmail.com (J. González-Pérez), afranco@us.es (A. Franco-Salas), rafafc@us.es (R. Fernández-Cañero).

http://dx.doi.org/10.1016/j.ufug.2014.04.009
1618-8667/

Notation

[Lamp's type]_A	higher light flux densities (closer to the light origin)
[Lamp's type]_B	lower light flux densities (farther from the light origin)
ADW	aerial dry weight [g plant^{-1}]
AFW	aerial fresh weight [g plant^{-1}]
CI	color index
ET	evapotranspiration [l d^{-1}]
ET_{lw}	water lost by plant transpiration plus substrate evaporation expressed on a living wall area basis [l d^{-1}]
ET_{vc}	water lost by plant transpiration plus substrate evaporation expressed per vegetation-cover unit area [l m^{-2} d^{-1}]
FL	fluorescence lamps
HPS	high-pressure sodium
IL	incandescent lamps
LA	individual leaf area [cm^2 leaf^{-1}]
LDW	leaf dry weight [g plant^{-1}]
LED	light-emitting diodes
LFW	leaf fresh weight [g plant^{-1}]
LW	living walls
MHL	metal halide lamps
OLW	outdoor living wall
PAR	photosynthetically active radiation
PPFD	photosynthetic photon flux density [μmol m^{-2} s^{-1}]
RDW	root dry weight [g plant^{-1}]
RFW	root fresh weight [g plant^{-1}]
SLW	specific leaf weight [g m^{-2}]
SO	*Soleirolia soleirolii*
SP	*Spathiphyllum wallisii*
SPAD	relative measure of chlorophyll content
TDW	total dry weight [g plant^{-1}]
TET	total evapotranspiration [l d^{-1}]
TET_{lw}	total water lost by plant transpiration, substrate evaporation and reservoir evaporation expressed on a living wall area basis [l d^{-1}]
TET_{vc}	total water lost by plant transpiration, substrate evaporation and reservoir evaporation expressed per vegetation-cover unit area [l m^{-2} d^{-1}]
TFW	total (whole-plant) fresh weight [g plant^{-1}]
TLA	total leaf area [cm plant^{-1}]

The most common lamps used as artificial lighting for growing plants are incandescent, fluorescent, high-intensity discharge lamps (like metal halide or high pressure sodium) and light-emitting diodes.

Incandescent lamps (IL) are the cheapest option and their use in horticultural lighting has been limited due to their low electrical efficiency, defined as the ratio between the total radiant power within the photosynthetically active radiation (PAR) region (400–700 nm) and the total input power (Thimijan and Heins, 1983), low light emission, unbalanced spectrum (reduced emission in the blue region) and short lifetime. Conversely, they are still used for the control of photomorphogenetic responses of ornamental plants thanks to their high and physiologically balanced emission of red and far-red radiation (Pinho et al., 2012).

Standard fluorescence lamps (FL) have intermediate luminous efficiency between IL and high-intensity discharge lamps, and a lifespan similar to that of metal halide lamps (MHL). FL are available in a range of spectral qualities. Cool white lamps, which are relatively inexpensive, and full-spectrum lamps are available options for supplementary and replacement lighting applications, respectively. MHL have a much greater luminous efficiency and lifespan than IL. They are full-spectrum lighting sources with an abundance in the blue spectrum, and can be used in plant growth to totally replace daylight or partially supplementing it during periods of low availability (Pinho et al., 2012).

High-pressure sodium (HPS) lamps are widely used in horticulture (e.g. for commercial greenhouse production in Northern Europe) due to their high PAR emission, electrical efficiency and lifespan (nearly double of MHL). However, HPS lamps' spectrum is poor in blue light (Wheeler et al., 1991; Mortensen and Fjeld, 1998) so they are mainly used as supplemental light sources, in some cases in conjunction with other blue-rich light sources. For this reason they were not used in this experiment. The use of light-emitting diodes (LED) as a lighting system for growing plants is expanding though this technology is still evolving and its cost is high for a rapid uptake in horticultural lighting (Olle and Virsile, 2013). However, LED lamps have great potential due to their long lifespan, low radiant heat output, their ability to emit in a controlled spectral composition (e.g. red and blue wavelengths) and the adjustment of light intensity (Morrow, 2008; Yeh and Chung, 2009). They have not been tested in this study but will be assessed in a follow-up experiment.

Despite the number of studies found in the specialized literature comparing either the performance of domestic lighting lamps (e.g. Khan and Abas, 2011; Aman et al., 2013) or the effects of different artificial lighting systems on plant growth and development (e.g. Feng et al., 2005; Pinho et al., 2012; Yen et al., 2013), to the best of our knowledge this is the first report that addresses a comparative study of conventional lighting systems to be used for indoor LW. The idiosyncrasies of these novel gardening concepts force the reevaluation and optimization of some of the plant growing facilities, such as irrigation (Pérez-Urrestarazu et al., 2014) or lighting system (this study).

Most studies about the effects of artificial lighting systems on vegetation are oriented toward optimizing crop yield, plant growth and fruit or flower quality. However, in the case of indoor LW, the objectives are notably different. Firstly, instead of maximizing production or quality, the lighting system must provide a light intensity and spectrum quality that gives plants a natural appearance for the human eye and enables enough plant growth to cover the wall and to be healthy but avoiding excessive growth at the same time (risking shading and maintenance/pruning). Secondly, given the variety of species grown in a LW, lighting systems that provide a broad (full) spectrum seem more appropriate than lamps emitting in a narrow waveband range. And thirdly, given that indoor LW are not production systems but primarily provide an ornamental and air-purifying function, their expansion and acceptance by users will be marked by the progressive lowering of investment and maintenance costs.

We hypothesize that, for similar electric light installation, vegetation performance and water consumption of LW are markedly affected by the artificial lighting system employed. Based on the above, the main objective of this work was to assess the response of two plant species grown in indoor LW to three types of artificial lighting systems and to two distances from the light source. The lighting systems selected according to the previous criteria were IL, i.e. the current cheapest conventional lighting option, and FL and MHL, i.e. two broad spectrum lamp types.

