University of Seville

Higher Technical School of Agronomic Engineering

Doctoral Thesis

Assessment and optimization of felt living walls in terms of water retention performance and artificial lighting

Author: Maria Pinelopi E. Kaltsidi

Directors: Dr. Luis Pérez Urrestarazu and Dr. Rafael Fernández Cañero

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TESIS DOCTORAL

“Estudio y optimización de la retención de agua y la iluminación artificial en jardines verticales textiles”

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Dr. Luis Pérez Urrestarazu and Dr. Rafael Fernández Cañero, supervisors of this Thesis, certify that it is ready to be presented.

Seville, 2020

Supervisors' signature

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The current doctoral thesis meets the requirement established by the University of Seville for its presentation as a compendium of articles, consisting of a minimum of two articles published in scientific journals included in the first three quartiles of the list of journals in the field of specialty and referenced in the latest data published by the Journal Citations Report (JCR):

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Abstract

Living walls, also referred as green walls or vertical gardens, are becoming a new reality worldwide, mainly in urban areas where the need to increase and enhance green spaces is of vital importance. Green infrastructures, such as living wall systems, can act as additional tools for improving the densely built cities' sustainability or even as a unique choice, in combination with green roof technology, in the case of the complete absence of appropriate terrestrial open spaces where community gardens, parks, urban forests and natural meadows could be installed. Thus, there are various commercial living wall systems and companies R&D departments promoting several innovative technologies. One of their objectives is to enable an adequate development of the living wall vegetation cover with low cost and maintenance needs, ensuring an aesthetically successful and high quality performance in the long term.

During the current doctoral thesis, Fytotextile®, a patented felt- based system, and its evolutions were studied in order to assess and optimize their performance in indoor and outdoor living wall installations. Therefore, two studies were conducted in order to evaluate the water management performance of four felt- based living wall systems and to optimize the living wall systems in terms of auxiliary illumination needs.

The first study, entitled "Improving the performance of felt- based living wall systems in terms of irrigation management" and published in the journal *Urban Forestry & Urban Greening*, focused on filling the knowledge gap on the performance of the commercial felt- based living wall system´s irrigation in terms of water management. Hence, the performance of the Fytotextile® commercial living wall system and of three new evolutions based on it was assessed based on the water retention capacity, drying speed and drainage rate, as well as plant performance. The results of the present study highlight (a) the potential of the materials used on felt- based living wall systems to contribute to the improvement of water management with a sustainable approach, (b) the importance of the implementation of the appropriate irrigation schedules and (c) the limited research on the specific field. Specifically, the Fytotextile system with a very highly absorbent engineered polymer fibre blanket (Fytotextile 4) and 4 mm thick

geotextile, revealed the most increased capacity to store irrigation water compared to the other three Fytotextile systems. Fytotextile with 4mm thick geotextile (Fytotextile 2) produced the smallest drainage volume in all irrigation schedules. However, all Fytotextile types seemed to be adequate to house the three different vegetation types used (*Erodium* x *variabile* 'Roseum', *Carex oshimensis 'Evergold'*, *Lavandula dentata*), maintaining an elevated aesthetically result in the short term. *Erodium* x *variabile* 'Roseum' presented the most satisfactory performance in all Fytotextile systems while *Lavandula dentata* the least robust. Finally, it is suggested the construction of living walls with suitable and tested materials that can support long life systems with the minimum losses in terms of water and materials (e.g. vegetation, geotextiles) in order to be effective in delivering the desired results.

During the second study, entitled "Assessment of different LED lighting systems for indoor living walls" and published in the journal *Scientia Horticulturae*, six commercial light- emitting diode (LED) lamps (Aster and Dahlia of Ignia Green, Logar CMH, CLH and Forum of Lledó, CF- UT01 of Panda Grow) for indoor installations were evaluated to determine their suitability and efficiency in the performance of living wall systems. CF- UT01 was the only projector designed for plant growth. The evaluation of the illumination was based on lighting pattern, temperature/ water consumption and effect on vegetation performance, along with the observers' perception for the visual quality of the light. Specifically, two indoor studies were carried out using the Fytotextile® system completely sheltered from sun exposure and two commonly used plant types in indoor living walls (*Soleirolia soleirolii* and *Spathiphyllum wallisii*). According to the findings of this study, Illuminance (as luminous flux per unit area) and PPFD were found to be positively correlated to the height of the module for each pocket. Logar CLH Superflood lamp presented the highest value for both traits, while the lowest values were attributed to CF- UT01 lamp. The living wall receiving the Dahlia illumination exhibited the most elevated average daily water consumption and Logar CMH Superflood the lowest. CF- UT01 projector was the only one not characterized as suitable for indoor living walls. Aster and Logar CMH Superflood performed poorly when placed farther from the module and Dahlia was the one that received the highest preference among questionees. Finally, it is highlighted that parameters such as the projector distance from the living wall infrastructure, its orientation, beam angle, energy consumption and the preferable visual quality of the light by the public should also be taken into consideration when evaluating the efficiency of lighting systems.

Resumen

Los jardines verticales, también denominados fachadas ajardinadas o muros verdes, se están convirtiendo en una nueva realidad en todo el mundo, principalmente en áreas urbanas donde la necesidad de aumentar y mejorar los espacios verdes es de vital importancia. Las infraestructuras verdes, como los sistemas de jardines verticales, pueden actuar como herramientas adicionales o incluso como una opción única para mejorar la sostenibilidad de las ciudades densamente construidas, también en combinación con la tecnología de techos verdes, en el caso de la ausencia total de superficie disponible donde poder instalar jardines comunitarios, parques, bosques urbanos y prados naturales.

En consecuencia, existen varios sistemas comerciales de jardines verticales y departamentos de I+D de empresas que promueven varias tecnologías innovadoras. Uno de sus objetivos es posibilitar un adecuado desarrollo de la cubierta vegetal de los jardines verticales con bajo coste y reducidas necesidades de mantenimiento, asegurando un desarrollo adecuado de la vegetación a largo plazo.

En la actual tesis doctoral se estudió el Fytotextile®, un sistema patentado a base de fieltro, y sus evoluciones, para evaluar y optimizar su rendimiento en instalaciones de jardines verticales interiores y exteriores. Por lo tanto, se llevaron a cabo dos estudios con el fin de evaluar el comportamiento en la gestión del agua de cuatro sistemas de jardines verticales de fieltro, y optimizar los sistemas de los jardines verticales en términos de necesidades de iluminación auxiliar.

El primer estudio, titulado "Improving the performance of felt- based living wall systems in terms of irrigation management" y publicado en la revista *Urban Forestry & Urban Greening*, se centró en llenar un vacío de conocimiento sobre el rendimiento de los sistemas de riego de jardines verticales comerciales de fieltro en términos de gestión del agua. Por lo tanto, se evaluó el comportamiento del sistema de jardín vertical comercial Fytotextile®, y de tres nuevas evoluciones de éste, con respecto a la capacidad de retención de agua, velocidad de secado y volumen de drenaje, así como el desarrollo de la planta. Los resultados del presente estudio destacan (a) el potencial de los

materiales utilizados en los sistemas de muros vegetales basados en fieltro para contribuir a la mejora de la gestión del agua con un enfoque sostenible, (b) la importancia de la implementación de programas de riego adecuados y (c) la limitada investigación desarrollada en este campo específico. Específicamente, el sistema Fytotextile con una manta de fibra de polímero muy absorbente (Fytotextile 4) y un geotextil de 4 mm de espesor, demostró una mayor capacidad para almacenar agua de riego en comparación con los otros tres sistemas Fytotextile. El Fytotextile con geotextil de 4 mm de espesor (Fytotextile 2) produjo el menor volumen de drenaje para todas las programaciones de riego. Por otro lado, las tres especies testadas (*Erodium* x variabile 'Roseum', *Carex oshimensis* 'Evergold', *Lavandula dentata*) funcionaron correctamente en todos los tipos de Fytotextiles, manteniendo un resultado estético elevado a corto plazo. *Erodium* x variabile 'Roseum' presentó el comportamiento más satisfactorio en todos los sistemas de Fytotextile mientras que para *Lavandula dentata* fue más deficiente. Finalmente, se sugiere la construcción de jardines verticales con materiales adecuados y testados, que puedan constituir sistemas de larga duración, que minimicen el uso de agua y materiales (por ejemplo, vegetación, geotextiles) para que sean eficientes en la obtención de los resultados deseados.

En el segundo estudio, titulado "Assessment of different LED lighting systems for indoor living walls" y publicado en la revista *Scientia Horticulturae*, seis lámparas comerciales de diodos emisores de luz (LED) (Aster y Dahlia de Ignia Green, Logar CMH, CLH y Forum de Lledó, CF- UT01 de Panda Grow), comúnmente usadas para instalaciones interiores, fueron evaluadas para determinar su idoneidad y eficiencia en el comportamiento de los sistemas de jardinería vertical. CF- UT01 fue el único proyector específicamente diseñado para el crecimiento de plantas. La evaluación de la iluminación se basó en el patrón de iluminación, el consumo de agua, la temperatura generada y el efecto sobre el comportamiento de la vegetación, junto con la percepción de los observadores de la calidad visual de la luz. Específicamente, se llevaron a cabo dos estudios en interiores, completamente protegidos de la exposición al sol, utilizando el sistema Fytotextile®, y dos tipos de plantas de uso común en interiores (*Soleirolia soleirolii* y *Spathiphyllum wallisii*). De acuerdo con los resultados de este estudio, se pudo determinar que la iluminancia (como flujo luminoso por unidad de área) y el PPFD estaban correlacionados positivamente con la altura del módulo para cada bolsillo. La lámpara Logar CLH Superflood presentó el valor más alto para ambos rasgos, mientras que los valores más bajos se atribuyeron a la lámpara CF- UT01. El jardín vertical que recibió la iluminación de Dahlia exhibió el consumo de agua medio diario más elevado, y Logar CMH Superflood el más bajo. El proyector CF- UT01 fue el único que demostró no ser adecuado para jardines interiores. Aster y Logar CMH Superflood tuvieron un comportamiento deficiente cuando se colocaron más lejos del módulo, y Dahlia fue la que recibió una mayor calificación entre los encuestados. Finalmente, se puede destacar que parámetros como la distancia del proyector a la infraestructura del jardín vertical, su orientación, ángulo de haz, consumo de energía y la calidad visual también deben tenerse en cuenta al evaluar la eficiencia de los sistemas de iluminación.

1. Introduction

1.1. Urbanization and vertical greening systems

An elevated percentage of the words' population lives in urban areas and according to United Nations Department of Economic and Social Affairs (UN DESA, 2018) in 2018 this percentage reached 55% and it is expected to increase to 68% by 2050. In this continuous urbanization, the key factor for the successful development of urban growth is the sustainable approach.

Referring to a sustainable approach that leads to a better quality of urban life, one of the challenges to be faced is the enrichment of the urban areas with green spaces. The development of urban forests, community gardens, natural meadows, wetlands, increased number of trees and shrubs, parks and landscaped streets, squares, green roofs, and vertical greening systems profoundly ameliorates the appearance and the environmental quality (e.g. biodiversity) of urban areas. According to Lynne M. Westphal (2003) green spaces can improve the quality of life with their impact on social issues such as health care, education, crime and economic development.

The conceptualization of increasing green spaces areas and reforming the densely built urban environment led to the evolution of applied technologies such as green roofs and vertical greening systems which allowed using the surface of the buildings to locate vegetation. However, the vertical greening systems are frequently subjected to criticism regarding their maintenance, installation and maintenance cost and the environmental sustainability focusing on the materials and the water usage (Manso and Castro-Gomes, 2015; Riley, 2017).

It is difficult to determine the origin of the vertical greening systems however there are literary references, fabrics and works of art that allow us to hypothesize their existence. A first reference that may combine green roofs and potential green facades (hanging plants) could be found in the Hanging Gardens of Babylon, one of the seven wonders of the ancient world, even if their existence is questionable. There are important documentary sources that could certify their existence such as Ktisias` (late 5th- early 4th century BC) book "*Persian*" ("*Περσικά*") and Strabo` (*64* BC- *24* BC) book "*The Geography of Strabo*" (*"Η Γεωγραφία του Στράβωνα"*) and Plutarch (45-120 AD) in "*Parallel Lives*" ("*Βίοι Παράλληλοι*") (Sikeliotis, 1396; Curtius, 1932). Later, various civilizations worldwide used climbing plants to cover buildings or facades. According to Pérez-Urrestarazu et al. (2015) living walls were potentially inspired by the epiphytic plant growth in the tropical forests and Hopkins and Goodwin (2011) mentioned that one of the main reasons living wall systems begun to develop was the need for shade in extreme climatic conditions in combination with aesthetically pleasing vegetation performance. Nowadays, Patrick Blanc, a French botanist, is considered the modern innovator of the living wall systems, initially named “Mur *Végétal”* (hydroponic felt system).

1.2. Types of living wall systems

Given the fact the living wall systems are a rapidly evolving technology currently on the rise, classification is not a common ground among scientists and marketing stakeholders (Loh, 2008; Manso and Castro-Gomes, 2015; Medl et al., 2017; Ascione et al., 2020). Living walls also referred to as green walls or even vertical gardens are advanced systems enveloping buildings or facades (slightly inclined or not) indoors or outdoors characterized by vegetation with the root system integrated in the vertical system (Loh, 2008; Pérez-Urrestarazu et al., 2015; Medl et al., 2017). The materials of the surfaces where living walls are fixed vary among concrete, concrete masonry unit (CMU), wood or metal frames or even structural steel. Based on the application method living walls can be classified into continuous (light and permeable layers planted in situ e.g. geotextile, polyamide) or modular (various elements with specific dimensions, frequently pre- planted) connected to the buildings´ walls by means of a substructure (e.g. galvanized stainless steel, timber) or even directly fixed (Manso and Castro-Gomes, 2015). Living walls may as well be divided into two main categories depending on the material used (Fig. 1), namely felt or cloth systems (*Fytotextile by Terapia Urbana, i-panel by Verdtical, Mur Végétal by Patrick Blanc, Pocket Panels Florafert*), and boxes or panel (e.g. *Biotexture, Ansglobal, Sagegreenlife*, *Mobilane, Sempergreen*) planted in situ or even frequently pre- planted. However, commercially there are several subcategories promoted as living walls (e.g. *gsky*, *NextGen*, DIY modular units by *Planter Designs, Botanicus, Windowbox, Mobilane, Maruja Fuentes Fuse Nature & Décor, Mercury Mosaics*).

Felt or cloth systems, can be continuous or modular and consist of flexible multilayer connected to a substructure fixed on a supporting wall. The various layers allow the aeration of the roots, the distribution of the irrigation water and the prevention of moisture problems in the supporting wall (waterproof layer). The plants may be housed in pockets with the initial potted growing medium (semi- hydroponic systems) or can be placed bare rooted directly into individual cuttings of the layers (hydroponic system) while additional nutrients are distributed through the irrigation system.

The boxes or panel systems are modular, mainly not flexible systems which consist of materials such as rockwool blocks, coco fiber blocks, rock fiber, sphagnum, where plants are housed in specified cavities. In most of the cases, the blocks are pre- planted maintaining the initial pot substrate and fixed on the structural system in situ with an irrigation system installed (Loh, 2008).

