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Lighting systems evaluation for indoor living walls

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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).

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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

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