Methods

Description of the experimental conditions and living walls

The study was conducted at the Urban Greening Laboratory of the School of Agricultural Engineering of the University of Seville

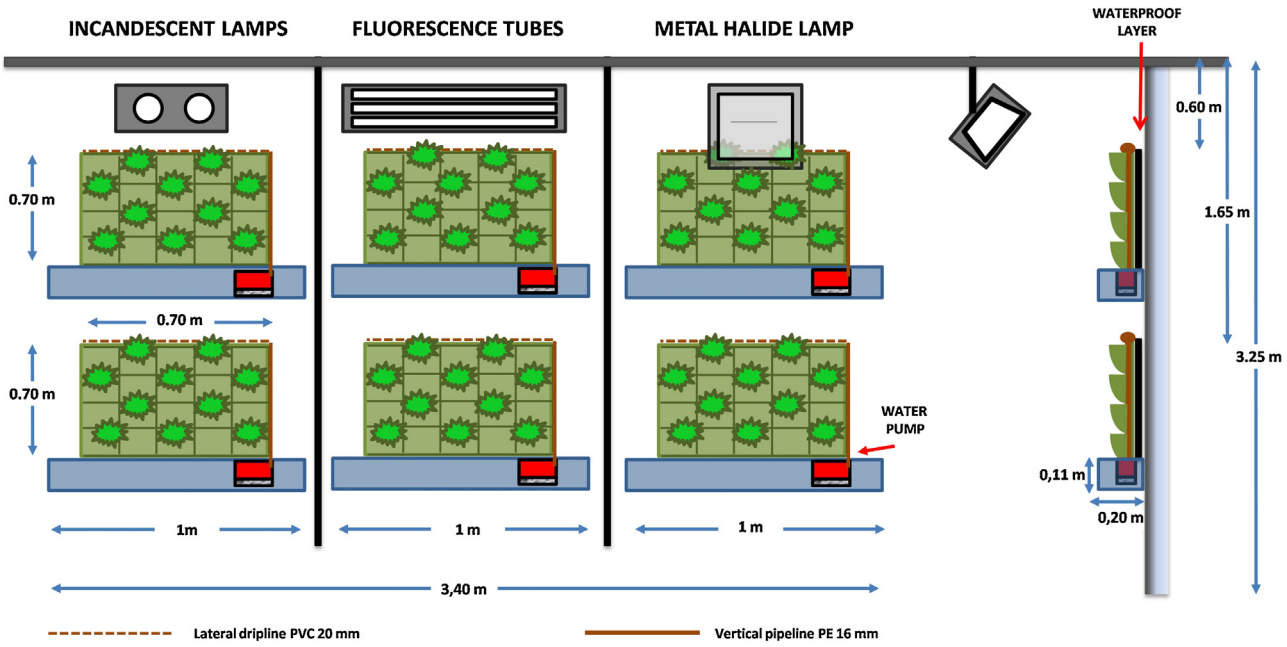

Fig. 1. Experimental layout.

(37°22′ N, 5° 59′ W, Seville, Spain). The experiment was conducted over the period mid-July to mid-October 2012. During this period, daily mean room temperature and relative humidity varied in the range 26.6 ± 2.5 °C and 54.1 ± 11.8%, respectively. The assessment of the performance of LW with six different *lighting system* × *light flux density* combinations was carried out by using six self-made LW prototypes (Fig. 1). The LW prototypes consisted of a 0.7 m (wide) × 0.7 m (high) modular growing system made of several synthetic textile layers with a reduced thickness (Pérez-Urrestarazu et al., 2014). The inner layers are responsible for the homogeneous distribution of water and nutrients, and the external layers are responsible for promoting the aeration of the plant root zone. The textile layers are sewn together forming a grid of 0.12 m × 0.12 m pocket-shaped containers in which plants are set by inserting the root ball between two textile layers through a horizontal opening in the uppermost pocket edge. The LW is isolated from the building wall via a waterproof layer that avoids humidity problems. As water retention is very limited in these growing systems, irrigation is compulsory for an adequate plant establishment and development. A recirculating irrigation system was used, which consisted of a vertical polyethylene (PE) pipeline, a lateral PVC dripline with perforations spaced 30 mm apart, a water tank placed at the bottom of the LW and a submerged compact water pump (Compact 600 11W, Ehim, Germany). Frequent 2-min irrigation events (6 per day) were scheduled to avoid undesirable effects of water deficit on plant development. Problems related to excess of water were not observed due to the high drainage capacity of the growing system.

In each LW, five plants of each species were planted at the beginning of the experiment. For the sake of results comparison, the distribution of plant species and individuals within each LW was similar. Before planting, the peat-based potted plants were irrigated, let to drain for at least 2 h and weighed for selection of plant individuals of similar size. The selected plant species for the experiment were *Spathiphyllum wallisii* Regel and *Soleirolia soleirolii* (Req.) Dandy, hereafter termed as SP and SO plants, respectively. SP, whose common name is "peace lily", is becoming very popular as an indoor ornamental plant in offices and houses due to its recognized ability to remove gaseous pollutants from indoor air (Missouri Botanical Garden, 2013). SO, commonly named as "baby's tears", is a perennial herb often used as indoor plant but also utilized in gardens as ground cover (Royal Horticultural Society, 1990). Its use in LW is also becoming very common.

An additional LW, with similar characteristics (i.e. size, materials, plants distribution, etc.) to the six described above, was installed outdoors (OLW) on a fully shaded wall that only received diffuse natural illumination along the daytime period. This shaded location was selected for two reasons. Firstly, to obtain levels of natural light similar to those received by the indoor LW (for comparison purposes) and, secondly, because SP and SO perform better in shade conditions and the light levels reached in sun-exposed locations over the period of study in Seville (July to October) greatly exceed their light requirements, therefore risking plants survival.

It should be noted that the differences in air temperature and humidity between indoor and outdoor (Fig. 2) conditions make indoor and outdoor LW not to be fully comparable. Yet, this LW was used to provide reference information on the plants performance under natural illumination.

Artificial lighting systems

Fig. 1 depicts a schematic representation of the experimental layout. The six LW were anchored to a laboratory wall forming a 2 × 3 LW grid. The three columns were isolated each another by placing an opaque plastic sheet (1.5 m wide) that avoided light interferences between the different lighting regimes. The two LW placed within a column were artificially illuminated with the same lighting system, but deliberately differing in the distance to the light source and thus in the light flux density reaching each LW surface. The artificial lighting systems were attached to the ceiling (≈0.4 m apart from the wall), so the lamps were placed just above the upper LW with an inclination angle to illuminate both the upper and lower LW (Fig. 1). In all three columns, the distances between the lamps and the center of the upper and lower LW were around 1 m and 1.5 m, respectively. The mean photosynthetic photon flux density (PPFD, $\mu mol\ m^{-2}\ s^{-1}$) reaching each LW was measured with a line quantum sensor (LI-191 Line Quantum Sensor, Li-Cor, Nebraska, USA) by the middle of the trial. Three PPFD readings were taken in the top, middle and bottom of each LW. Table 1 shows the mean PPFD values measured during the light-time period in all six LW.