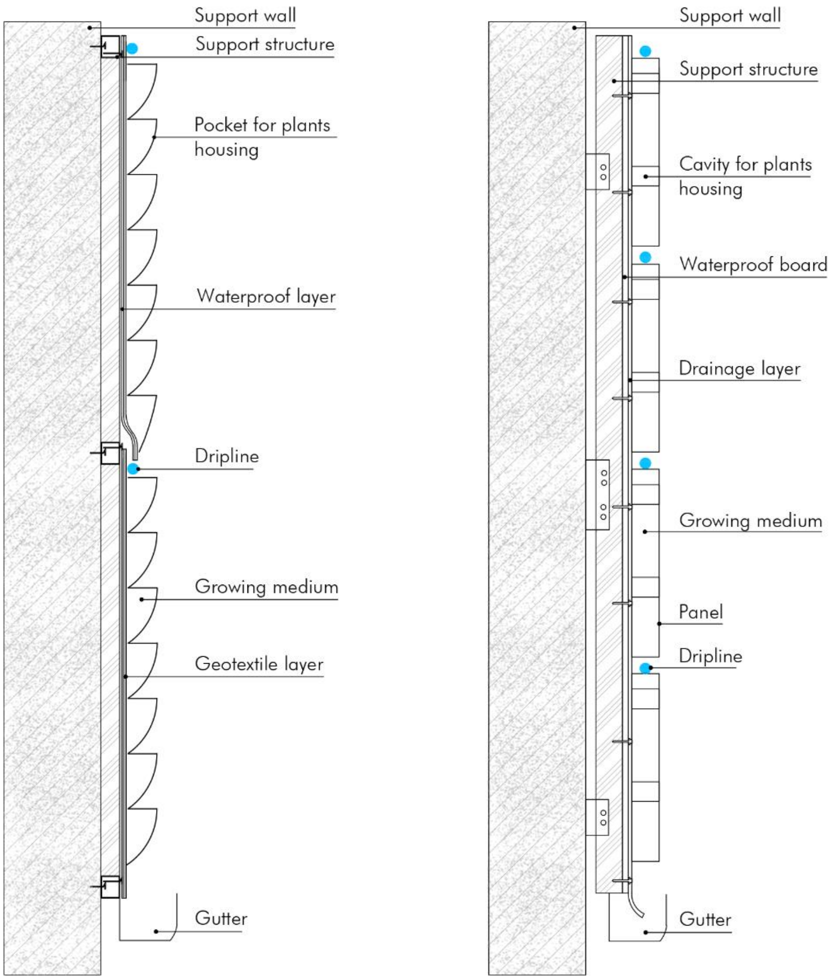

Figure 1. Examples of different living wall systems; left a felt or cloth system and right a panel or box system (figure by Maria Pinelopi Kaltsidi)

Some authors mention some subcategories that are considered to belong to the category of modular living wall systems and consist of containers, and/or trellis system, trays, vessels, planter tiles (Loh, 2008; Manso and Castro-Gomes, 2015). In these systems, plants are grown in containers or placed directly with the pot into the system and in some cases climb onto trellises.

1.3. Benefits and barriers of indoor and outdoor living wall systems

Both outdoor and indoor living wall systems present considerable advantages that drive their ongoing rise as a novel approach to urban greening. According to our knowledge of the existing literature (Loh, 2008; Ottelé et al., 2010; Perini et al., 2011a; b, 2017; Coma et al., 2017; Medl et al., 2017; Ascione et al., 2020), living walls have been found to:

- lower energy consumption of the building and, therefore, greenhouse gas emissions
- increase the thermal performance of buildings, thus lowering energy costs
- reduce the Urban Heat Island (UHI) effect
- have a beneficial effect on hydrology and improve Water Sensitive Urban Design (WSUD)
- improve air quality by filtering particles
- reduce noise pollution
- increase urban biodiversity and urban food production
- improve health and well- being (biophilia)

However, the vast implementation of living wall systems faces several barriers, at least regarding the current development of this technology. The major drawbacks of living walls can be summarized as follows (Ottelé et al., 2011; Perini et al., 2011b; Manso and Castro-Gomes, 2015; Ascione et al., 2020):

- high investment/ installation cost
- complex implementation that demands highly- trained personnel for the design and installation
- high maintenance cost due to the need for frequent maintenance

- in some cases, high water and nutrients consumption that may increase the environmental burden of some materials
- unavailability of a shared constructive standard
- difficult understanding of not uniform experimental results
- absence of tested and certified commercial simulation models

Though the aforementioned assets and liabilities are common to all living wall systems, their intensity varies among the different types and also in reference to distinct technical and/ or vegetation traits (Mårtensson et al., 2014; Pérez-Urrestarazu et al., 2014; Lausen et al., 2020). Such variability highlights the imperative need of careful and detailed design of living wall systems in order to accomplish the desired outcome, while it also pinpoints the need for further research on the multivariate response of living wall systems under different conditions.

The specific characteristics of each living wall type give rise to distinct advantages and disadvantages (Perini et al., 2011b; Manso and Castro-Gomes, 2015). Continuous systems offer higher plant growth and water/ nutrients distribution uniformity, while, in modular systems, the size of the module represents a barrier. Moreover, continuous systems are a lightweight option when compared to modular systems that are generally heavier. On the contrary, modular systems can be easily disassembled when needed for maintenance purposes and they also allow a higher control over irrigation, nutrition and drainage.

It is worth mentioning that while common to both outdoor and indoor living wall systems, the needs for irrigation and lightning present different peculiarities. Therefore, water management can be more challenging in the case of outdoor living walls, which are further exposed to changing and difficult to control environmental factors. On the other hand, the lighting requirements of indoor living wall systems, often located in places characterized by low exposure or even absence of natural light, make the use of artificial lighting systems necessary.

1.4. Water management of living wall systems

1.4.1. Water requirements

Water is an essential factor to ensure plant survival and robust growth, thus water management is of utmost importance when designing and maintaining any vegetation system. However, fulfilling the water requirements of a living wall can be more complex due to the particular characteristics of the specific system.

Indoor living walls cover exclusively their water needs by means of irrigation in a relatively stable environment (room temperature, stable relative humidity, illumination). However, irrigation for outdoor living wall systems needs to be carefully programmed taking into account the microclimatic conditions that vary during the year and the location (precipitation events, hours of direct sunlight, exposure, relative humidity, average, max. and min. temperature). In general, the diverse outdoor living wall systems present little or none horizontal area where water could be stored, thus plants can use solely the amount of water retained by the substrate and/ or the porous supporting structure (Pérez-Urrestarazu et al., 2019). Along with the location of a living wall (indoors or outdoors and its orientation) and the climatic conditions, the plant selection and the substrate employed affect water needs and irrigation requirements. The plant palette of a living wall may consist of plants that prefer well or poorly drained, constantly moist or not, growing medium. On the other hand, apart from the synthetic material used on living wall, the composition of the growing medium such us peat, coconut coir, perlite, rockwool etc. affects the frequency and the duration of an irrigation program.

An additional fact that should be taken into consideration when estimating water requirements is that the plants are cultivated for their ornamental and aesthetic value. Therefore, irrigation should be designed in order to reassure the healthy appearance of the vegetation and coverage of the wall, not prioritizing biomass production, as it is the case for most cultivated plants. An unsuccessfully designed irrigation programming may lead to significant water waste and anti- environmental, non- ecological and unsustainable approach, as well as an elevated cost due to high maintenance demands (frequent inspection and maintenance visits, increased labor hours, plant pruning or replacement, substrate filling, high susceptibility to pests and diseases).

1.4.2. Irrigation systems

Each type of living wall system dictates the design and application of distinct irrigations systems that will reassure a robust water management specifically adapted to the specific features of each living wall type. However, apart from their differences, the majority of the irrigation systems (built in or not) used for living walls have as common trait their high dependence from gravity (Pérez-Urrestarazu et al., 2019), thus demanding more complex solutions in order to mitigate water losses due to runoff and percolation and to achieve a uniform water distribution along the living wall. An appropriate irrigation guarantees an adequate homogeneous water supply and nutrients (fertirrigation) to the entire surface of each system and their availability to the plants.

There are two irrigation designs for living walls, namely recycled/ recirculating and run- to- waste. The recycled solution consists of a closed circuit connected to a tank where runoff from the irrigation events is collected at the bottom of the living wall and reused. A run- to- waste system, usually recommended for small and medium sized living walls, is connected to a water supply and the excess of water goes directly to the drain so the irrigation water is used solely once.

The most common irrigation system in the different living wall types is the drip irrigation (Fig. 2). Drip emitters or drippers are normally inserted directly to the mainline or through thinner tubing using a straight connector at its base. Pressure- compensating emitters are suggested due to their capacity to deliver a precise amount of water even in the change of water pressure, though it depends on the water flow (4, 2, 1.5 L h^{-1}). The drip emitters release water to the upper level and at different levels depending on the size of the living wall. Therefore, the water can move vertically downwards due to the gravity and laterally between lines by diffusion (Pérez-Urrestarazu et al., 2014).

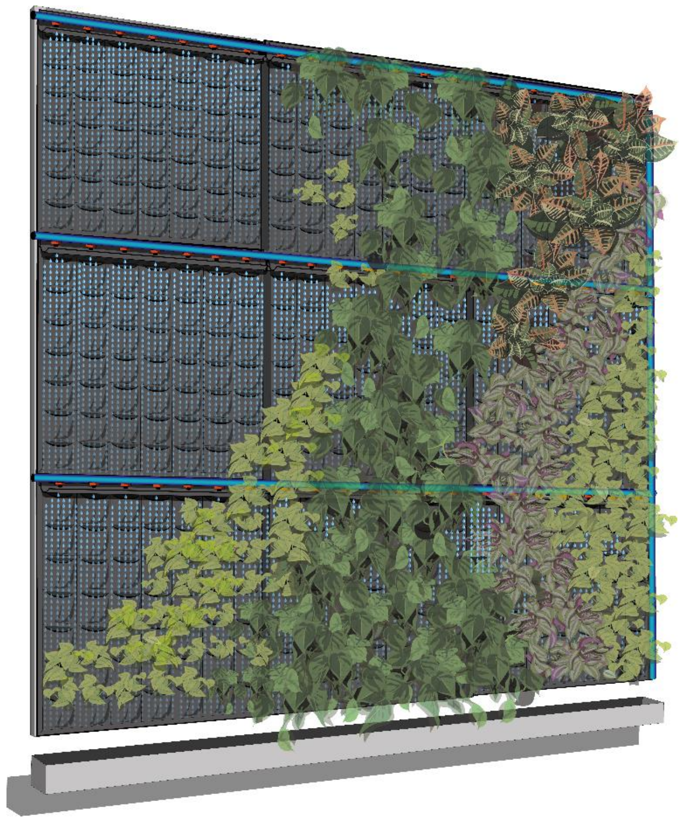

Figure 2. Drip irrigation system example with driplines placed on the top of each module of the felt- based Fytotextile system (Photo courtesy of Terapia Urabana L.S., image modified by Maria Pinelopi Kaltsidi)

There are more irrigation systems less frequently applied, such as exudative irrigation systems which can be used in small sized living. They consist of tubes which exude water through the tiny pores of the textile porous pipe and produce a continuous and uniform strip of moisture along the irrigation lines. Moreover, there are systems where plants receive water and nutrients through the capillary action when the cloth comes in contact with the irrigation water and the roots intertwine with the cloth. Another irrigation system is applied, in the case of trays, where the irrigation water is collected in the trays with the located potted plants and the substrate absorbs the water from the openings of the bottom of the pot and overflow drain to the tray below. Drainage lines can be connected directly to the trays assuring neat and spotless foliage.

1.4.3. Water retention and irrigation scheduling

The water retention capacity of a living wall system depends on the characteristics of the morphology of each system. The layers, for instance, of the felt or cloth systems act as a support to the plants and at the same time they serve as a media to provide water and nutrients to the root systems. Due to the traits of the different cloths (e.g. geotextile, polyamide), this system presents a decreased water retention capacity and it dries in less time than those systems based on containers. These special traits force the application of frequent irrigation events to provide the water required by the vegetation (Pérez-Urrestarazu et al., 2014) and water distribution uniformity (Pérez-Urrestarazu et al., 2014; Segovia-Cardozo et al., 2019). An ideal felt system should be able to absorb increased amounts of water and retain them available to the plants for a long time taking into consideration the plants needs (Lausen et al., 2020). However, the reduced thickness of the felt, allowing a lower water volume stored, and the verticality of the system make necessary to perform improvements of the properties of the cloth system utilized in order to maximise the water retention capacity and ease the management of the irrigation.

Regarding the living wall systems based on boxes or panels, which limit the root growth and development (e.g., root- bound symptoms) due to the materials utilized and to the morphology of the system (technical construction), they frequently exhibit an undesirable reduction of their growth rate, final development and coverage of the living wall system surface (Pallardy, 2008). Even if the increased thickness of these systems leads to a higher water storage capacity, the importance of the characteristics of the growing medium utilized (e.g., rockwool) and the water accessibility to the plants should be taken into consideration, given that they will affect the frequency and the duration of the irrigation events. In this case the systems present a greater lateral diffusion of water and in the case of drip irrigations fewer emitters will be needed and the driplines may be spaced apart.

An adequate irrigation scheduling should take into consideration diverse variables. Initially, attention should be given to the morphologies and traits of each system. The location of the living wall (indoors, outdoors), the materials used (felt or boxes or panels), the existence (semi- hydroponic system) or absence (hydroponic system) of substrate and the selected method of water management (lost or recycled solution). The size and the dimensions of the living wall (vertical or horizontal development) as well as the exposure (wind speed and direction) or the orientation (hours of direct sunlight or shade) and the climatic and microclimatic conditions of the installation area (relative humidity, average, max. and min. temperature, cloud cover categories, precipitation events frequency, evapotranspiration) are integral factors that cannot be omitted.

The next crucially important step, after collecting the aforementioned information, is to design and apply an irrigation schedule (frequency, duration) achieving a high degree of uniformity throughout the wall while at the same time minimizing water losses (Pérez-Urrestarazu et al., 2014). This step should be carried out by experienced and well trained personnel based on the irrigation system method and the wide and varied needs of the living wall. For instance, in the case of drip irrigation, the emitter type and flow and the quantity of the emitters (dripline spacings) should be carefully chosen in order to avoid unnecessary use and consumption of water which may also adversely affect plants performance.

1.5. Light requirements and supplementary lighting in living wall systems

1.5.1. Plants and light

Light is vital for plant development and reproduction as it serves as the energy source for photosynthesis ($6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$). Light is also strongly related to the physiological process of photorespiration, i.e. the uptake of atmospheric O_2 with a concomitant release of CO_2 by illuminated leaves.

Moreover, light acts as a regulator to various developmental processes that cover the entire lifespan of plants, from germination to senescence. This phenomenon also referred to with the collective term photomorphogenesis. The plant response to the length of day or night is known as photoperiodism and it affects several plant traits of particular commercial interest, such as the initiation of flowering, the asexual reproduction, the formation of storage organs, and the onset of dormancy.

Another significant plant response to light is phototropism, which refers to the alteration of plant growth patterns in response to the direction of incident radiation, especially in the blue spectrum. However, plants also respond to non- directional light, with many plant species folding their leaves during night (nyctinasty) and opening them at dawn (photonasty) (Taiz et al., 2015).

1.5.2. Quality of light

When referring to light, one essentially refers to both its energy content and its frequency. Photoreceptors are the plant proteins that ‘sense’ the presence of light and initiate the response via signaling pathway. Given that photochemical responses are stimulated only when light is absorbed by the respective photoreceptor, the quality of light is of paramount importance when examining any plant reaction.

For example, in the case of photosynthesis, only the photosynthetically active radiation (PAR), i.e. 400- 700 nm, is used, as this is the spectrum range where chlorophylls a and b -the main photosynthetic pigments- exhibit absorption. In that sense, when considering photosynthesis and light, it is appropriate to express the quantity of light received as photosynthetic photon flux density (PPFD)- the flux of light (usually expressed as micromoles per square meter per second [μmol m^{-2} s^{-1}]) within the PAR.

In regard to photomorphogenesis, phytochromes are the photoreceptors that respond to red and far- red light, while cryptochromes respond to UV- A/blue light (320-500 nm). Blue light photoreceptors also include phototropins (involved in directing organ, chloroplast, and nuclear movements, solar tracking, thus optimizing photosynthesis) and ZEITLUPE (ZTL) proteins, which have been found to participate in circadian cycles and flowering.

1.5.3. Artificial lighting for living walls

Fulfilling the light requirements of plants used on living walls pose an intriguing challenge, as many factors have to be taken into consideration. Both outdoor and indoor living wall systems are challenged by the fact that the presence of the support system inevitably blocks the light from that direction, thus highlighting the importance of proper orientation in order to fulfill lighting needs and avoid adverse effects of phototropism.

However, indoor living walls often present the need to receive artificial lighting in order to achieve one or multiple goals, such as to provide light (when no natural light is available) or add to that received in order to cover lighting needs, manipulate photoperiod in order to achieve the desired results in respect to growth and flowering and highlight the ornamental and aesthetic value of the living wall (Egea et al., 2014; Tan et al., 2017).

Among the different lightning systems commercially available, light- emitting diode (LED) lamps are the ones most widely applied mainly due to the fact that they present high energy efficiency and low cost, while emitting light at a narrow spectrum (20- 40 nm). The latter led to the use of combined blue and red LED lamps, which aim at higher photosynthetic activity due to the excitation of several photoreceptors (blue light, 460- 475nm) and the match to the absorption peak of chlorophylls and phytochromes (red light, 650- 665nm). However, while this might be efficient for plants grown for biomass, the application of such lightning systems at living walls can have detrimental effects as it leads to unnaturally high speed of plant growth, and, therefore, increased maintenance requirements and subsequently increased cost. Moreover, plants under blue- red light tend to appear purplish gray (Kim et al., 2005), thus severely inhibiting their ornamental value.

Given all the above, white light is considered to be more adequate for the lighting of living walls. White light is produced by a mixture of wavelengths, thus resembling more to the complete spectrum of sunlight. In consequence, white light sources are often to a more natural appearance of plants and enhanced aesthetic attributes. Still, as white lights are produced by different mixtures of colours, the variation among them can be notable. Colour temperature (e.g. warm yellowish to cool bluish light) and, Colour Rendering Index (CRI), which classifies light sources according to their colour rendering properties, are additional factors which should as well be taken into consideration when choosing a lighting system for living walls.

2. Objectives of the Doctoral Thesis

2.1. General objective

The technology of living wall systems should be continuously evaluated and evolved to achieve a sustainable result. A sustainable approach should have as an objective the need for low maintenance, the decreased use of natural resources, the use of environmentally friendly materials, and economical solutions. Based on this mentality, the doctoral thesis had as a general objective the optimization of felt- based living wall systems in order to propose and establish a sustainable approach of the aforementioned infrastructures in terms of water and energy consumption. Precisely, it was focused on the amelioration of the water management performance of four outdoor felt-based semi- hydroponic living wall systems and the optimization of an indoor felt- based living wall system, in terms of auxiliary illumination needs. To do so, two experimental studies were carried out, entitled “Improving the performance of felt-based living wall systems in terms of irrigation management” and “Assessment of different LED lighting systems for indoor living walls”.

2.2. Specific objectives

2.2.1 Improving the performance of felt-based living wall systems in terms of irrigation management

The objective of the first study was the assessment of the performance of a commercial living wall system (Fytotextile 1) and three new developments based on it

(Fytotextiles 2 to 4) focusing on the irrigation management and water retention performance. The irrigation management was defined assigning as priorities the water retention capacity, drying speed and drainage rate of the aforementioned living wall systems, as well as plant performance. Specifically, three outdoor experiments were performed using four semi- hydroponic living wall systems vertically located and with sunny exposure (south- facing aspect).

2.2.2 Assessment of different LED lighting systems for indoor living walls

The principal objective of the second study was the assessment of the suitability and efficiency, in terms of plant growth, development, performance and visual quality, of six commercial LED lamps for indoor living wall systems installations. More specifically, two indoor experiments were carried out using the Fytotextile living wall system completely sheltered from sun exposure. The projectors used were designed for indoor illumination and not specifically for plant growth, apart from one case. Finally, the observers' perception was considered in order to assess the result of the visual quality of the light.

3. Overall summary of the results

3.1. Improving the performance of felt- based living wall systems in terms of irrigation management

The principal experiment of the first study focused on the water retention capacity and drying speed of the different living wall systems, revealed the increased capacity of Fytotextile 4 to store irrigation water compared to the other three Fytotextile systems (Appendices- Publication 1- Table 1 and Fig. 4). Fytotextile 4 exhibited the most elevated water retention capacity due to its consistence of a highly absorbent engineered polymer fibre blanket (Vivapol®) which showed a better performance than

Aquaten used in Fytotextile 3. Fytotextiles 1 (original patent) and 2 which only consisted of geotextiles of different thickness presented the lowest water retention capacity.

The drainage test, organized in 7 irrigation schedules (S1 to S7) combining 4 different durations (5, 10, 20, 40 min) and 5 different frequencies (1, 2, 4, 8 events d^{-1}) (Appendices- Publication 1- Table 2), revealed that in all cases Fytotextile 1 produced the highest drainage volume followed by Fytotextile 4, and Fytotextile 3, while Fytotextile 2 produced the smallest drainage volume (Appendices- Publication 1- Table 3). However, the four tested Fytotextile systems presented similar patterns in the evolution of the average drainage water volume during a day (Appendices- Publication 1- Fig. 5). The main differences appeared in schedules 1, 2 and 5 (S1, S2, S5) with higher frequencies applied (8, 4, 4 events d^{-1}, respectively).

Finally the three plant types used for the vegetation performance test, *Erodium x variabile 'Roseum', Lavandula dentate, Carex oshimensis 'Evergold'*, with a trailing, bushy and tufted habit, respectively, exhibited high survival and a satisfactory performance in terms of aesthetics (Appendices- Publication 1- Fig. 7) in all modular Fytotextile types. Specifically, Fytotextile 3 and 4 presented the least number of dead plants followed by Fytotextile 1, and 2 in which more dead and unhealthy plants were observed (Appendices- Publication 1- Table 4). Regarding variability among the plant species under examination, *Erodium* x *variabile* 'Roseum' presented the most satisfactory performance in all modules. On the contrary, the highest number of dead plants across all modules was recorded for *Lavandula dentata*. Simultaneously, the daily recorded substrate moisture levels (%) showed that Fytotextile 4 presented the lowest percentage followed by Fytotextile 1. Fytotextiles 3 and 2 presented variability through time that did not reveal a concrete moisture pattern while they exhibited the highest substrate moisture (Appendices- Publication 1- Fig. 8).

3.2. Assessment of different LED lighting systems for indoor living walls

This study consisted of two experiments testing the performance of *Soleirolia soleirolii* (*Soleirolia*) and *Spathiphyllum wallisii* (*Spathiphyllum*) under six different LED lighting systems (A- F) (Appendices- Publication 2- Table 1)., with D, E and F light sources being placed closer (system marked with ‘1’) or farther (system marked with ‘2’) from the felt- based living wall modules (Appendices- Publication 2- Fig. 2).

In terms of illuminance, the highest luminous flux per unit area was usually recorded at the middle of the upper module, while the lower illuminance was obtained at the bottom of each module (Appendices- Publication 2- Fig. 3). In order of descending illuminance, the lighting systems were ranked as follows: E1, A, B, D1, F1, E2, F2, D2, C. Regarding the Photosynthetic Photon Flux Density (PPFD, μmol m^{-2} s^{-1}), it was found to be higher at the middle of the upper modules (Appendices- Publication 2- Table 2). The highest value was recorded for lighting system E1 and, decreasing, in: D1, F1, E2, A1, F2, D2, B1, C. Both illuminance and PPFD presented a sharp drop when the distance increased up to 1 m, followed by a milder decrease as the distance increased further (Appendices- Publication 2- Fig. 4). All lighting systems presented a satisfactory correlation between illuminance and PPFD. A robust correlation was also identified between illuminance simulation and actual measured values (Appendices- Publication 2- Fig. 5).

Regarding temperature close to the modules, this was found to be ~5°C higher in modules A, B, C compares to D1, D2, E1, E2, F1 and F2. Among the latter, a small difference of ~1°C was recorded between almost all upper and lower modules. The relative humidity (50- 70%) was higher for D1, D2, E1, E2, F1 and F2 and among them, higher in D2, E2 and F2 (Appendices- Publication 2- Fig. 7).

Significant variability was observed among modules in terms of average daily water consumption, with the highest values being attributed to D2 and the lowest to B (Appendices- Publication 2- Fig. 8).

In reference to vegetation performance, the traits measured were: total, root and aerial fresh and dry weights (g $plant^{-1}$), number of white flowers, green cover (%), Normalized Difference Vegetation Index (NDVI), and the relative measure of chlorophyll content (SPAD). Moreover, the indices on aerial to root dry weight and total fresh to total dry weight were calculated, while mean leaf area (cm^2 $leave^{-1}$) was measured only for *Spathiphyllum* plants. In general, the root and aerial fresh and dry weights presented their highest values in module A and their lowest in modules D2 and E2, in the case of *Spathiphyllum* (Appendices- Publication 2- Table 3). For *Soleirolia*, the highest values were attributed to modules D1 and E1 and the lowest to modules C and F2 (Appendices- Publication 2- Table 4). The upper modules exhibited a higher green cover compared to the lower modules, except for module C (Appendices- Publication 2- Fig. 9) and the number of *Spathiphyllum* white flowers was high in modules D1, E1, F1, D2, E2 and F2, with no significant differences among them (Appendices- Publication 2- Fig. 10). The mean NDVI after 4 and 10 weeks since planting was higher in module D2, while only module B did not present any significant differences between weeks 4 and 10 (Appendices- Publication 2- Table 5). Furthermore, *Spathiphyllum* leaves were found to contain less chlorophyll in the upper modules of D1, E1 and F1, while the highest content was attributed to modules D2 and F2 (Appendices- Publication 2- Fig. 11).

Lastly, regarding both in the attractiveness of colours and in the natural appearance of plants under each lighting system (Appendices- Publication 2- Fig. 12), observers preferred lamps D and F, followed by E. On the contrary, lamps A and C presented low values of acceptance by the questionees (Appendices- Publication 2- Table 6).

4. General discussion of the results

4.1. Improving the performance of felt- based living wall systems in terms of irrigation management

The aforementioned allegation of the need for continuous evaluation and development of the living wall systems is supported by the findings of the present study as the original Fytotextile® system (Fytotextile 1) exhibited inferior performance compared to its evolutions (Fytotextile 2- 4). Precisely, Fytotextile 3 and 4 presented a higher water retention capacity and they conserved the water for a longer time due to the traits of the intermediate layers. However, the hydrophilic behavior of the interlayers of felt- based living wall systems must be taken into account to estimate whether there is high water availability for plant roots. In the current study, the vegetation was not affected by the hydrophilic performance of the intermediate layer, although further investigation with a longer duration is suggested to determine its influence over time.

According to the findings of the drainage test, the elevated total volume of water drained for Fytotextile 4 was the result of the initial increase in water content prior to the irrigation events. This increased water content is due to the higher retention capacity of the Vivapol® intermediate layer. Thus, it is expected that irrigation frequencies lower than those currently tested (1, 2, 4, 8 events d^{-1}) will present better results which allow further research focused on the use of the specific material.

In contrast, Fytotextile 2 showed the lowest total volume of water drained potentially due to its fast drying capacity but elevated water storage. However, it exhibited the highest drainage flows in most cases and mainly at the beginning of the irrigation event, which makes the option of an irrigation program with shorter duration events inefficient. This result is consistent with the finding of Pérez- Urrestarazu et al. (2014) and Cortês et al. (2019) for modular systems.

Regarding the application of the different irrigation schedules, it was concluded that the combination of high frequency and reduced duration is the optimal option, results that are in accordance with Pérez- Urrestarazu et al. (2014) study. Applying this irrigation schedule, the peak drainage flow would potentially be reduced in the initial stages of irrigation and the total volume of water drained would not be too elevated.

Concerning the vegetation performance, there is no correlation between the plant losses or the low appearance results and the different Fytotextile systems. However, the application of longer- term studies is suggested to appreciate the influence of the living wall system on the distinct types of plants and the constant attention to the proper plant selection based on the needs of each plant type.

The present study revealed new questions about the existence of various commercial felt- based living wall systems and their utilization on appropriate occasions. The selection of the living wall systems that will be considered appropriate in different environmental conditions should be based on prior long-term studies to test the performance of the materials used. From a sustainability point of view, the performance of materials should also focus on water and carbon footprint, as well as environmental benefits such as water and energy consumption, CO_2 fixation, improvement of biodiversity, fertilization and the implementation of pesticides.

4.2. Assessment of different LED lighting systems for indoor living walls

The use of indoor living walls frequently creates a need for auxiliary illumination that needs to be efficient in terms of enhancing vegetation and appearance, and, at the same time, have the least possible energy consumption and with low heat production. These aspects make LED lamps the obvious choice, yet, the lamps which produce more light within the PAR spectrum are considered ideal.

Significant variance was observed among the different lighting systems under examination in terms of vegetation development and PPFD values. One of the findings that need to be highlighted is that the CF- UT01 (C) lamp, though specifically designed for plant growth, was the one which exhibited the lowest PPFD values and the less adequate plant performance. This can be attributed to the fact that such lamps are designed to be placed at a very close distance from the plants, thus being unsuitable for being used to light living wall systems. Moreover, such lamps result in a non- natural appearance of plants, which severely diminishes the ornamental value of the living wall.

In addition, the vertical gradient of illuminance (Chen, 2005) is an additional factor that needs to be considered when evaluating lighting systems for indoor living walls. The results of the present study, slightly higher than the ones reported in the literature Thiel et al. (1996), indicated that the average loss of illuminance per metre of distance to the light source was between 48 % [Forum (F)] and 64% [Logar CMH Superflood (B)], with the exception of CF- UT01 (C) lamp, for which the loss reached 78.6 %. It should be noted, though, that the loss was significantly higher in the first metre. Given the fact that PPFD values presented a similar, yet smoother, direct correlation to the distance from the lamp, it is suggested that the lower part of living walls cannot be at a large distance from the light source, as PPFD levels exhibit an acute decrease within the first few metres.

Moreover, the vertical gradient introduces a lack of illuminance uniformity that needs to be considered when selecting plant species. Plants with higher light demands should be placed at the upper sections of the living wall, as the results of the present study indicated that uniformity values are considerably higher at the upper modules.

In terms of PPFD values, the mid- section of upper living walls was found to receive more light in all treatments, while PPFD values below the upper modules for Aster Ignia Green (A), Logar CMH Superflood (B), and CF- UT01 (C) lighting systems were found to be inadequate for plant survival. According to this, different lamps should be used for living walls higher than 1 m.

In order to assess the effect of the duration (number of hours) of artificial lighting on vegetation performance, the photosynthetic daily light integral (DLI) was estimated. DLI refers to the cumulative amount of PAR delivered to a specific area over a 24- h period (Fausey et al., 2005). Regarding dry biomass production, the results of *Soleirolia* plants in the present study confirm that higher DLI values are correlated with higher dry biomass (Warner and Erwin, 2005; Oh et al., 2009). However, this argument could not be supported by the performance of *Spathiphyllum* plants, whose dry biomass did not increase at elevated DLI values, possibly due to *Spathiphyllum*'s high adaptation to lower light exposure. While Faust, (2001) proposed a DLI value of 4 mol $m^{-2}d^{-1}$ as ideal for *Spathiphyllum* plants, in the present study, Aster lamp (A) showed the highest dry biomass when receiving only 1.8 mol $m^{-2}d^{-1}$. Apart from any inconsistencies that need to be further investigated, it should be highlighted that *Spathiphyllum* was found to be more susceptible to DLI variations.

Aster Ignia Green (A) and Logar CMH Superflood (B) lamps presented fewer flowers than Dahlia (D2) and Forum (F2) lamps. Given the fact that all those lamps were characterized by similar DLI values, the results are not in accordance with previous findings supporting that higher DLI induces higher flowering (Oh et al., 2009; Currey and Erwin, 2011). Though needed to be further examined, lack of variance among the aforementioned treatments might be associated with differences in temperature, a fact that it is known to affect flowering (Meng and Runkle, 2014; Blanchard et al., 2011).