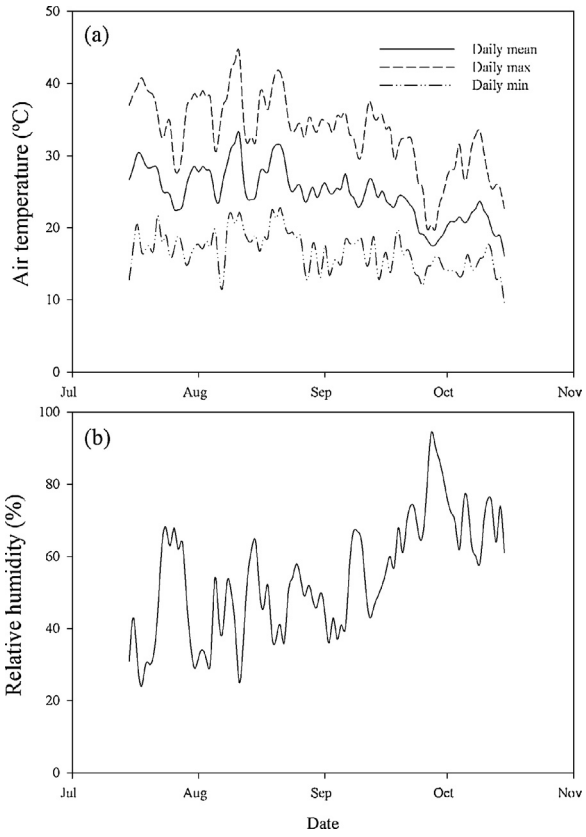

Fig. 2. Outdoor air temperature and relative humidity over the period of study.

Mean PPFD reaching the outdoor LW was also measured at noon and on a sunny day (PPFD = 44.6 ± 2.5 μmol m^{-2} s^{-1}).

For the three artificial lighting systems assessed (IL, FL, MHL), an electric light installation of ~250 W was installed. To accomplish this, one IL (250 W), seven FL (7 × 36 W = 252 W) and one MHL (250 W) were used. The IL was a reflector light bulb with a luminous efficacy of 12 lm/W (model Philips PAR38 E27 FL, Royal Philips Electronics, The Netherlands). The FL were 1.2 m long T8 Gro-lux® tubes (Havells-Sylvania Spain S.A.) mounted on a white flat panel, with enhanced level of blue and red radiation as compared to standard T8 tubes and a luminous efficacy of about 26 lm/W. The MHL projector used a daylight lamp (Powerstar HQI-T/D, Osram GmbH, Germany) with luminous efficacy of 82 lm/W.

The Urban Greening Laboratory, placed in the basement of the Agricultural Engineering School building, lacks of windows and thus natural illumination. Ventilation is provided by means of an extractor fan. All three lighting systems were operated with a digital clock timer to provide a constant photoperiod of 14 h d^{-1} over the course of the trial.

Plant growth measurements

Plant growth was characterized by harvesting all ten plants per LW at the end of the experiment. Once plants were detached individually from the living wall, the root system was carefully washed with tap water, as per Bashan and de-Bashan (2005) to remove the growing media and dried with absorbing paper. Fresh weights of the whole plant, aerial part (i.e. leafy shoots), leaves and root system were measured with a precision balance (Precision Instruments Ltd. XB4200C, Switzerland). Plant leaf area was measured with a LI-3100 Leaf Area Meter (Li-Cor, Nebraska, USA). In SP plants, the number of leaves was also measured to determine individual leaf area. This could not be performed in SO plants due to their small leaf size. The different plant organs were then oven-dried at 80 °C for 48 h and weighed to determine the respective dry weights. The fraction of the living wall area covered by vegetation was measured throughout the experiment by taking pictures of each living wall on a weekly basis. The vegetation area was determined by using the image-processing package ImageJ (Abramoff et al., 2004).

Table 1
Mean photosynthetic photon flux density (PPFD, μmol m^{-2} s^{-1}) values received by the different LW.

Distance to light source	Lamp type		
	IL	FL	MHL
A: 1 m	19.4 ± 2.5	44.3 ± 1.7	93.1 ± 6.8
B: 1.5 m	8.6 ± 0.8	18.4 ± 1.9	16.2 ± 3.6

Each value is the mean of three measurements per LW (n = 3).

Colorimetric analyses and chlorophyll meter readings

Leaf color of both plant species was measured in three harvested plants per species and LW before they were oven-dried. Color was measured with a spectrophotometer (model CM-5, Konica Minolta Sensing Inc, Japan) using the CIELAB color space and the standard illuminant D65 in combination with CIE 1964 10° standard observer. The colorimetric coordinates L^* (black-white), a^* (green-red), and b^* (blue-yellow) as well as a color index [CI = 1000a^*/(L^*b^*)] were determined. Two weeks before the end of the experiment, the "greenness" or relative chlorophyll content of SP leaves was measured with the hand-held Minolta SPAD-502 chlorophyll meter (Konica Minolta Optics, Inc., Japan). Five SPAD (relative measure of chlorophyll content) measurements per leaf were taken in three leaves per plant and three plants per living wall. No SPAD measurements were performed on SO leaves due to their small leaf size.

Water consumption and surface temperature

Water lost by evapotranspiration (ET) was determined over the last month of experiment in all LW. In indoor LW with recirculating irrigation systems, the only water losses are due to the processes of plant transpiration and growing system plus reservoir evaporation. Likewise, the only water inputs are due to reservoir refilling, thus ET can be calculated from the water balance for a particular time interval as ET ≈ volume of water refilled, as long as the moisture content of the growing system and the reservoir water level are similar after two consecutive water refilling events (i.e. time period over which water balance was computed). As irrigation frequency was high and water balance was always applied right after reservoir refilling, differences in moisture content and reservoir water level were neglected. To separate the contribution to ET of reservoir evaporation from that of plant transpiration plus growing system evaporation, mean reservoir evaporation was determined for each lighting regime at the end of the experiment during a week and for similar environmental conditions (e.g. light, temperature and relative humidity) to those prevailing through the experimental period. After plant harvesting and irrigation cut-off, the LW growing system was allowed to dry out before determining reservoir evaporation.

Surface temperature of both plant species was measured under all lighting regimes and at three sampling dates with an infrared thermometer (TP4, Trotec, Austria). Three measurements (sampling area of around 5 cm^2) per plant species and living wall were performed at each sampling date.