As expected, the lighting systems under examination were associated with different values of water consumption, with the highest one being attributed to Dahlia (D2) and the lowest to Logar CMH Superflood (B). While these results are in accordance with the literature Egea et al. (2014) in terms of variability, the values of daily water consumption recorded during the present study were much lower than the ones reported by the aforementioned authors.

The modules that were closer to the light source presented a more robust vegetation cover, a trait of particular importance for living walls. Yet, it should be highlighted that Dahlia (D), Logar CLH Superflood (E), and Forum (F2) lamps, plants growing closer to the light source presented a deteriorating appearance in the course of time, a trend that was more acute for *Soleirolia*.

Furthermore, plants in modules receiving a lower PPFD presented higher chlorophyll content, thus coinciding with literature (Dibenedetto, 1991; Krause and Winter, 1996; Zhang et al., 2016) suggesting an inverse correlation between luminous flux and chlorophyll content. Lower PPFD values were also associated with higher NDVI, a trend that has been previously reported (Mielke and Schaffer, 2010) and attributed to alternated pigment composition and protective mechanisms against excess light.

Lastly, while Jost-Boissard et al. (2009) have reported that colour composition and temperature of lighting systems affect the opinion of the people observing the living wall; in the present study this could not be confirmed. The questionees were found to prefer lamps Dahlia (D) and Forum (F), which were the ones to luminous flux (lm) rather elevated than all other lighting systems though with no important colour and/ or temperature differences (Appendices- Publication 2- Table 1), highlighting the importance of further examining the effect of the traits to the degree of acceptance by observers. Moreover, questionees show a higher level of acceptance towards lamps which produce a more homogenous light distribution rather than a single beam.

5. General Conclusions

5.1. Improving the performance of felt- based living wall systems in terms of irrigation management

The first study aimed at further assessment of the potential of the commercial felt-based living wall system, Fytotextile®, to improve the irrigation management by altering the materials used and applying the correct irrigation schedule in each case. Synopsizing the basic findings, it should be highlighted that:

- Fytotextile 4 revealed the most increased capacity to store irrigation water compared to the other three Fytotextile systems.
- Fytotextile 2 produced the smallest drainage volume in all irrigation schedules.
- All Fytotextile types seemed to be adequate to house different vegetation types maintaining an elevated aesthetically result in the short term. Living walls with Fytotextile 3 and 4 presented the lowest plant losses, though with different substrate moisture levels (%), while Fytotextile 4 presented the lowest substrate moisture level and Fytotextiles 3 and 2 the highest.
- *Erodium* x *variabile* 'Roseum' presented the most satisfactory performance in all Fytotextile systems while *Lavandula dentata* the worst.

In conclusion, the results of the present study highlight, on the one hand, the potential of the materials used on felt-based living wall systems to contribute to the improvement of water management with a sustainable approach. On the other hand, it is revealed the importance of the implementation of the appropriate irrigation schedules and the lack of knowledge in this sector.

It is suggested for living walls to be constructed with suitable and tested materials that can support long life living wall systems with the minimum losses in terms of water and materials (e.g. vegetation, geotextiles) in order to be effective in delivering the desired results.

5.2. Assessment of different LED lighting systems for indoor living walls

The second study aimed at the evaluation of six commercially available LED lighting systems regarding their suitability for indoor living walls. This evaluation was based on lighting pattern, temperature/ water consumption and effect on vegetation performance, along with the degree of acceptance according to questionees. According to the findings of this study:

• Illuminance (as luminous flux per unit area) was found to be positively correlated to the height of the module for each pocket. PPFD was also higher at the middle upper module. Logar CLH Superflood lamp in treatment E1 presented the highest value for both traits, while the lowest values were attributed to CF- UT01 lamp (treatment C).

• Temperature was higher for lamps Aster Ignia Green, Logar CMH Superflood and CF-UT01 (treatments A, B and C, respectively). Moreover, a small difference of ~1°C was recorded between almost all upper and lower modules of treatments in test 2 (D1, D2, E1, E2, F1 and F2).

• Relative humidity (50- 70%) was higher for Dahlia (D2), Logar CLH Superflood (E2) and Forum (F2) lamps.

• Dahlia (D2) exhibited the most elevated average daily water consumption and Logar CMH Superflood (B) the lowest.

• Among the examined lighting systems, CF- UT01 lamp (treatment C) was the only one that was not characterized as suitable for indoor living walls. Moreover, Aster (treatment A) and Logar CMH Superflood (treatment B) performed poorly when placed farther from the module.

• Dahlia lamp (treatment D) was the one that received the highest level of approval among questionees.

In conclusion, this study highlighted the impact of LED lighting systems on the performance of living walls, while revealing that, along with lamp type, other parameters such as its distance from the living wall, its orientation, beam angle, energy consumption and level of acceptance by the public should also be taken into consideration when evaluating the efficiency of lighting systems.

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Appendices

The following two articles, entitled "Improving the performance of felt- based living wall systems in terms of irrigation management" and "Assessment of different LED lighting systems for indoor living walls" are presented in the format prior to be sent to Urban Forestry & Urban Greening and Scientia Horticulturae journals, respectively, to comply with the embargo period of these journals.

1. Publication 1

Improving the performance of felt-based living wall systems in terms of irrigation management

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Abstract

Vertical greening systems are becoming a new reality worldwide in urban areas in order to increase and enhance green spaces. Commercially there are many systems employing various materials which aim to enable an adequate development of the vegetal cover, ensuring long-term successful performance. Irrigation represents one of the main key factors, but there is a knowledge gap involving the performance of commercial systems in terms of water management. Felt-based systems present more difficulties due to the smaller water retention capacity, which is an important drawback, especially in warm climates. This work aims to improve an existing commercial system (Fytotextile) in order to optimise water retention and vegetation performance in harsh climate conditions. Therefore, three evolutions of the Fytotextile system were tested in terms of water retention capacity, drainage and vegetation performance. Fytotextiles 3 and 4 vastly improved the initial water retention capacity of the commercial system (2.9 and 5.8 times that of Fytotextile 1, respectively) but the former exhibited a lower volume of water drained and a slightly better behaviour of the plants.

Keywords: Fytotextile; green walls; vertical greening systems; water management; water retention capacity

1. Introduction

Nowadays, the use of vertical greening systems is spreading worldwide under different outdoor climates and microclimate conditions as well as indoor environments (Ghazalli et al., 2019; Medl et al., 2017; Pérez-Urrestarazu et al., 2015). However, despite the multiple known benefits and ecosystem services provided by them (Collins et al., 2017; Ghazalli et al., 2019; Larcher et al., 2018; Medl et al., 2017; Pérez et al., 2016), these green technologies are often subjected to criticism, especially regarding their maintenance and environmental sustainability. Precisely, the excessive water use becomes one of the main concerns (Manso and Castro-gomes, 2015; Riley, 2017).

Regardless of the green wall technology used, watering the vegetation is compulsory, mostly by means of integrated irrigation systems (Medl et al., 2018). This is particularly important in the cases of installation in warm climates where a proper irrigation schedule can be critical for the performance or even the survival of the vegetation. However, water management related to living walls has not been broadly studied, so there is a knowledge gap in this matter (Pérez-Urrestarazu et al., 2015).

There are different living wall systems in the market (Manso and Castro-gomes, 2015; Medl et al., 2017; Pérez-Urrestarazu et al., 2015). Some of them are based on boxes or containers, which limit the roots development (e.g., root-bound plants) as they are confined (Weinmaster, 2009) and, frequently, they do not allow enough gas exchange, leading to an undesirable reduction of their growth rate (Pallardy, 2008). As an alternative, the ‘felt’ (also referred to as ‘cloth’) systems are usually formed by at least two textile-like layers (a geotextile is the material most employed), in between which the plants are placed, bare rooted or in an inert substrate. The layers serve as a support to the plant and at the same time they act as a media to provide water and nutrients to the roots. This kind of systems solves the problem of excessive size (thickness) and weight of those based on containers. The major drawbacks of this system are its low water retention capacity which forces having frequent irrigation events to provide the water required by the vegetation (Pérez-Urrestarazu et al., 2014) and less water distribution uniformity (Pérez-Urrestarazu et al., 2014; Segovia-Cardozo et al., 2019). This is particularly problematic in warm climates and usually results in excessive water use (especially when the system is not recirculated). Also, as felt-based living walls can be considered a hydroponic system (since usually the plant's organic medium of development is changed for an inorganic one) (Manso and Castro-gomes, 2015), additional nutrients must be incorporated (and part of them lost with the drainage water).

In order to ameliorate these problems, some systems are composed of a special configuration of the geotextile layers, forming pockets where the plants are housed with their root ball, thus reducing the transplant stress. Hence, they can be considered as 'semi-hydroponic' systems. In this case, the outer layer must have a good air permeability to avoid problems of root asphyxia.

The most commonly used irrigation system for living walls is localised irrigation using low flow emitters (drippers) placed in pipes at different heights of the living wall (Pérez-Urrestarazu and Urrestarazu, 2018). Due to the action of gravity and the capillarity of the inner geotextile layer based on cotton fibres, the water is distributed throughout the living wall surface (Pérez-Urrestarazu et al., 2014). This textile fabric should be able to absorb as much water as possible and retain it for a long time. This is difficult due to the reduced thickness of the felt (less volume for storage) and the vertical position in which it is placed. Hence, the challenge is to improve the properties of the system employed in order to maximise the water retention capacity and ease the management of the irrigation.

The aim of this study is the assessment of the performance of four felt-based living wall systems in terms of water management (prioritising availability for the vegetation but minimising at the same time the water losses). To do so, four semi-hydroponic outdoor living walls were tested in order to evaluate (1) the water retention capacity and drying speed, (2) the volume of drained water and the maximum drainage flow obtained with different irrigation schedules (varying both their duration and the interval between irrigation events), and (3) the vegetation performance in each of them.

2. Materials and methods

2.1.Experimental setup and systems tested

The experiment was set in an exterior courtyard in the Aljarafe region of Seville, Spain (37º23'7 "N, 6º 6'53" W), which has a Hot-summer Mediterranean climate (Csa) according to the Köppen–Geiger climate classification system. It was conducted from November 2016 until July 2017. Four living walls of 2 by 1 m (height x width) were installed facing south using, in each one of them, two 1 x 1 m felt modules based on the Fytotextile® system (Terapia Urbana S.L., Seville, Spain), widely used in European countries (Figure 1). Each of them was comprised of different inner textile layers, having in common the outer layer composed of a sheet of polyamide and a waterproof back layer. The inner textile layer of each of the four types of Fytotextile modules tested was:

- Fytotextile 1 (standard Fytotextile): 2.6 mm thick geotextile (Protex 300, Projar, Valencia, Spain) made of polypropylene and other recycled natural fibres (cotton, wool, etc.), which are non-woven and micro-perforated to improve their permeability to water, (unit weight: 300 g m^{-2}).

- Fytotextile 2: 4 mm thick geotextile (VLS-500, Diadem, APP Kft., Győr, Hungary), with the same composition of Fytotextile 1 (unit weight: 500 g m^{-2}).

- Fytotextile 3: another layer is added to the geotextile of Fytotextile 2. This layer is made of Aquaten (Aquaten Ltd., UK), a highly absorbent, engineered polymer fibre matrix blanket (1.2 mm thick) that enhances the water retention capacity.

- Fytotextile 4: Fytotextile 2 geotextile plus and added layer made of Vivapol® (Reimann Emsdetten, Germany), a very highly absorbent (according to the manufacturer, with a water retention capacity of 3 L m^{-2}), engineered polymer fibre blanket (4-5 mm).

The outer and inner layers were attached by sewing with resistant synthetic yarn forming grids of 15 cm. Each living wall had 98 pockets (49 pockets/m^2) in which the plants were inserted with their root balls. In order to protect the facade from damp problems, a third back layer was added to all the modules. To do so, a waterproof sheet of flexible PVC, sewn and thermo-sealed in the perimeter of the back of the modules, was used. Finally, in order to be able to fix the modules to the façade, a metallic fastening profile was screwed to an auxiliary metallic structure.

Once the modules had been fixed to the structure, a horizontal pipe with drip emitters was placed in the upper part of each module between the mid and outer layer. Each irrigation line had 7 self-compensated emitters (Netafim, Israel) with a flow of 2 L h^{-1}. The two irrigation lines were connected by a vertical pipe that led to the entrance of the water supply network (Figure 1). The irrigation control was performed with a programmer connected to four electrovalves, one for each system tested. The water inlet to the irrigation system was measured by a 3/4" MTK (ZENNER International GmbH & Co. KG, Germany) multi-stream cold water meter with pulse emitter (1 L $pulse^{-1}$).

To collect the water drained by each living wall a rectangular galvanized steel gutter was installed with a sufficient slope to pour the water into a Rain-O-Matic rain gauge (Ponamic, Denmark) with a reed relay connected to a digital pulse counter (Figure 1).

In order to measure the substrate moisture content, 4 FDR model ECH2O EC-5 capacitive type soil moisture sensors (Decagon Devices, Pullman, WA, USA) were installed in the upper (H1) and lower(H2) row of each module (Figure 1).

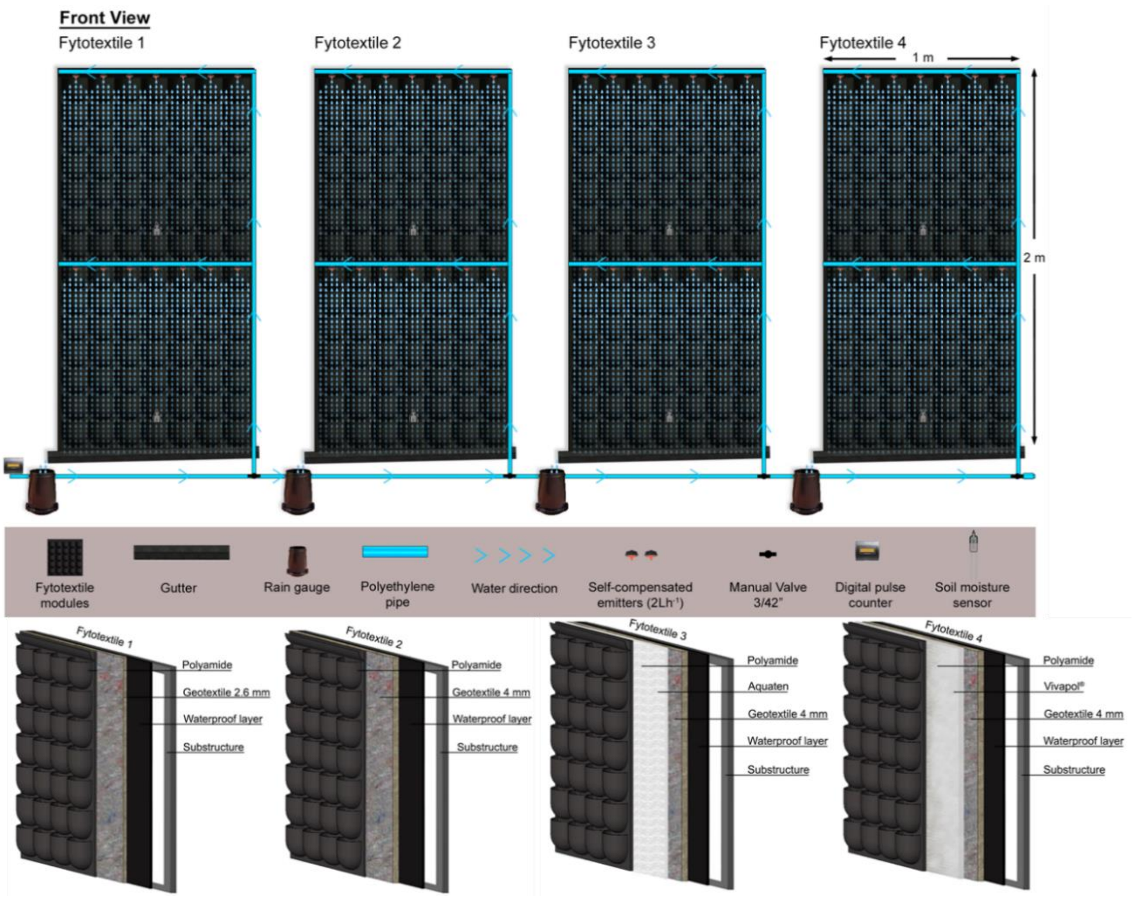

Figure 1. Schematic layout of the irrigation system and drainage collectors. 3D details of each Fytotextile system.

A HOBO S/THB-M002 Temp/HR probe (Onset Corporation, Pocasset, Massachusetts, USA) with a resolution of 0.25° C and 1%, respectively, was used to monitor the air temperature and relative humidity. A HOBO S-LIB-M003 solar radiation probe (Onset Corporation, Pocasset, Massachusetts, USA) with a measurement range of 0 to 1280 W m^{-2} over a spectral range of 300 to 1100 nm was also employed. These sensors were placed at a distance of 0.3 m from the middle of the living walls. All the parameters were recorded in a HOBO model data logger H22-001-C (Onset Corporation, Pocasset, Massachusetts, USA).

Three different experiments were performed in order to fulfil the three predefined objectives: water retention capacity and drying test, drainage test and plant performance test.

2.2. Water retention capacity and drying test

This test was performed for all the modules without plants or substrate. The water holding capacity (WHC) gives information about how much water is retained/stored in the modules after water saturation. In order to obtain its value, three samples of each type of Fytotextile module were weighed using a Hyindoor portable digital electronic hanging scale with a maximum capacity of 50 kg when completely dry (after 48 hours of solar exposition) and then immersed in water for 30 minutes. Once saturated, they were removed from the water and placed vertically, eliminating by gravity all the water that was not retained. When the modules stopped dripping, they were weighed again. This procedure was repeated 3 times in order to obtain an average value for each module. The WHC was calculated as follows:

$$WHC\ (\%) = \frac{W_w - W_d}{W_d}$$

Where W_w is the module wet weight and W_d, the dry weight.

In order to determine the drying curve, they were vertically exposed to the sun under clear sky conditions, making ten weight measures during the day from 10:00 a.m. to 10:00 p.m. The experiment took place in September 2016. During this period, the temperature varied between 19 and 29°C, there was no rain, the relative humidity ranged between 23.1 and 60.5 %, and the maximum radiation was 785 W m^{-2}.

2.3. Drainage test

The pockets of the living wall modules were filled with an equivalent volume to pots of 9 cm of diameter (0.2 L) of coconut peat (bulk density of 0.8 g cm^3) but were not planted for this test in order to avoid the inclusion of other variables that could affect the results (different plant size and water uptake). This test was conducted between December 23rd, 2016 and January 15th, 2017.

Seven different irrigation schedules (S1 to S7) were used (see Table 2 in the Results section) for the current study. In four of the irrigation schedules the irrigation time (5 minutes/irrigation) was the same, reducing the irrigation frequency (different daily dose of irrigation water). In the other 3 schedules, the daily irrigation doses were maintained but the number of irrigation events and their duration changed.

Prior to the beginning of the drainage test, the flow rate discharged by the emitters was measured in order to determine the uniformity coefficient and mean values. Four replicates were performed for each irrigation schedule in consecutive days with similar initial substrate moisture and climatic conditions. In each repetition, the volume (L) of irrigation water applied and the drainage flow rates (L h^{-1}) and total volume (L) recovered at the bottom of each living wall were registered for each living wall throughout the day. The substrate moisture in the central zone of each living wall, the incident solar radiation, the air temperature and the relative humidity were also measured to control the conditions in which the test was performed.

2.4.Vegetation performance test

This experiment was conducted between May 27th and July 11th, 2017. In order to evaluate the plant performance in each of the living walls, three different species commonly found in outdoor living walls in warm climates were planted. The species selected, *Carex oshimensis*, *Erodium x variabile 'Roseum'* and *Lavandula dentata*, were placed in vertical rows (two, three and two rows, respectively) in order to avoid any influence regarding their height placement (Figure 2). The plants were acquired in a nursery with a pot size varying between 0.12 and 0.15 m of diameter, and a volume of 300 cm^3 of substrate composed by a mixture of coconut fibre and peat. No additional nutrients were added with the irrigation water.

Figure 2. Living wall systems (1 to 4), each one planted with *Carex oshimensis 'Evergold'* (right), *Erodium x variabile 'Roseum'* (middle) and *Lavandula dentata* (left).

Two different irrigation schedules were used. There were three irrigation events per day in both of them, at 8:00 am, 2:00 pm and 7:00 pm, but with different durations: 15 minutes from May 27th to June 19th and 10 minutes from June 19th to July 11th. The objective of diminishing the irrigation duration was to evaluate the performance of the plants in a context of water shortage.

The volume of irrigation and drainage water was registered for each living wall throughout the study period. The substrate moisture in the central zone of each living wall (Figure 1), the incident solar radiation and the air temperature and relative humidity were also measured to control the conditions in which the vegetation performance test was performed (Figure 3).

Photographs of each of the four living walls were taken weekly in order to observe the evolution of the vegetation during the trial. Also, a visual inspection was performed, recording the number of dead plants and any anomalies detected concerning the normal expected plant development.

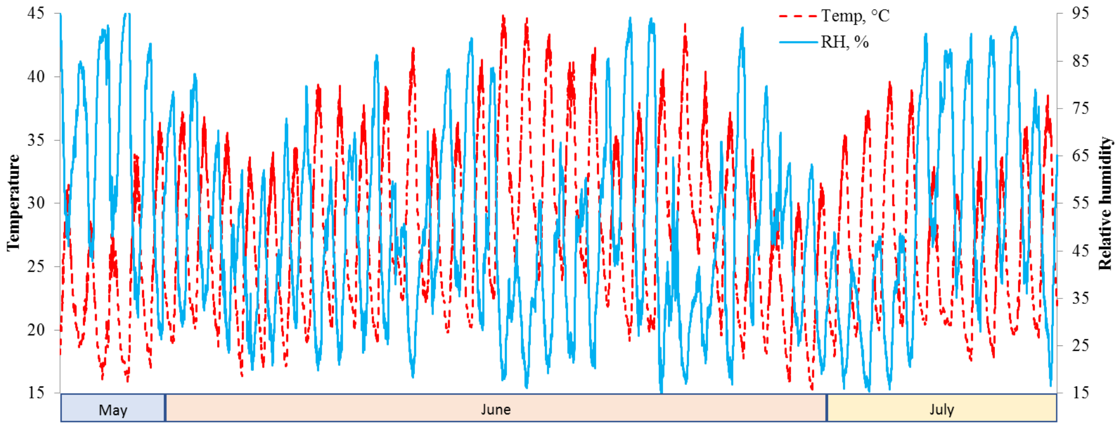

Figure 3. Temperature (Temp, ºC) and Relative Humidity (RH, %) during the vegetation performance test

3. Results

3.1. Water retention capacity

The results obtained in the characterisation of the WHC for the 4 types of water-saturated modules analysed are shown in Table 1. Fytotextile 4 is the one with the highest water volume stored (7.85 L m^{-2}) followed by Fytotextile 3 (3.95 L m^{-2}) and Fytotextile 2 (1.51 L m^{-2}), with considerable higher values than the standard module (Fytotextile 1) (1.35 L m^{-2}). Therefore, Fytotextile 4, 3 and 2 presented an increase in water retention of 481.5 %, 192.6 % and 11.9 %, respectively, compared to Fytotextile 1.

Table 1. Average values for Fytotextile dry and wet weight (kg), maximum water stored per unit area (L m^{-2}) and WHC (%)

	Fytotextile 1	Fytotextile 2	Fytotextile 3	Fytotextile 4
W_d (kg)	2.33	2.43	2.76	3.14
W_w(kg)	3.68	3.93	6.72	10.99
Water stored (L m^{-2})	1.35	1.51	3.95	7.85
WHC (%)	57.87	62.20	143.06	250.37

Figure 4 shows the drying rate for the different tested Fytotextile modules. It can be observed that Fytotextile 1 and 2 lost all the water retained 395 minutes (6 hours and 35 minutes) after the beginning of the drying phase. However, Fytotextile 3 and 4 kept much water after 10 hours, still showing water content values of 0.79 L m^{-2} and 4.16 L m^{-2}, respectively.

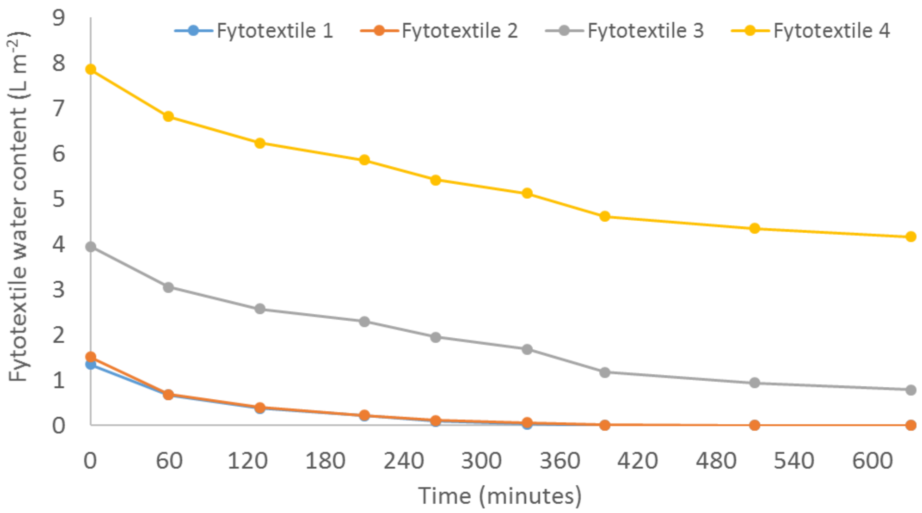

Figure 4. Evolution of the Fytotextile (1, 2, 3, 4) water content (L m^{-2}) over 10 hours (drying curve)

3.2.Drainage test

The mean total volumes and maximum flows of water drained in a day from the 4 types of Fytotextile living walls for the seven different irrigation schedules are summarised in Table 2. Important differences can be observed between the types of Fytotextile modules and the irrigation schedules used. Obviously, when the duration of the irrigation event was the same, , there was a higher volume of drained water in all the modules tested for higher irrigation frequencies, given that the modules still have some water retained from the previous irrigation event. Nevertheless, when the volume applied is the same in all the frequencies considered (S1, S5, S6 and S7), the differences in drainage volumes measured are lower (though the drainage volume is slightly higher when there are more irrigation events).

Table 2. Average values of maximum drainage flow (F_{max}, L h^{-1}) and drained water volume (DWV, mm/d) for different irrigation schedules (S1 to S7)

Irrigation schedule	Duration (minutes)	Frequency (events d^{-1})	Fytotextile 1		Fytotextile 2		Fytotextile 3		Fytotextile 4	
			F_{max} (L h^{-1})	DWV (mm/d)	F_{max} (L h^{-1})	DWV (mm/d)	F_{max} (L h^{-1})	DWV (mm/d)	F_{max} (L h^{-1})	DWV (mm/d)
S1	5	8	7.97	15.48	21.67	8.65	5.29	10.88	5.94	14.30
S2	5	4	3.05	7.29	8.85	4.36	2.21	4.79	2.46	6.68
S3	5	2	1.88	3.36	1.54	1.83	1.91	2.05	1.56	2.78
S4	5	1	1.56	1.37	0.64	0.52	1.76	0.56	0.78	0.90
S5	10	4	16.88	13.29	19.33	8.53	13.79	8.59	20.39	11.98
S6	20	2	36.41	11.74	23.33	8.06	21.32	7.96	28.13	11.22
S7	40	1	37.03	11.00	24.87	7.47	24.12	7.69	31.56	10.46

Fytotextile 1 produced the highest drainage volume in all the irrigation schedules tested, followed by Fytotextile 4 with an average reduction of drained water of 12.4 % over Fytotextile 1. Notwithstanding, according to the water retention capacity test, Fytotextile 4 is precisely the one that retains the highest volume of water. Hence, even for lower irrigation frequencies, its water content is still high. This fact leads to a higher volume drained, which means that for this system the irrigation duration or its frequency should be reduced even more. On the other hand, Fytotextile 2 generates the smallest amount of drainage water in all the cases (an average of 41.6 % smaller than Fytotextile 1), followed by Fytotextile 3 (37.1 % less drainage than Fytotextile 1) (Table 3). This difference is more remarkable for the lower irrigation frequencies. For instance, a reduction of 62 and 59.1 % was observed (for Fytotextiles 2 and 3, respectively) in the volume of drained water measured with one five-minute irrigation event per day. Fytotextile 2 showed, however, higher drainage peak flows than Fytotextile 1 for high frequencies (four or more irrigation events each day) while Fytotextile 3 produced the lowest values.

Table 3. Comparative drained water results and average values

Irrigation schedule	Run off comparative (% of reduction)		
	Fytotextile 2 to Fytotextile 1	Fytotextile 3 to Fytotextile 1	Fytotextile 4 to Fytotextile 1
S1	44.15	29.74	7.63
S2	40.23	34.31	8.28
S3	45.51	38.95	17.26
S4	61.87	58.68	34.48
S5	35.82	35.40	9.85
S6	31.39	32.19	4.44
S7	32.09	30.07	4.95
Average	41.58	37.05	12.41

The volumes of accumulated drainage water recovered from the four living walls tested throughout a day are depicted in Figure 5 for irrigation schedules 1 to 4. The behaviour in all the schedules was similar though the differences between types of Fytotextile modules were, as already stated, more important with higher frequencies. These differences were due to the content of water of each module before each irrigation event.

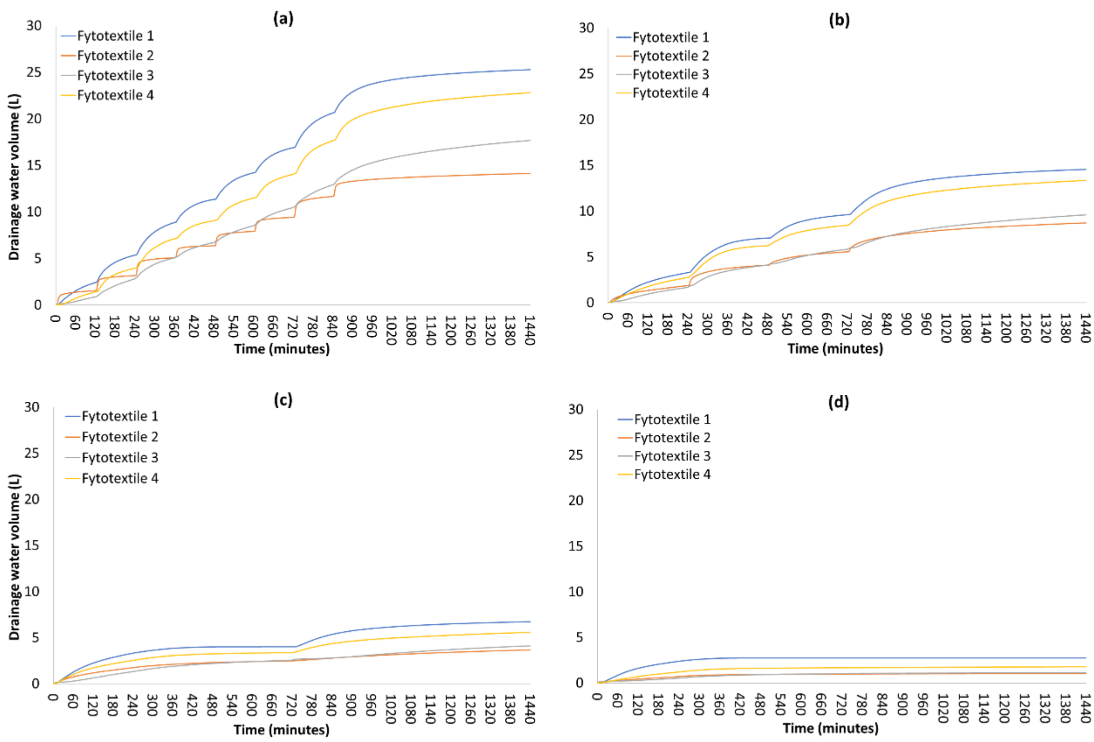

Figure 5. Evolution of the average cumulative drainage water volume (L) during a day in the four tested Fytotextile systems for 8 (a), 4 (b), 2 (c) and 1 (d) irrigation events of 5 minutes.