Statistical analysis

Each LW was considered as an experimental unit with five replicates per plant species. Statistical analyses of the data were

Table 2
Plant structural traits determined at the end of the experiment for *Spathiphyllum* plants grown under the seven lighting regimes. TFW: total (whole-plant) fresh weight; RFW: root fresh weight; AFW: aerial fresh weight; LFW: leaf fresh weight; TDW: total dry weight; RDW: root dry weight; ADW: aerial dry weight; LDW: leaf dry weight; TLA: total leaf area; LA: individual leaf area; SLW: specific leaf weight.

Measured variables	Lighting regimes							
	IL_A	IL_B	FL_A	FL_B	MHL_A	MHL_B	OLW	*P* value
TFW (g plant^{-1})	75.4c	87.9c	121.0a	93.7c	117.3ab	88.2c	96.6bc	0.001
RFW (g plant^{-1})	25.4bc	27.0b	33.8a	25.0bc	37.4a	20.1c	20.8bc	<0.001
AFW (g plant^{-1})	50.0d	60.9cd	87.2a	68.7bc	79.9ab	68.0bc	75.8abc	0.002
LFW (g plant^{-1})	16.8b	20.0ab	27.0a	21.8ab	20.9ab	21.4ab	28.4a	0.045
AFW/RFW	1.98c	2.30bc	2.62bc	2.75b	2.13bc	3.42a	3.69a	<0.001
TDW (g plant^{-1})	8.4b	8.7b	12.4a	8.2b	13.0a	8.5b	9.6b	<0.001
RDW (g plant^{-1})	2.4bc	2.2cd	3.0b	1.8cde	3.7a	1.5e	1.7de	<0.001
ADW (g plant^{-1})	5.9b	6.5b	9.5a	6.3b	9.4a	7.0b	7.9ab	0.006
LDW (g/plant)	1.8b	2.5ab	3.7a	2.5ab	2.9ab	2.5ab	3.4a	0.040
ADW/RDW	2.47c	3.10bc	3.28bc	3.44b	2.56bc	4.88a	4.64a	0.002
LDW/LFW	0.105b	0.126ab	0.138a	0.114b	0.138a	0.117ab	0.121ab	0.025
TLA (cm^2 plant^{-1})	733.6b	971.8ab	1238.8a	1051.2ab	1015.6ab	1089.5ab	1339.0a	0.045
LA (cm^2 leaf^{-1})	13.7	14.8	17.1	17.2	18.6	18.8	19.6	0.396
SLW (g m^2)	24.0	26.1	30.0	23.7	28.4	23.0	25.7	0.153

For each row, mean values followed by different letters indicate significant differences following Duncan's multiple range test (alpha = 0.05). Each value is the mean of five replicates per LW (n = 5).

performed with the statistical package Statgraphics (Statgraphics Centurion XV). The effects of lamp type and the distance to the light source on the LW performance (e.g. plant growth traits, water consumption, colorimetric indices and surface temperature) were analyzed through analysis of variance (ANOVA). The Duncan's multiple range test was used for means separation.

Results

Vegetation growth

Tables 2 and 3 show the performance of the two plant species grown in the LW under the different *lighting system* × *light flux density* combinations. For higher light flux densities (hereafter referred to as 'A'), fluorescent tubes and metal halide lamps (FL_A and MHL_A) led to a better plant performance than incandescent lamps (IL_A). SP grown under FL_A and MHL_A had about 50% more whole plant biomass (expressed either on a fresh or dry weight basis) and about 55% more total leaf area (TLA) than IL_A (Table 2). All other comparisons showed no significant differences.

SO response to lighting regime was similar to that described for SP (Table 3). At the end of the experiment, total dry weight was about 55% higher in FL_A and MHL_A than in IL_A. However, MHL_A and IL_A plants presented about 45% lower root dry weight (RDW) values than FL_A plants, which resulted in a significantly higher aerial-to-root dry weight ratio (ADW/RDW) in MHL_A as compared to IL_A and FL_A. Moreover, SO plants growing under MHL_A presented lower TLA than FL_A for a similar ADW, which resulted in significantly higher SLW values (Table 3).

For lower light flux densities (hereafter referred to as 'B'), plants responses were somewhat different to those observed when the light source was closer. In the case of SP plants, almost no significant differences were observed among the different lighting regimes (Table 2). The distance to the light source did not affect plant weight under IL but it was reduced by about 25% (TFW) and 35% (TDW) under FL and MHL. However, and despite the significant plant weight reduction observed with these lamps, TLA remained similar to the values observed under higher light flux densities (Table 2). SO plant weights (both on a fresh and dry basis) were also similar among the different lighting regimes when light flux density was lower (Table 3). Within each lighting system, no significant differences in TFW were observed between SO plants grown under different light flux densities (i.e. A or B lighting regimes). TLA was significantly higher in MHL_B than in MHL_A SO plants despite that plant weight was unaffected by the distance to the light source (Table 3). As a consequence, MHL_A SO plants presented higher SLW values than MHL_B SO plants.

Table 3
Plant structural traits determined at the end of the experiment for *Soleirolia* plants grown under the seven lighting regimes. TFW: total (whole-plant) fresh weight; RFW: root fresh weight; AFW: aerial fresh weight; LFW: leaf fresh weight; TDW: total dry weight; RDW: root dry weight; ADW: aerial dry weight; LDW: leaf dry weight; TLA: total leaf area; SLW: specific leaf weight.

Measured variables	Lighting regimes							
	IL_A	IL_B	FL_A	FL_B	MHL_A	MHL_B	OLW	*P* value
TFW (g plant^{-1})	16.9b	16.1b	29.9a	23.1ab	27.5ab	20.1ab	28.5ab	0.040
RFW (g plant^{-1})	5.3	4.4	7.7	5.9	5.8	5.4	5.1	0.448
AFW (g plant^{-1})	11.5b	11.7b	22.3a	17.3ab	21.7a	14.8ab	23.4a	0.043
AFW/RFW	2.3c	2.7bc	3.4abc	2.9bc	3.9ab	2.8bc	4.6a	0.001
TDW (g plant^{-1})	3.7bc	3.2c	6.1a	3.9bc	5.3ab	4.0bc	4.1bc	0.029
RDW (g plant^{-1})	0.9b	0.7b	1.6a	0.8b	0.9b	0.9b	0.7b	0.037
ADW (g plant^{-1})	2.7c	2.5c	4.6a	3.0bc	4.4ab	3.2abc	3.3abc	0.028
ADW/RDW	3.07b	3.85ab	4.03ab	3.79ab	5.33a	3.59ab	4.56ab	0.049
ADW/AFW	0.26a	0.22ab	0.18bc	0.18bc	0.21abc	0.23ab	0.15c	0.011
TLA (cm^2 plant^{-1})	457.9b	493.6b	966.9a	641.7b	580.2b	892.2[a]	962.7a	<0.001
SLW (g m^{-2})	65.3ab	51.2bc	41.8c	47.5bc	76.4a	35.3c	34.7c	0.007

For each row, mean values followed by different letters indicate significant differences following Duncan's multiple range test (alpha = 0.05). Each value is the mean of five replicates per LW (n = 5).