Though Table 2 shows the peak flow of drainage water, it is also important to pay attention to the evolution of flows over time. As an example, when comparing the distribution of flows in Fytotextiles 1 and 2 (Figure 6a), although the highest peak flow is observed in Fytotextile 2 at the beginning of each irrigation event, the rest of the recorded flows are lower than in Fytotextile 2. The distribution of flows for Fytotextile 3 is even more uniform (Figure 6b).

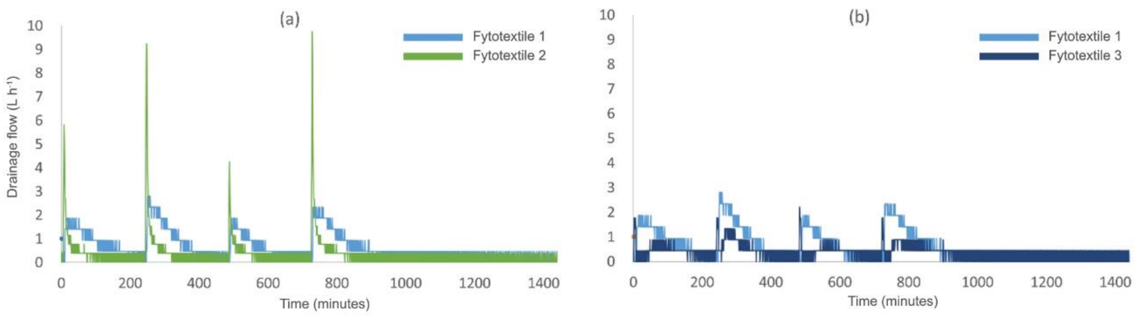

Figure 6. Distribution of drainage water flows (L h^{-1}) recorded during an average day for irrigation schedule S2. Comparison between Fytotextile 1 and 2 (a) and Fytotextile 1 and 3 (b). Fytotextile 1 is represented in light blue, Fytotextile 2 in green and 3 in dark blue.

3.3. Performance of the plants

Table 4 shows the number of plants of each species that did not survive or were in bad condition at the end of the test. *Erodium x variabile 'Roseum'* had a good performance in all the modules while *Lavandula dentata* showed the highest number of dead plants. Fytotextile 2 had the worst results with 8 dead plants and 2 unhealthy ones (10 %), followed by Fytotextile 1 (5 dead, 3 unhealthy). Fytotextiles 3 and 4 only presented two dead plants.

Table 4 Plant mortality and those in bad condition for each species: number of dead plants (DP), percentage out of the total planted (DP%) and number of unhealthy plants (UP).

Species	Fytotextile 1			Fytotextile 2			Fytotextile 3			Fytotextile 4		
	DP	DP%	UP	DP	DP%	UP	DP	DP%	UP	DP	DP%	UP
Carex oshimensis 'Evergold'	0	0 %	2	1	4 %	1	0	0%	2	0	0%	3
Erodium x variabile 'Roseum'	0	0 %	0	0	0 %	0	0	0%	0	0	0%	0
Lavandula dentata	5	18%	1	7	25%	1	2	7%	3	2	7%	3

In general, even under difficult conditions (i.e., high temperatures and low substrate moisture), the three plant species used had a quite good evolution in all the cases during the test, being sufficient for aesthetic purposes (Figure 7).

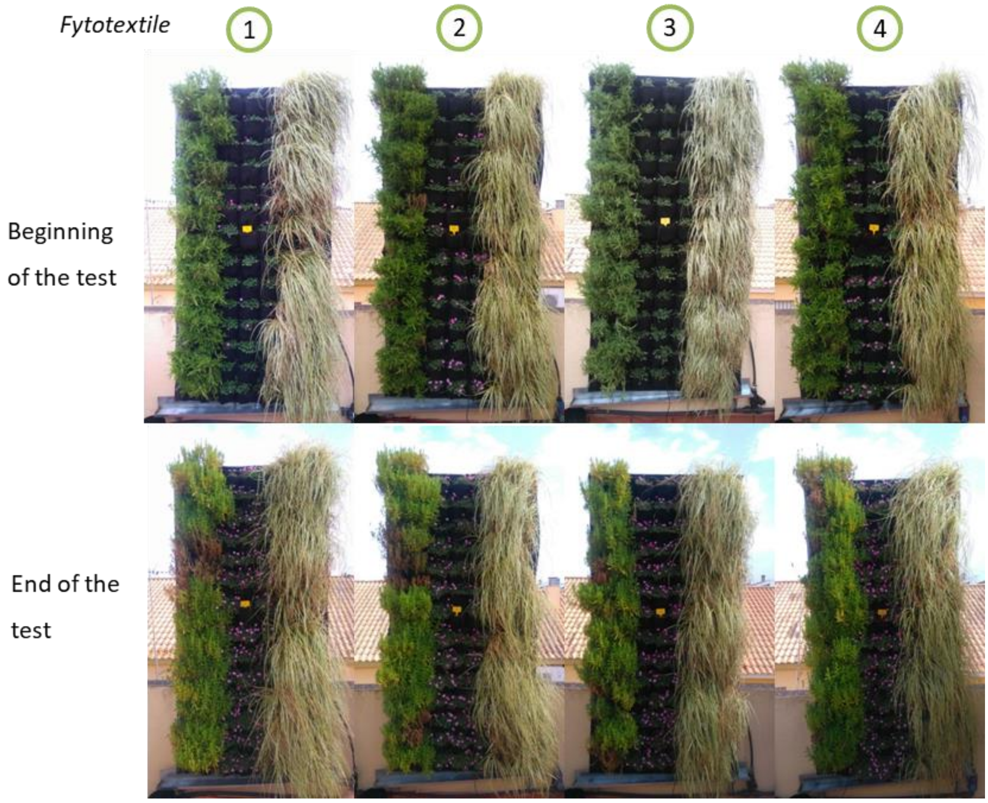

Figure 7. Visual evolution of the plants in the different Fytotextile systems (1 to 4) tested at the beginning and end of the vegetation performance test.

In terms of the moisture of the substrate inside the pockets, differences can be appreciated between the different systems tested (Figure 8). Fytotextiles 2 and 3 (averaging 35 and 36 %, respectively) showed the highest values while Fytotextile 4 had the lowest moisture level during the entire test (average value: 26 %).

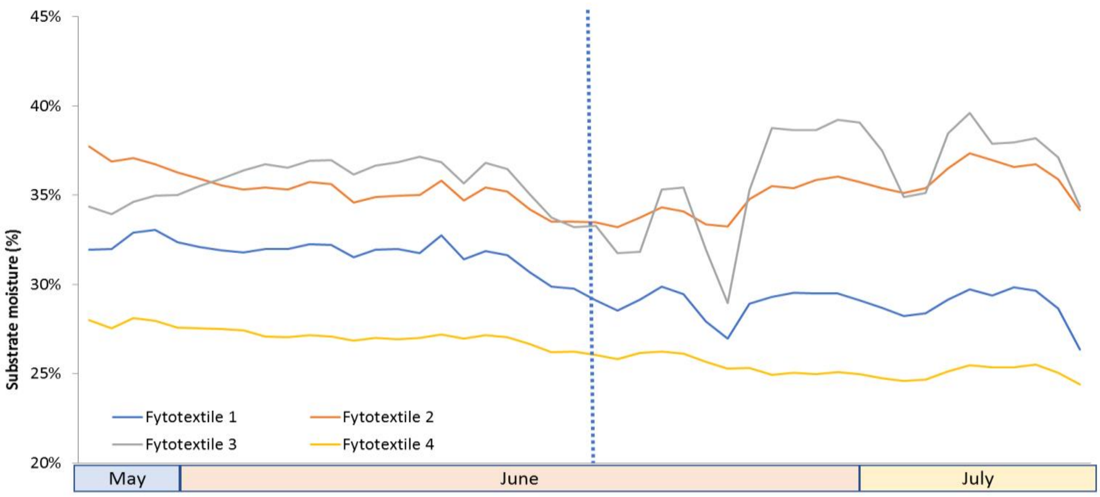

Figure 8. Evolution of the average daily substrate moisture (%) in the pockets throughout the test. The dotted vertical blue line denotes the moment when the irrigation duration changed from 15 to 10 minutes.

4. Discussion

The evolutions of the commercial Fytotextile system developed proved to have a superior performance compared to the standard system. Fytotextile 3 and 4 showed the best results in water retention capacity compared to the standard Fytotextile 1 (1.35 L m^{-2}), with a water storage increment of 2.6 and 6.5 L m^{-2}, respectively. Fytotextile 2 showed a minimum increase with only 0.16 L m^{-2} more. In addition, Fytotextile 3 and 4 conserved the water for a longer time. They kept 0.79 and 4.16 L m^{-2}, respectively, after 10 hours drying. However, achieving a higher capacity for water storage does not imply that the water is readily available for the plants, as a fraction of it can be difficult to absorb by the roots due to the high water retention of the material used. As observed in the drying curves (Figure 4) and the substrate moisture evolution (Figure 8), this can happen especially with Fytotextile 4, given the hydrophilic properties of the intermediate layer. Hence, the substrate in contact with this layer dries out faster. This is an undesirable fact especially right after planting (and until the roots anchor to the intermediate layer) and might influence the performance of the vegetation depending on the drought tolerance of the plants selected. However, this was not a problem in the present study, as observed in the test with vegetation.

The drying rate will affect the irrigation scheduling and will obviously depend on environmental conditions (i.e., solar radiation, air temperature and humidity, and wind speed). Nonetheless, the values shown in this study with the same conditions for all the systems allow a comparison between them.

In terms of the total volume of water drained, the worst behaviour (not counting Fytotextile 1) was observed for Fytotextile 4. This was caused by a higher initial water content prior to the irrigation events, due to the higher water holding capacity of the material used in it. Therefore, a better performance is expected for even lower irrigation frequencies than the ones tested. Fytotextile 2 presents the smallest amount of drainage water. This may be explained by it drying as fast as Fytotextile 1, but it can store a larger volume of water. In contrast, it is the one that produces the greatest drainage flows in most cases. This may happen due to the initial stages of the irrigation when the water is not absorbed, and the drainage water is produced basically because of the run-off, especially when the module’s initial water content is low. The same behaviour was described by Pérez-Urrestarazu et al. (2014) for a similar felt system and by Cortês et al. (2019) for a modular system using cork agglomerate boards. This is an undesired effect, given that most of the drainage volume is produced at the beginning of the irrigation event. Therefore, reducing the amount of water that drains just shortening the duration of irrigation is not possible in this case.

The irrigation schedule has a great influence on the excess of water wastage. In general terms, the daily water volume applied being the same, if the frequency (number of irrigation events in a day) is high, the drainage volume is also slightly higher, but the peak drainage flow is considerably reduced. Therefore, in order to optimise the water application efficiency, a high frequency is recommended provided the duration of the irrigation evens is reduced. Hence, the peak drainage flow would be reduced in the first stages of irrigation, but the total volume of water drained would not be too high. This is consistent with the findings of Pérez-Urrestarazu et al. (2014), who offered similar recommendations based on their results.
According to the vegetation performance, in all the cases the appearance results based on the health, growth, development and survival of the plant species were sufficiently satisfying. Fytotextile 3 and 4 showed better results in terms of plant survival, thought this is not necessarily due to the type of system employed as death of plants could have been caused by a number of factors (e.g. unhealthy plant before planting in green wall, poor plant handling, pests, etc). Nonetheless, the importance of the appropriate plant choice for a green wall based on the needs of each species should be underlined.

Figure 9 shows a graphic summary of the results obtained in the comparison of the four Fytotextile systems regarding different attributes.

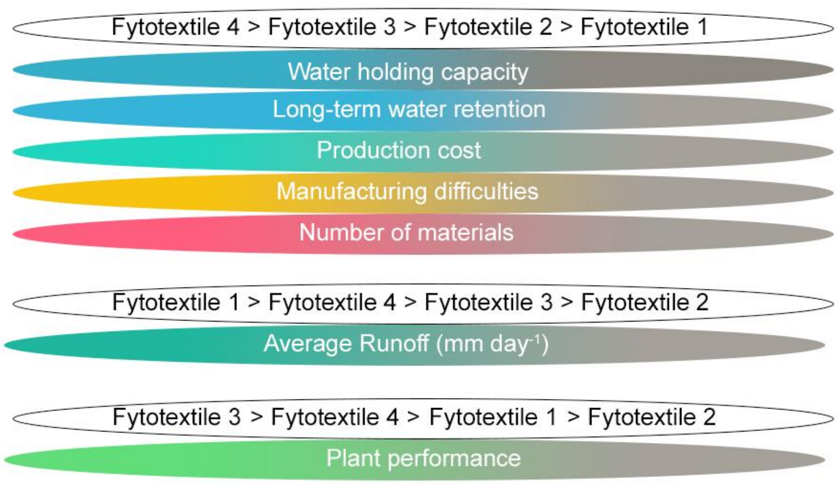

Figure 9. Comparative summary of results for each type of Fytotextile system. The '>' sign indicates a higher value in the attributes described below.

Apart from the results obtained, some other issues should be considered to determine which system is most suitable for the installation of a living wall. For instance, the standard module (Fytotextile 1) can be employed when the environmental conditions are not harsh (e.g., temperate climate, indoor locations), so an added water retention capacity is not really required. Also, the production costs, the manufacturing difficulties or the dynamic performance of the module are important variables to consider. For instance, Fytotextile 4 showed several deformations because of the expansion and contraction due to the hydration and drying phases, making it less suitable. In this sense, longer tests to assess the durability of the systems should be performed. The quantity and type of materials required should be considered too, as this influences both in the costs and the environmental impact. For example, only two layers are employed for Fytotextiles 1 and 2, while an additional polymer-based layer is added in Fytotextiles 3 and 4.

As mentioned above, the different types of Fytotextile studied are made using various materials. Some of them, such as polypropylene, have the possibility of being recycled later, when the lifespan of the living wall is over. However, in the future, it could be interesting to carry out other assessments such as a life cycle analysis, or calculating the carbon or water footprint. With that information it would be possible to make a more in-depth comparison between the different systems, also taking into account other parameters such as water consumption, energy consumption, CO_2 fixation, biodiversity enhancement, and other environmental benefits. In this way, it would be possible to choose those systems that are most suitable from the point of view of sustainability.

5. Conclusions

When using a felt-based system, its characteristics in terms of material selection and performance, number of layers, production cost and ease of manufacturing has proven to be important. There is a great abundance of various materials potentially appropriate for living wall systems. Thus, in the current study, three different evolutions of a broadly used standard commercial Fytotextile® system were assessed. The correct selection and combination of the materials affected several variables such as the water retention capacity and its duration, the drying speed of the system as well as the plant performance thus the sustainability of the living wall system.

However, not only the importance of a suitable irrigation management should be taken into account when selecting materials. The sustainability of the living wall system is provided by a complexity of parameters that need to be studied in the whole. For instance, further studies about the environmental impact of the materials used are necessary.

The irrigation performance is subjected, among other variables, to the system employed to build a proper, complete, and successful living wall. An adequate management of irrigation is required to keep a living wall in good condition, since a lack of water supply in periods of maximum demand can quickly produce a dehydration of the growing media and cause irreversible damages to the plants´ health.