Table 4
Colorimetric analysis of leaf tissues of *Soleirolia soleirolii* and *Spathiphyllum* sp. performed at the end of the experiment.

Treatment	*Soleirolia*				*Spathiphyllum*			
	L	*a*	*b*	CI	*L*	*a*	*b*	CI
IL_A	37.9	−6.8b	18.3	−9.8b	34.1	−7.8	13.3	−17.8
IL_B	35.4	−6.2b	18.7	−9.4b	32.2	−7.0	10.9	−20.4
FL_A	32.7	−4.7b	15.0	−8.9b	33.3	−7.8	12.3	−19.0
FL_B	32.3	−5.7b	15.9	−11.1b	32.5	−6.7	9.9	−20.9
MHL_A	27.4	1.5a	13.3	5.0a	33.3	−7.3	12.1	−18.2
MHL_B	33.0	−5.4b	15.4	−10.7b	31.7	−6.7	9.6	−22.0
OLW	31.3	−3.4b	15.8	−7.0b	32.9	−7.0	10.9	−19.6
P value	0.4367	0.0154	0.4802	0.0069	0.2219	0.0824	0.1491	0.3929

Within each column, mean values followed by different letters indicate significant differences according to Duncan's Multiple Range test (alpha = 0.05). Each value is the mean of three replications per LW ($n = 3$).

Table 5
Crown temperature (°C) of *Soleirolia soleirolii* and *Spathiphyllum* sp. determined at three sampling dates over the experimental period.

Treatment	*Soleirolia*			*Spathiphyllum*		
	Date 1	Date 2	Date 3	Date 1	Date 2	Date 3
IL_A	29.8a	30.2a	29.0a	30.4a	30.3a	29.6a
IL_B	29.1bc	27.9bc	28.5ab	29.7b	28.2c	28.6b
FL_A	28.7c	28.0bc	28.6ab	29.6b	29.2b	28.6b
FL_B	27.2d	27.7c	26.9c	28.9c	28.8b	28.1b
MHL_A	29.5ab	30.0a	28.2b	30.1ab	30.3a	28.3b
MHL_B	26.1e	28.5b	25.4d	28.2d	29.0b	26.8c
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Within each column, mean values followed by different letters indicate significant differences according to Duncan's multiple range test (alpha = 0.05). Each value is the mean of three replicates per LW ($n = 3$).

SP plants grown outdoors (OLW) presented lower TDW (9.6 g/plant) than FL_A (12.4 g/plant) and MHL_A (13.0 g/plant) SP plants, while no differences in TDW where observed between OLW, IL_A, IL_B, FL_B and MHL_B SP plants (Table 2).

The time-course of the LW area covered by vegetation revealed differences between the lighting regimes (Fig. 3). IL_A showed the lowest vegetation cover at the end of the experiment, whereas IL_B, FL_B, MHL_B, MHL_A and FL_A were higher than the values of IL_A by 12%, 21%, 32%, 49% and 62%, respectively.

Quality attributes

The colorimetric analyses showed that leaf color of SP plants was not affected by the lighting regime (Table 4). The color index (CI) determined for this species (≈−17.8 to −22.0) reflects its characteristic leaf green color. SO leaves showed a more yellowish green color, as denoted by their higher CI values (≈−7.0 to −11.1 for all lighting regimes, except MHL_A). Under MHL_A lighting, SO leaves presented significantly higher CI values (≈+5.0) as a result of higher (and positive) *a* values, indicative of a reddish leaf tone (Table 4).

Although the colorimetric analyses did not reveal differences in leaf color of SP plants, SPAD values, a surrogate of actual chlorophyll content in the leaf, were significantly lower (≈52) in IL_A than in FL_A, FL_B and MHL_B SP plants (Fig. 4).

Vegetation surface temperature and water consumption

Vegetation surface temperature was affected by the lighting regimes (Table 5). Plants grown under IL_A and MHL_A tended to reach the highest leaf temperatures whereas MHL_B showed the lowest temperatures. Water lost by plant transpiration plus growing system evaporation expressed on a LW area basis (ET_{lw}) was significantly higher in FL_A (≈0.82 l d^{-1}) as compared to the rest of lighting regimes (Table 6). Except MHL_B with IL_A, all other comparisons showed no significant differences. When expressed per vegetation-cover unit area, plant transpiration plus substrate

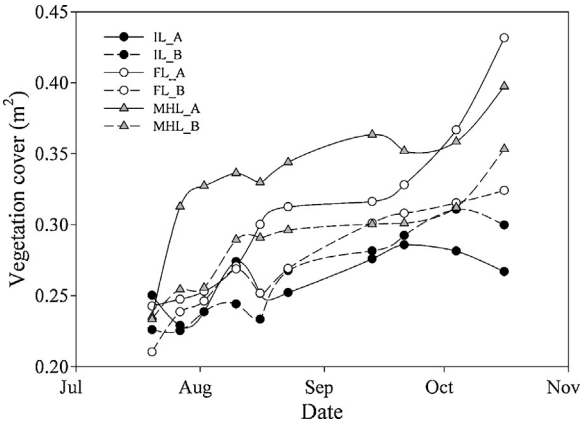

Fig. 3. Evolution of the (living-wall) area covered by vegetation in the six experimental lighting regimes.