The choice of a suitable irrigation schedule (number of irrigation events and their duration) had a great impact on the results. Short irrigation events and higher frequencies are expected to help to enhance the water use efficiency. This would lead to less water usage and, consequently, more sustainable living wall systems. In any case, the water content of the living wall must be enough to ensure a correct appearance of the vegetation, as it is an important factor which can profoundly affect the aesthetic value and maintenance costs, as well as the sustainability, of a green wall installation.

Given the complexity of the water management of living walls, further and long-term scientific analysis is necessary in order to obtain affordable and sustainable green wall systems. An improvement and optimisation of the existing commercial systems coupled with expanding knowledge to help irrigation scheduling could lead to reaching this goal.

The proper material selection and improvement of the irrigation management will also facilitate the plant selection process. Species less resistant to water scarcity could be incorporated, expanding the range of plants that could be used on green walls under demanding climate conditions. Thus, new market options in locations with extreme climate conditions (hot and dry, with not much water available) could be opened.

Acknowledgments

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2. Publication 2

Assessment of different LED lighting systems for indoor living walls

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Abstract

Building-integrated vegetation systems, such as living walls (LW), are becoming common tools for improving the sustainability of cities as well as an aesthetic resource. When used indoors, LW usually require a lighting system to ensure both an adequate plant development and a correct appearance. In this study, six commercial LED lighting systems are tested in order to assess their suitability for the proper performance of LW. The LW monitored were composed of two plant species (*Soleirolia soleirolii* and *Spathiphyllum wallisii*) frequently used in indoor LW. All the lamps tested (Aster and Dahlia of Ignia Green, Logar CMH, CLH and Forum of Lledó) proved to be apt for their use to light LW (except for the case of CF-UT01 of Panda Grow), as they showed a favourable performance in terms of plant development, with few differences between them in biomass production and green cover. The tested Aster (Ignia Green) and Logar CMH (Lledó) lamp models were not efficient for long distances between the vegetation and the light source. Despite these results, as illumination is one of the factors that determines the indoor ambience, aesthetics and viewers' preferences were also studied. According to the observers' perception, the Dahlia model (Ignia Green) was preferred by 54.4 % of the respondents, while the rest of the lamps were preferred less.

Keywords: vertical greening system, ornamental lighting, plant development, urban greening, viewer's perception

Nomenclature

Symbol	Units
ADW: Aerial Dry Weight	g plant^{-1}
AFW: Aerial Fresh Weight	g plant^{-1}
CRI: Colour Rendering Index	--
ET: Evapotranspiration	l d^{-1}
LED: Light-Emitting Diodes	--
LW: Living Wall (s)	--
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}
RH: Relative Humidity	%
Soleirolia: *Soleirolia soleirolii*	--
Spathiphyllum: *Spathiphyllum wallisii*	--
SPAD: relative measure of chlorophyll content	--
T: Temperature	ºC
TDW: Total Dry Weight	g plant^{-1}
TFW: Total (whole-plant) Fresh Weight	g plant^{-1}
LA: mean Leaf Area	cm^{2}leave^{-1}

Introduction

Nowadays, the inclusion of vegetation in the built environment in the form of green roofs and vertical greening systems is spreading. They are usually located outdoors, but in the case of living walls (LW), indoor installations are becoming frequent, given the multiple benefits which they offer, improving indoor air quality (particles and VOC retention), environmental conditions (temperature and humidity levels), acoustics and wellbeing (Gunawardena and Steemers, 2019; Moya et al., 2019). However, when plants are grown inside a building, one of the main constraints is the light that they receive. The available natural light in indoor environments is frequently not sufficient, thus auxiliary artificial lighting is often required for adequate plant growth and development (Tan et al., 2017).

Selecting the proper lighting system for indoor plant growth is a demanding process that requires an accurate prior study. It should ensure certain characteristics in terms of intensity (the amount of light received by the vegetation) and quality (the spectral composition of the light source) (GOTO, 2003). In the case of LW, regulating the intensity is even more complicated, given that the lamps are usually located in the ceiling, so the lighting is not uniform over the entire vertical surface. In terms of quality, not only obtaining an effective spectral range is essential but also ensuring that the LW have a proper appearance (Egea et al., 2014).

Artificial lighting technologies have been used in crop production for many years, with incandescent, fluorescent or high-intensity discharge lamps having been those most employed. However, the advance of solid-state lighting using light-emitting diodes (LEDs), with a great technical development in the last years and an important cost reduction, has displaced the other types of lamps. LEDs show several advantages such as a much longer lifespan and producing a high luminous flux with a low radiant heat output (Morrow, 2008; Yeh and Chung, 2009). This makes them more competitive in energy efficiency and economic terms (Singh et al., 2015).

LEDs also have the ability to emit in a controlled spectral composition (Olle and Viršile, 2013), which is an advantage when growing plants. Given that LEDs emit in a very narrow spectrum (20-40 nm), the specific peak absorption bands of chlorophyll can be targeted. This improves the use of energy as most emitted light can be used for photosynthesis. Precisely, that is the basis of commercial LED grow lights, which mainly emit in the blue and red regions. Nevertheless, they give plants an unnatural appearance due to their colour (red/blue), so they are not so apt for aesthetical purposes, including LW lighting. In addition, some studies indicate that a better plant growth is achieved when using a broader spectrum with additional wavelengths (Kim et al., 2006). This makes white light more adequate. In order to obtain white LEDs, blue LEDs are usually coated with phosphor. Though this makes them less efficient than the single-wave-peak LEDs, the visualisation of plants greatly improves (Massa et al., 2008).

In artificial lighting, the term white light refers to light formed by a mixture of colours. However, not all whites are the same, since they depend on the colours that compose them. In this sense, a white with a higher proportion of red will favour a "warmer" lighting and a white with a higher proportion of blues will give a "cooler" appearance. Colour temperature is used to classify the different types of white light and to facilitate comparison with "full spectrum" sunlight (Morrow, 2008). This concept refers to the type of light that a black body radiates when heated to a specific temperature, so that the higher the colour temperature, the colder the light source. For instance, at 2,000-3,000 K, the colour of the light will look white yellow; at 4,000 K, neutral white, and at 5,000-7,000 K, cold white. Shaw (2018) suggested that colour temperature has an effect on the growth of hydroponic lettuce seedlings, as plants under 6,000 K lights grew more than under 3,000 K. However, even when two light sources have the same colour temperature, the surfaces can be seen in different colours, given that two lights that appear to produce the same white may be the result of different wavelength mixes. For this reason, the concept of colour rendering is used to elucidate the similarity between the natural colour of an object (that is, in daylight conditions) and its colour under artificial lighting. Based on this concept, the colour rendering index (CRI) classifies light sources according to their colour rendering properties: the higher the CRI, the closer it is to natural colour.

LED lighting in horticultural production has been widely addressed (Islam et al., 2012; Massa et al., 2008; Morrow, 2008; Olle and Viršile, 2013; Samuoliene et al., 2013; Singh et al., 2015), but it has not been studied when it is used with an ornamental purpose (as is the case of LW illumination). Only Tan et al. (2017) and Egea et al., (2014) have addressed this topic. The former quantified the impact of growth light provision on indoor greenery and the light compensation point of two ornamental species. The latter analysed different artificial lighting systems for LW, but in their study LEDs were not contemplated.

The main objective of the current study was to assess the adaptation of six different commercial LED lamps (five of which were not specifically designed for plant growth) for the lighting of indoor LW. Both the performance and correct development of the vegetation under each lamp and its appearance were taken into consideration. The study was completed with an analysis of public preferences.

Materials and methods

Experimental setup and tests performed

The study was performed at the Urban Greening Laboratory of the School of Agricultural Engineering of the University of Seville (Seville, Spain), with no natural light. Six different types of lamps were tested in this study and two experiments were carried out. Five of the lamps were conventional white LED lamps (4000 K) while one (C) was a commercial Grow-LED lamp specially designed for plant cultivation. Table 1 presents the main characteristics of each lamp and Figure 1 shows the relative emission intensity spectrum, when available. The first experiment involved lamps A to C and was conducted over the period mid-May to end-July 2018 (68 days). During this period, the daily mean room temperature and relative humidity were 24.9±0.7ºC and 68± 5 %, respectively. Lamps D, E and F were tested in a second experiment from mid-February to end-April (70 days). In this case, the daily room temperature was 22.4 ± 0.6 ºC and the relative humidity was 56 ± 7 %.

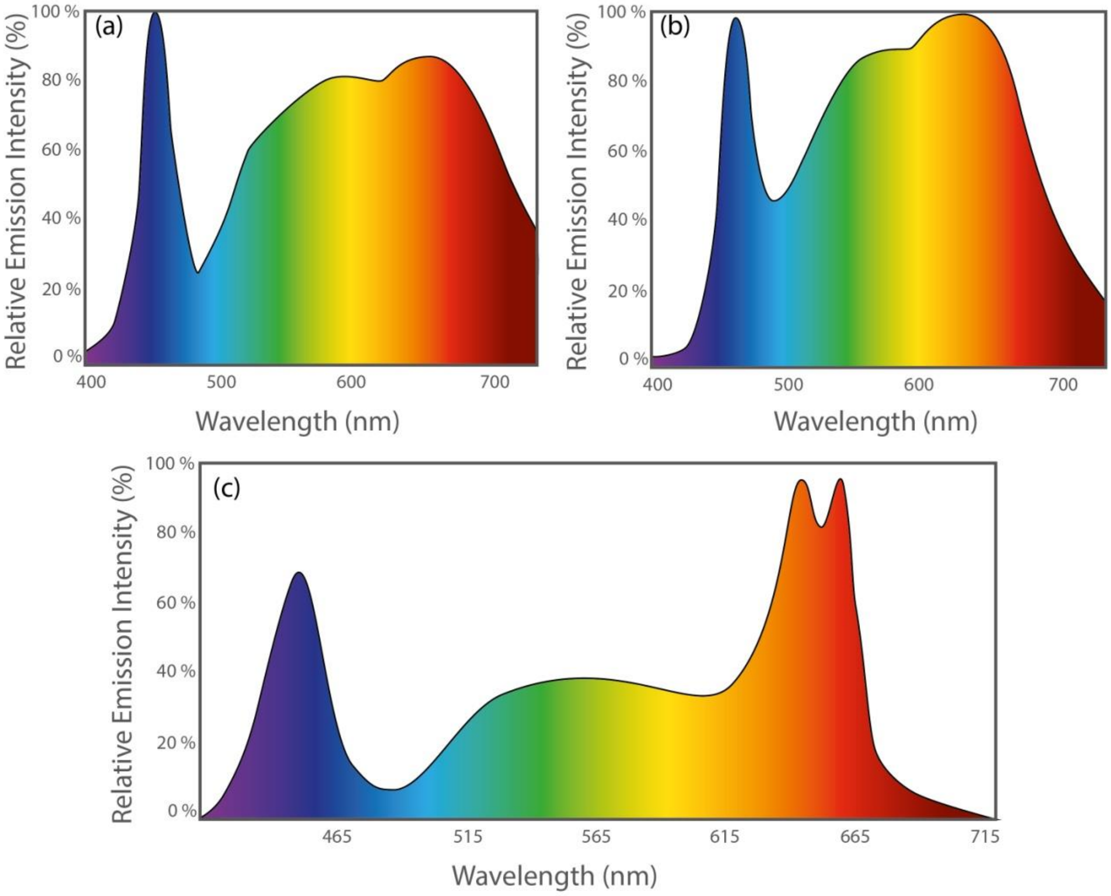
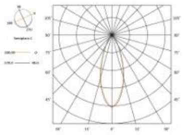
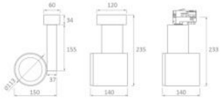
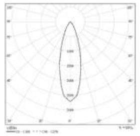
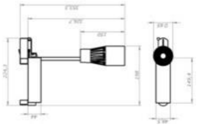
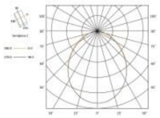
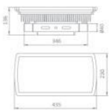
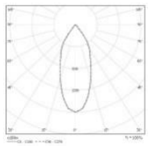
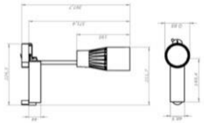
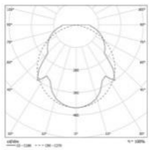
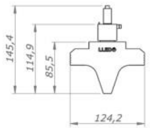


Figure 1. Relative emission intensity (%) spectrum for a) Lledo, Forum lamp b) Lledo, CMH, CLH lamps and c) Ignia Green, Aster and Dahlia. (Graphs courtesy Lledo and Ignia green, images modified)

Table 1. LED lamps used in the study and their characteristics. The different letters (A, B, C, D, E, F) refer to different lamp type treatments and the different numbers (1 or 2) refer to module closer (1) or farther (2) to the light source.

Lamp Model	Projector	Curves	Dimensions	Manufacturer	LW module	Power (W)	Flux (lm)	CRI	Beam angle (º)	Colour temperature (K)	Type of light
Aster				Ignia Green (Girona, Spain)	A1	40	2.575	>90?	36º	3.700	White
Logar CMH Superflood				Lledó (Madrid, Spain)	B1	35	2.650	>90	31º	4.000	White
CF-UT01		NA		Panda Grow (Shenzhen, China)	C1	100	5.000	NA	120º	NA	Blue/red
Dahlia				Ignia Green (Girona, Spain)	D1-D2	110	7.950	>90?	97º	3.700	White
Logar CLH Superflood				Lledó (Madrid, Spain)	E1-E2	48	3.300	>90	*41º	4.000	White
Forum				Lledó (Madrid, Spain)	F1-F2	83	7.350	>80	68º	4.000	White

* Due to its small beam angle, two identical lamps of this model were placed at the same spot with different angles pointing at the centre of each of the two modules. NA: Not available

In the first test, only one lamp per LW module was placed at a distance of 1 m from the wall where the LW modules were installed, pointing at the centre of each LW module (100º) (Figure 2). In the second test, as the light intensity provided by the lamps was adequate at a higher distance, a second LW module was added right below the existing ones to test the capacity of these lamps to light a higher LW up. D and F lamps were pointing between the two LW modules at a distance of 1 m from the wall and with a 120º inclination angle. E1 was pointing at the centre of the upper LW module (100º), 0.80 m apart from the LW module surface. E2 was angled to face the centre of the lower module (140º), at a distance of 1.50 m from it. The 3 phase electrified rails of the lamps B, E, F and the lamps A, C, D were attached in a metallic base 0.50 m from the ceiling. Thus, all lamps were placed just in front of the middle of the upper LW module.