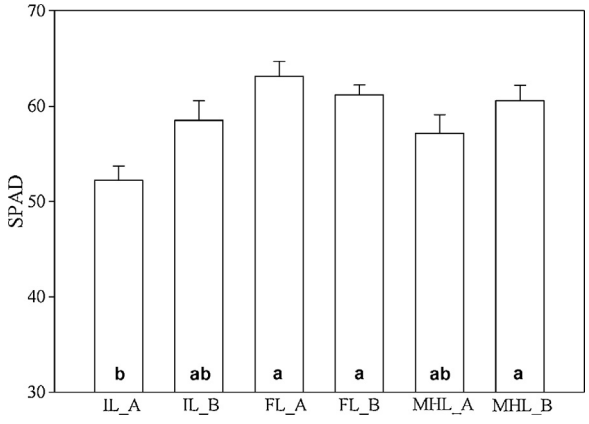

Fig. 4. Mean SPAD values measured in *Spathiphyllum* sp. about two weeks before the end of the experiment. Bars with different letters indicate significant differences according to Duncan's multiple range test ($P < 0.05$). Each value is the mean of three replicates per LW ($n = 3$).

Table 6
Daily mean evapotranspiration (ET: plant transpiration plus substrate evaporation) and total evapotranspiration (TET: ET plus reservoir evaporation) determined for the different lighting regimes over the last month of experiment. The subscripts 'lw' and 'vc' refer to water consumption expressed on a 'living wall' or 'vegetation cover' basis, respectively.

Treatment	ET_{lw} ($l\,lw^{-1}\,d^{-1}$)	ET_{vc} ($l\,m^{-2}\,d^{-1}$)	TET_{lw} ($l\,lw^{-1}\,d^{-1}$)	TET_{vc} ($l\,m^{-2}\,d^{-1}$)
IL_A	0.61b	2.31a	1.34a	5.03a
IL_B	0.55bc	1.77ab	1.01b	3.30b
FL_A	0.82a	2.22a	1.24a	3.32b
FL_B	0.51bcd	1.45ab	0.88b	2.63bc
MHL_A	0.44bcd	1.03b	0.87b	2.19c
MHL_B	0.34cd	1.14b	0.66c	2.13c
P value	<0.001	0.013	<0.001	<0.001

Within each column, mean values followed by different letters indicate significant differences according to Duncan's multiple range test (alpha = 0.05). Each value is the mean of five measurements per LW ($n = 5$).

Table 7
Annual estimation of lamps replacement and energy costs for the three tested systems.

	IL	FL	MHL
Power (W)	250	252	250
Photoperiod ($h\,d^{-1}$)	14	14	14
Lifespan (years)	0.39	1.47	2.35
Energy use (kWh/year)	1277.5	1287.7	1277.5
Mean energy cost (€/kWh)[a]	0.14	0.14	0.14
Initial cost of lamps[a] (€)	4.5	98.0	35.0
Replacement cost (€/year)	11.5	66.8	14.9
Annual energy cost (€/year)	178.9	180.3	178.9
Total annual cost (€/year)	190.0	247.0	194.0

[a] These values are approximate current local market prices. Note that these prices may considerably vary among countries.

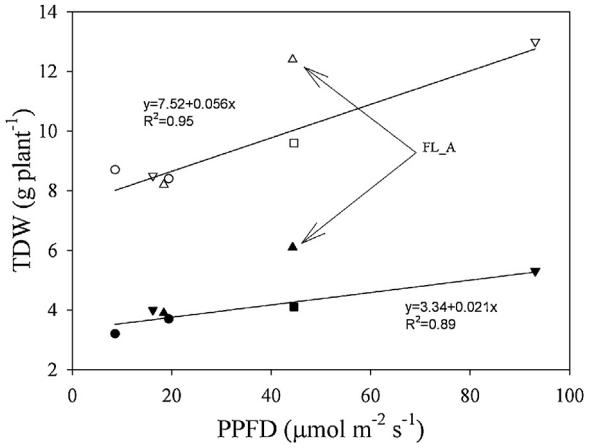

Fig. 5. Relationship between total dry weight (TDW) and the mean photosynthetic photon flux density (PPFD) for *Spathiphyllum* (open symbols) and *Soleirolia* (filled symbols) plants grown under IL (circles), FL (triangles up), MHL (triangles down) and OLW (square) lighting conditions. The straight lines represent the regression lines for both datasets when FL_A data are excluded.

evaporation (ET_{vc}) was similar in IL_A, IL_B, FL_A and FL_B lighting regimes ($ET_{vc} \approx 1.45$–$2.31\,l\,m^{-2}\,d^{-1}$), whereas ET_{vc} was significantly lower in MHL_A and MHL_B ($ET_{vc} \approx 1.03$–$1.14\,l\,m^{-2}\,d^{-1}$) as compared to IL_A and FL_A lighting regimes. Total evapotranspiration water losses (i.e. the sum of water lost by plant transpiration, growing system plus reservoir evaporation) expressed on a LW area basis (TET_{lw}) was significantly higher under IL_A and FL_A lighting systems ($TET_{lw} \approx 1.24$–$1.34\,l\,d^{-1}$), whereas MHL_B showed the lowest value ($\approx 0.66\,l\,d^{-1}$) (Table 6). When evapotranspiration losses were expressed per unit of area covered by vegetation (TET_{vc}), IL_A had the highest values ($TET_{vc} \approx 5.03\,l\,m^{-2}\,d^{-1}$), whereas MHL_A and MHL_B showed the lowest TET_{vc} values ($TET_{vc} \approx 2.13$–$2.19\,l\,m^{-2}\,d^{-1}$).

Discussion

Artificial lighting solutions for indoor LW must guarantee ornamental function while minimizing the economic resources devoted, as no direct incomes are expected from these systems. Table 7 shows an estimation of the annual cost of the three systems assessed, which is somewhat higher for FL and rather similar for IL and MHL. Regarding the ornamental LW performance, it is pertinent to point out the observed differences in lamp efficiency to yield photosynthetically active radiation. Dividing PPFD by the input power (i.e. ≈250 W) allows obtaining the lamps' PPFD efficiency at each tested distance, which was (for A lighting regime) 0.078 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (IL), 0.176 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (FL) and 0.372 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (MHL). For B lighting regime, the obtained PPFD efficiency was 0.034 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (IL), 0.073 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (FL) and 0.065 $\mu mol\,m^{-2}\,s^{-1}\,W^{-1}$ (MHL). At short distances, IL had about half the PPFD efficiency of FL while the latter had about half the PPFD efficiency of MHL. These differences in PPFD efficiency did not hold under greater distances from the light source (i.e. B lighting regime), as FL doubled IL PPFD efficiency but MHL showed slightly (≈10%) lower PPFD efficiency than FL. These results indicate that, irrespective of the lighting system used, LW design must account for the existing vertical light gradient by planting species with lower light requirements in the LW zones with lower illuminance, and by avoiding species with high vegetative vigor in the upper LW zones that may shade the lower LW zones.

Plant biomass production has commonly been reported to be linearly related to intercepted photosynhtetically active radiation (e.g. Monteith, 1977; Dewar, 1996). Our results also support this experimental evidence as whole plant dry weight at the end of the trial was linearly related to mean PPFD reaching each LW (Fig. 5). However, it can be observed that, for a given PPFD, FL increased plant growth as compared to MHL, IL and diffuse natural illumination (OLW). Nevertheless, the better performance of FL was not observed at any PPFD, but plants grown at PPFD values below $\approx 45\,\mu mol\,m^{-2}\,s^{-1}$ (i.e. greater distance to light source) behaved similarly to plants grown under IL and MHL receiving similar PPFD. In any case, plant growth was, to some extent, sensitive to light quality in both species. However, plants sensitivity to light quality seems to be species-dependent, as there are species that are strongly influenced by spectrum quality (Goto, 2003) while others have small or no response to modifications in the light spectrum for a similar PPFD (Aphalo and Letho, 1997).

Changes in plant structural and physiological traits are commonly observed in the acclimation process of plants to growth irradiance (Egea et al., 2012). Particularly, aerial-to-root ratio (ADW/RDW) has been reported to increase with decreasing irradiance (Fetcher et al., 1983; Valladares et al., 2005), in agreement with our observations for SP plants grown under MHL which had a greater PPFD gradient (76.9 $\mu mol\,m^{-2}\,s^{-1}$) between A and B zones

(Table 2). This also led to significant SLW changes in SO plants (Table 3), responding to a well-reported adaptive mechanism of plants to low irradiance levels (e.g. Marini and Sowers, 1990; Valladares et al., 2000).

Other adaptive mechanisms to varying irradiance levels have been reported for some plant species. For instance, the amount of leaf nitrogen allocated to chlorophylls has been shown either to increase (Lichtenthaler et al., 2007) or drop (Montpied et al., 2009) with decreasing natural irradiance levels. Besides the biochemical implications, variations in leaf pigment contents with lighting regime may also have consequences on some quality (e.g. plant color) attributes of ornamental plant species. In our case study, leaf color was little affected by the different artificial and natural lighting regimes (Table 4). The tendency toward a more reddish leaf color of MHL_A SO plants (Table 4), probably due to an increased vegetative anthocyanin pigmentation (Albert et al., 2009), may be ascribed to the inherent spectral quality differences among the lighting systems. Unlike IL and FL lamps, MHL produce a high energy fraction in the near UV-blue region (Yorio et al., 1995). Exposure to near UV (UV-A) radiation (300–400 nm) is known to promote the synthesis of leaf anthocyanins (Li and Kubota, 2009), which are used by shade-adapted species as photo-protectors (Close and Beadle, 2003).

Water consumption was markedly affected by the lighting regimes (Table 6). The driving forces for evapotranspiration (ET) can be of advective and radiative nature (Allen et al., 1998). As the experiment was performed under controlled laboratory conditions, the advective component of ET (strongly wind speed dependent) is expected to be of low relative importance and similar among the lighting regimes. Thus, the observed ET differences are expected to result from differences in the radiative component of ET. As no clear relationship can be established between the amounts of visible radiation reaching each LW (Table 1) and water consumption (Table 6), it is argued that the energy fractions that lamps are 'losing' as heat are responsible for the observed ET differences. Heat losses matches inversely with lamps' light efficiency, being higher in MHL (≈80 lm/W), followed by FL (≈25 lm/W) and IL (≈12 lm/W). When expressed per unit of area covered by vegetation, TET was higher under IL, followed by FL and MHL, which agrees with the hypothesis that lamp heat losses are causing the observed TET differences.

LED lamps may present lower impact on LW water consumption, as they have lower radiant heat losses than conventional lamps. Given that LED technology is rapidly progressing both in cost and providing solutions for multiple applications, a follow-up research study will examine LW performance under conventional (e.g. FL and MHL) and LED lighting systems. Nevertheless, it should be noted that available commercial LED solutions for horticulture emitting in a narrow spectrum of light to minimize energy wastage are not recommended for plants that are required to be viewed (e.g. indoor LW) because they give plants an unnatural appearance. Broader spectrum LED lamps would therefore be preferable to be used in LW, although it will probably reduce their energy efficiency advantage.

Conclusions

The three artificial lighting systems assessed showed differing LW performances. For the same input electric power of ≈250 W, differences in plant growth were only observed at distances of about 1 m from the light source but not at greater distances (≈1.5 m). Despite the lower PPFD efficiency of FL against MHL, FL light composition allowed that plants grown in the upper LW (closer to light source) reached a similar size to plants grown under MHL. Plant quality attributes were generally not affected by light type or distance to the light source. However, important differences were observed in water consumption. IL and FL generated similar and higher total (i.e. transpiration plus evaporation) water losses than MHL when expressed per LW. FL and MHL reduced water consumption as compared to IL by 34% and 56%, respectively, when expressed per unit of LW area covered by vegetation. In summary, our results indicate that both FL and MHL outperform IL and have a similar ornamental performance, whereas MHL are more advantageous than FL in terms of water consumption and annual cost.

Acknowledgments

The work was funded by the University of Seville (project 238/US Research Program). We thank the spin-off company *Terapia Urbana* (Seville, Spain) for providing the materials to build the living walls prototypes. We are also grateful to Dr. Manuel Pérez-Ruiz (US) and Dr. Alfonso Moriana-Elvira (US) who kindly lent the Infrared thermometer and PAR sensor, respectively. Finally, we thank two anonymous reviewers for their useful comments that have helped to improve the manuscript.

References

Abramoff, M.D., Magalhaes, P.J., Ram, S.J., 2004. Image processing with ImageJ. Biophoton. Int. 11, 36–42.
Albert, N.W., Lewis, D.H., Zhang, H., Irving, L.J., Jameson, P.E., Davies, K.M., 2009. Light-induced vegetative anthocyanin pigmentation in *Petunia*. J. Exp. Bot. 60, 2191–2202.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation Drainage Paper No. 56. FAO, Rome, Italy.
Aman, M.M., Jasmon, G.B., Mokhlis, H., Bakar, A.H.A., 2013. Analysis of the performance of domestic lighting lamps. Energy Policy 52, 482–500.
Aphalo, P.J., Letho, T., 1997. Effects of light quality on growth and N accumulation in birch seedlings. Tree Physiol. 17, 125–132.
Bashan, Y., de-Bashan, L.E., 2005. Fresh-weight measurements of roots provide inaccurate estimates of the effects of plant growth-promoting bacteria on root growth: a critical examination. Soil Biol. Biochem. 37, 1795–1804.
Close, D.C., Beadle, C.L., 2003. The ecophysiology of foliar anthocyanin. Bot. Rev. 69, 149–161.
Dewar, R.C., 1996. The correlation between plant growth and intercepted radiation: an interpretation in terms of optimal plant nitrogen content. Ann. Bot. 78, 125–136.
Egea, G., González-Real, M.M., Baille, A., Nortes, P.A., Conesa, M.R., Ruiz-Salleres, I., 2012. Effects of water stress on irradiance acclimation of leaf traits in almond trees. Tree Physiol. 32, 450–463.
Feng, C., Feng, H., Jin, S., Gao, J., 2005. The research of lamp for the growing of green plants. Proc. SPIE – Int. Soc. Opt. Eng. 2005, 192–197.
Fernández-Cañero, R., Urrestarazu, L.P., Franco-Salas, A., 2012. Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate. Indoor Built Environ. 21, 642–650.
Fetcher, N., Strain, B.R., Oberbauer, S.F., 1983. Effects of light regime on the growth, leaf morphology, and water relations of seedlings of two species of tropical trees. Oecologia 58, 314–319.
Francis, R.A., Lorimer, J., 2011. Urban reconciliation ecology: the potential of living roofs and walls. J. Environ. Manage. 92, 1429–1437.
Goto, E., 2003. Effects of light quality on growth of crop plants under artificial lighting. Environ. Control Biol. 41, 121–132.
Hopkins, W.G., 1999. Introduction to Plant Physiology, 2nd ed. John Wiley & Sons, Inc., New York, NY.
Khan, N., Abas, N., 2011. Comparative study of energy saving light sources. Renew. Sustain. Energy Rev. 15, 296–309.
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. Build. Environ. 45, 1287–1303.
Li, Q., Kubota, C., 2009. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ. Exp. Bot. 67, 59–64.
Lichtenthaler, H.K., Ac, A., Marek, M.V., Kalina, J., Urban, O., 2007. Differences in pigment composition, photosynthetic rates and chlorophyll fluorescence images of sun and shade leaves of four tree species. Plant Physiol. Biochem. 45, 577–588.
Loh, S., 2008. Living Walls – A Way to Green the Built Environment. BEDP Environment Design Guide. ACT, Australia, pp. 1–7, Retrieved from http://www.environmentdesignguide.net.au/media/TEC26.pdf (04.110.13).
Marini, R.P., Sowers, D.L., 1990. Net photosynthesis, specific leaf weight, and flowering of peach as influenced by shade. HortScience 25, 331–334.
Mattson, N.S., Erwin, J.E., 2005. The impact of photoperiod and irradiance on flowering of several herbaceous ornamentals. Sci. Hortic. 104, 275–292.
Missouri Botanical Garden, 2013. *Spathiphyllum* (group) – Plant Finder, Retrieved from http://www.missouribotanicalgarden.org (13.11.13).
Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. Lond. Ser. B 281, 277–294.

Montpied, P., Granier, A., Dreyer, E., 2009. Seasonal time-course of gradients of photosynthetic capacity and mesophyll conductance to CO_2 across a beech (*Fagus sylvatica* L.) canopy. J. Exp. Bot. 60, 2407–2418.
Morrow, R.C., 2008. LED lighting in horticulture. HortScience 43, 1947–1950.
Mortensen, L.M., Fjeld, L., 1998. Effects of air humidity, lighting period and lamp type on growth and vase life of roses. Sci. Hortic. 73, 229–237.
Mortensen, L.M., Gislerød, H.R., 1999. Influence of air humidity and lighting period on growth, vase life and water relations of 14 rose cultivars. Sci. Hortic. 82, 289–298.
Mortensen, L.M., Grimstad, S.O., 1990. The effect of lighting period and photon flux density on growth of six foliage plants. Sci. Hortic. 41, 337–342.
Niinemets, Ü., 2006. The controversy over traits conferring shade-tolerance in trees: ontogenetic changes revisited. J. Ecol. 94, 464–470.
Olle, M., Virsile, A., 2013. The effects of light-emitting diode lighting on greenhouse plant growth and quality. Agric. Food Sci. 22, 223–234.
Pérez-Urrestarazu, L., Egea, G., Franco-Salas, A., Fernández-Cañero, R., 2014. Irrigation systems evaluation for living walls. J. Irrig. Drain. Eng. 140, 04013024.
Pinho, P., Jokinen, K., Halonen, L., 2012. Horticultural lighting – present and future challenges. Light. Res. Technol. 44, 427–437.
Royal Horticultural Society, 1990. RHS Plant Selector *Soleirolia soleirolii*, Retrieved from http://apps.rhs.org.uk (13.11.13).
Thiel, S., Dohring, T., Kofferlein, M., Kosak, A., Martin, P., Seidlitz, H.K., 1996. A Phytotron for plant stress research: how far can artificial lighting compare to natural sunlight? J. Plant Physiol. 148, 456–463.
Thimijan, R.W., Heins, R.D., 1983. Photometric, radiometric, and quantum light units of measure: a review of procedures for interconversion. HortScience 18, 818–822.
Valladares, F., Arrieta, S., Aranda, I., Lorenzo, D., Sánchez-Gómez, D., Tena, D., Suárez, F., Pardos, A., 2005. Shade tolerance, photoinhibition sensitivity and phenotypic plasticity of Ilex aquifolium in continental Mediterranean sites. Tree Physiol. 25, 1041–1052.
Valladares, F., Wright, S.J., Lasso, E., Kitajima, K., Pearcy, R.W., 2000. Plastic phenotypic response to light of 16 congeneric shrubs from a Panamanian rainforest. Ecology 81, 1925–1936.
Wheeler, R.M., Mackowiak, C.L., Sager, J.C., 1991. Soybean stem growth under high-pressure sodium with supplemental blue lighting. Agron. J. 83, 903–906.
Yeh, N., Chung, J., 2009. High-brightness LEDs – energy efficient lighting sources and their potential in indoor plant cultivation. Renew. Sustain. Energy Rev. 13, 2175–2180.
Yen, H., Lee, C., Chan, S., 2013. Artificial-lighting sources for plant growth. Proc. Int. Conf. Power Electron. Drive Syst. 2013, 799–803.
Yorio, N.C., Mackoviak, C.L., Wheeler, R.M., Sager, J.C., 1995. Vegetative growth of potato under high-pressure sodium, high-pressure sodium SON-Agro, and Metal Halide lamps. HortScience 30, 374–376.