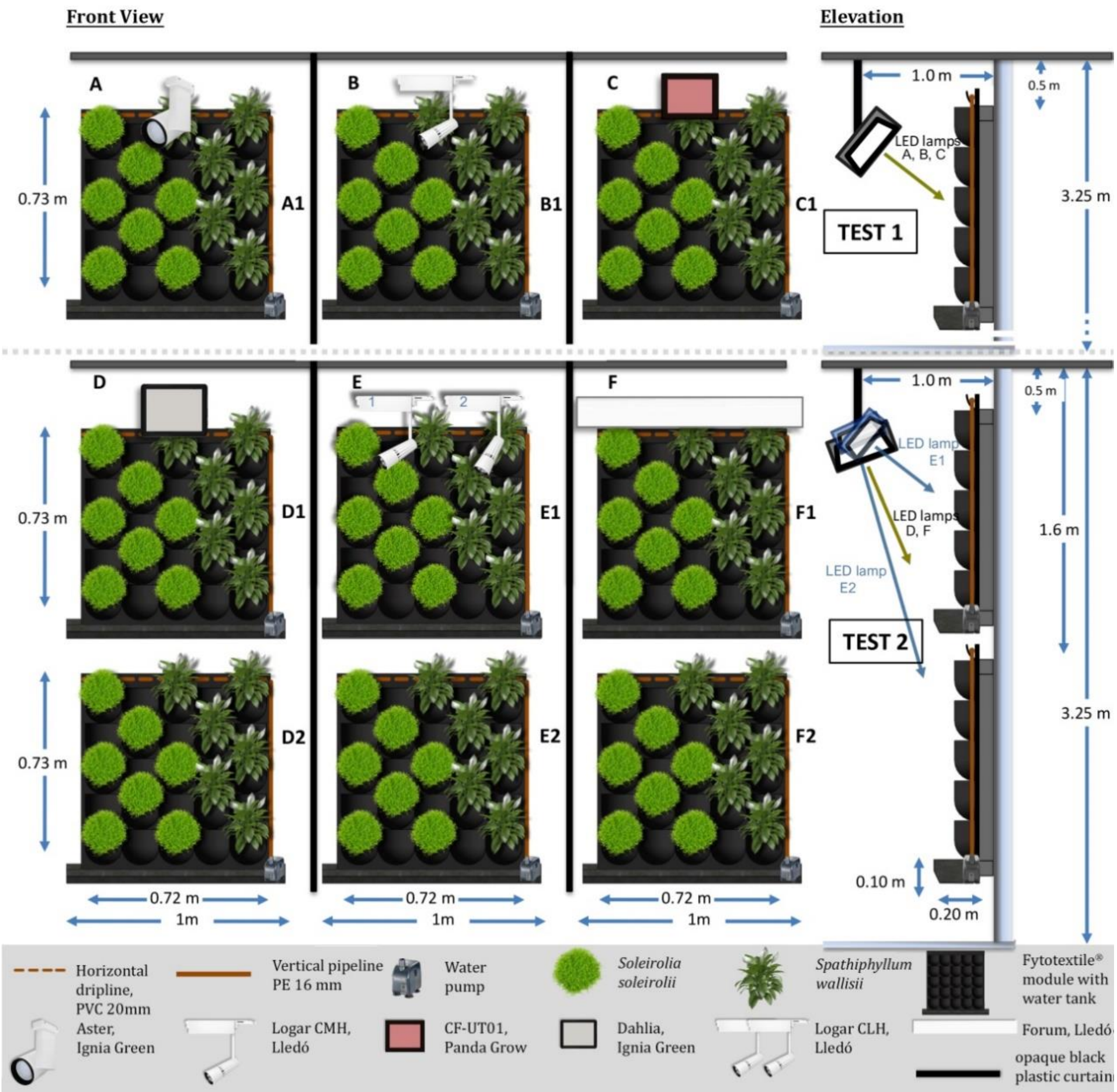


Figure 2. Layout of the experiment. Distribution of lamps and living wall modules and location of the plants for tests 1 (up) and 2 (down).

The inclination angles were determined by doing a simulation using the professional DIALux evo lighting design software (DIAL, Lüdenscheid, Germany) for professional light planning, to optimise their illumination. The different LW modules were separated from each other using opaque black plastic curtains and a constant photoperiod of 14 hours per day was provided during both trials.

The LW modules, similar to those employed in Egea et al. (2014), were based on a felt commercial system (Fytotextile®, Terapia Urbana S.L, Spain), with dimensions of 0.72 m wide by 0.73 m high. Each of the LW modules' structures was composed of three synthetic layers: an outer hydrophobic layer made of polyamide; an inner layer of recycled hydrophilic fibres (geotextile) which contributed to homogeneously distributing the water; and a waterproof back layer. The first two layers were sewn together with nylon thread forming a 13.5 cm x 13.5 cm grid resulting in 25 pockets (5 rows and 5 columns) where the plants were inserted. Watering was provided by means of a lateral PVC dripline with perforations spaced 30 mm apart, connected by a vertical polyethylene (PE) pipe to a submerged compact water pump with a flow of 250 L h^{-1} (Compact 600 7 W, Eheim, Germany) located in a water tank placed at the bottom of the LW module. The tank served as a water reservoir, collecting the excess of water drained from the modules at the same time. Electrical conductivity and pH were periodically measured in the water tanks in order to ensure that there were no other factors affecting the results whereas there was neither a fertilizing nor pesticide implementation. Three-minute irrigation events twice a day were scheduled for all the modules during both tests. The recharge volume used to fill each tank up was recorded in order to determine water consumption due to evapotranspiration (ET).

Air temperature (T, ºC) and relative humidity (RH, %) readings of the LW surface were obtained hourly for each LW module throughout both tests using a HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger (Onset Computer Corporation, Bourne MA, USA). The sensors were placed at the same level as the central pocket of each module and separated 0.2 m from the module.

Plant species used and planting design

In order to be able to compare the results obtained in this study with previous experiments (i.e., Egea et al., 2014; Pérez-Urrestarazu et al., 2019), *Spathiphyllum wallisii* Regel (*Spathiphyllum*) and *Soleirolia soleirolii* (Req.) Dandy (*Soleirolia*) were the two species selected for the trials. *Spathiphyllum*, commonly known as peace lily, is an evergreen perennial flowering plant in the Araceae family, grown for its foliage and flowers, suitable for indoor use. *Soleirolia*, commonly known as baby's tears or Irish moss, is a mat forming usually evergreen prostrate perennial with small, round, vivid green leaves in the Urticaceae family (Christopher Brickell, 2011). Both of them are very commonly used in indoor LW installations. Thus, *Spathiphyllum* was specifically chosen in order to monitor the flowering, while *Soleirolia* was used to address the vegetal covering. In each of the LW modules, the number of plants (7 of *Soleirolia* and 6 of *Spathiphyllum*) and their distribution was the same (depicted in Figure 2). All plants used had the same size (9 cm pot diameter for *Spathiphyllum* and 10.5 cm for *Soleirolia*) and were planted at the beginning of each test, inserting the rootball, without adding any growing media, in the pockets of the LW modules.

Plant development monitoring

From when the LW modules were planted, the number of flowers per individual *Spathiphyllum* was counted weekly. Moreover, in order to assess the evolution of the vegetation cover during the tests, RGB images of each LW module were taken on a weekly basis from the same position. The fraction of the LW area covered by vegetation was determined using the image-processing software ImageJ (Rueden et al., 2017), separating the pixels corresponding to green cover from the background.

Photosynthetic activity (as an indirect measure of greenness,determined by the relative chlorophyll content) was measured at the end of each test in *Spathiphyllum* leaves by means of a hand-held Minolta SPAD-502 chlorophyll meter (Konica Minolta Optics, Inc, Japan). Thus, five measurements per leaf were performed in three leaves per plant and six plants per module. The Normalised Difference Vegetation Index (NDVI), is a unitless index which indicates the health and vigour of the plants and ranges from −1 to 1, corresponding the highest positive values to healthy vegetation (Turvey and Mclaurin, 2012). NDVI was obtained by making five measurements in each LW module at the middle and end of each test using a GreenSeeker handheld crop sensor (Trimble, Sunnyvale, CA, USA).

At the end of each test, all the plants were detached from the LW in order to characterise the total biomass production. Subsequently, the growing media was thoroughly removed from the roots by carefully washing with tap water. Next, the aerial part of each of the plants was separated from the root system, in order to separately obtain fresh and dry weights of both parts using an AH-300 precision scale (I.C.T, S.L., La Rioja, Spain). Before drying the *Spathiphyllum* leaves (in an oven during 48 h at 80 ºC), an LI-3100 Leaf Area Meter (Li-Cor, Nebraska, USA) was used to determine total leaf area (TLA, $cm^2 \cdot plant^{-1}$) per plant.

Light measurements

The light intensity reaching different points of the LW modules was determined both at the beginning and at the end of the tests. A line quantum sensor (LI-191 Line Quantum Sensor, Li-Cor, Nebraska, USA) was used to obtain the mean photosynthetic photon flux density (PPFD, $\mu mol\ m^{-2}\ s^{-1}$). Three PPFD readings were taken at the top, middle and bottom of each LW module. At the same time, the PPFD values were obtained for each lamp at different distances (from 0.5 m to 5 m) from the light source. Also, the illuminance (luminous flux per unit area, lx) was measured in 13 points of each LW module (corresponding to the location of the plants) by means of a lux meter (model 0635 0545) attached to a multifunctional meter (Testo SE & Co. KGaA, Lenzkirch, Germany) and compared with a simulation carried out using the DIALux evo software.

Observers' perception

A survey was performed in order to evaluate the observers' perception of the LW using each of the LED lamps. A hundred random observers (50 were male and 50 female; 5, 35, 49 and 11 participants were in the age range of 18-25, 26-40, 41-65 and over 65 years old, respectively) were presented with a questionnaire after watching each of the upper LW (with lights on) at the final stage of the experiment. The perception study only contemplated the lamps used, not the distance to the light source. Therefore, only the upper modules were involved in the observers' questionnaire. Following a similar approach to Jost-Boissard et al. (2009), they were asked for each case if the colours under that lamp were attractive and if the plants had a natural appearance. They had to answer using a Likert scale from 1 (not much) to 5 (very). They were also asked to arrange the different lighting systems by preference from the most suitable to the least.

Statistical analysis

Each of the nine LW modules constituted a discrete experimental unit with six and seven replicates for *Spathiphyllum* and *Soleirolia*, respectively, within each unit. An Analysis of Variance (One-Way ANOVA) was performed having as a factor the lamp type (6 types) per distance (1 m, 1.5 m) and eight dependent variables (aerial and root dry and fresh weight, total fresh and dry weight, mean leaf area and NDVI). Thus, the analysis assessed the impact of the lamps and the corresponding distances to the light source on vegetation performance and on the daily water consumption. For the statistical analysis of daily water consumption, a comparison of means was realized using the values observed in each day of the experiment. For the NDVI analysis and due to the nature (i.e., percentages) of our data, the arcsin transformation was applied prior to statistical analysis (McDonald, 2014). The analysis was carried out using the statistical package Statgraphics (Statgraphics Centurion XVII) and Duncan's multiple range test was used for means separation at the significance level P ≤0, 05.

Results

Lighting pattern

The distribution of the luminous flux per unit area received in the different points of the LW modules is shown in Figure 3. The highest illuminance values are observed in all cases in the middle of the upper LW module, while they are usually lower at the bottom of the module. The highest average value of illuminance was observed in module E1 (6453 lx), followed by A (4310 lx) and B (3957 lx). In the latter, the luminous flux was more focused in the centre of the LW module, while in the rest of the modules, the illuminance values were more homogeneous. Module C was the one receiving a lower illuminance in all the points (average of 424 lx). D1 and F1 showed a similar illuminance distribution (mean values of 3778 and 3605, respectively), though in the latter the luminous flux was more centred in the middle, the upper and lower parts of the module receiving less light. In D2 and F2, the illuminance values were obviously lower (averages of 1252 and 1362 lx, respectively) and decreased from the top to the bottom. The illuminance values observed in E2 were, however, much higher (with an average of 3045 lx), with similar levels to those observed in D1 and F1 (though at the bottom of the module they considerably decreased).

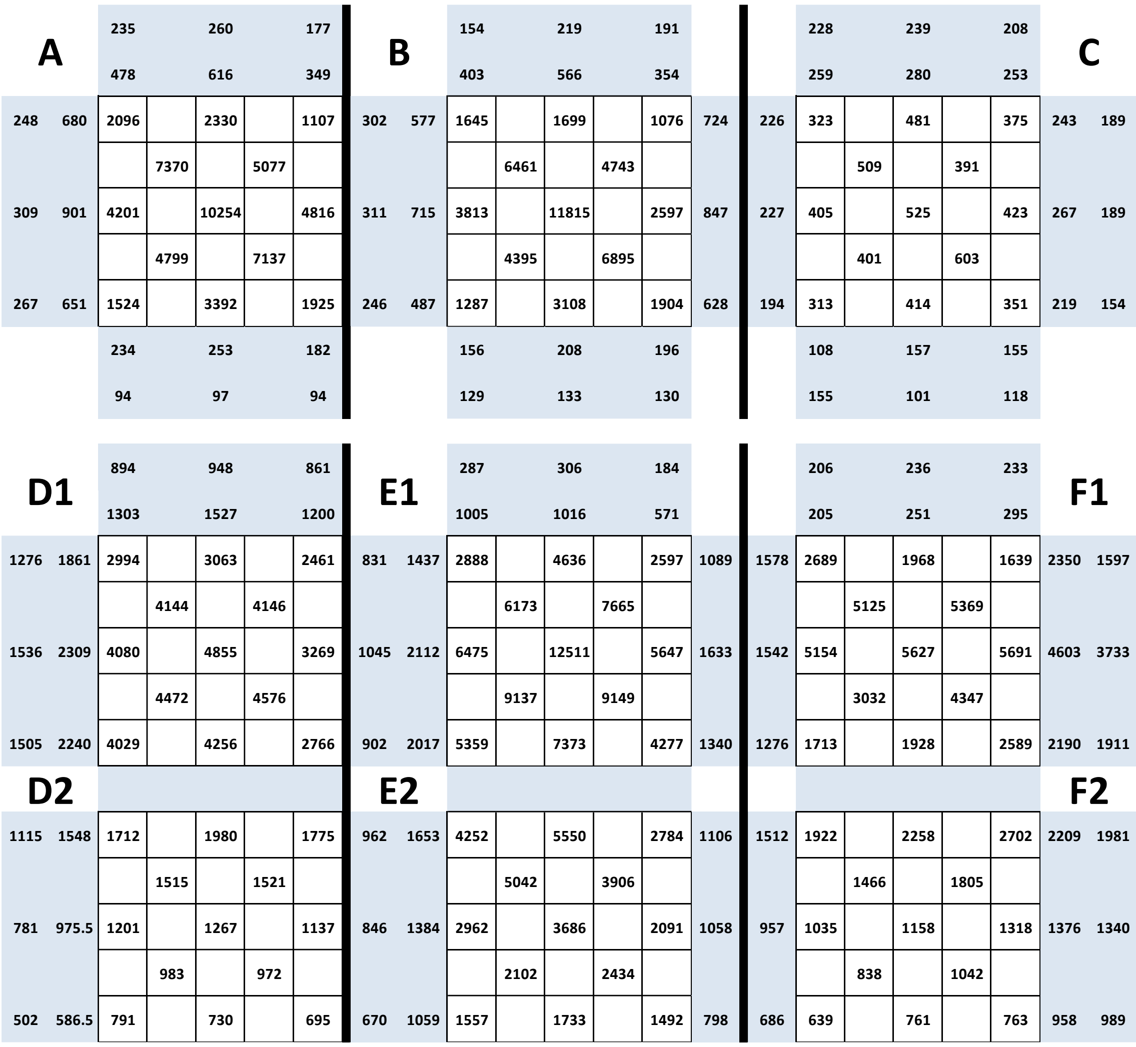


Figure 3. Illuminance values (lx) in different locations of the living wall modules and close to them for tests 1 (up) and 2 (down)

Table 2 shows the mean PPFD values measured at three heights in each module. For lamps A, B and C, the PPFD was also obtained in the locations where the lower modules would have been, but the values were below 3 μmol m^{-2} s^{-1} (making plant survival very difficult). As in the case of the illuminance levels, the highest values are obtained in the middle of the upper modules. E1 was the LW module receiving a higher value (an average of 82.5 μmol m^{-2} s^{-1}), followed by D1 and F1 (71.9 and 60.3 μmol m^{-2} s^{-1}). Conversely, A1 and B1 showed similar PPFD values (35.7 and 25.6 μmol m^{-2} s^{-1}, respectively) to those observed in the lower modules in the second test (27.8, 48.8 and 32.3 μmol m^{-2} s^{-1}

for D2, E2 and F2, respectively). Module C received very poor values (7 μmol m^{-2} s^{-1} in average).

Table 2. Mean Photosynthetic Photon Flux Density values (μmol m^{-2} s^{-1}) for all lamps (A to F) in the upper (1) and lower (2) modules at three different heights (Up, Mid, Down) within each module.

		A	B	C	D	E	F
	Up	28.9	13.3	7.3	62.6	58.6	58.0
1	Mid	55.2	43.7	7.7	78.7	109.9	88.8
	Down	23.0	19.8	5.9	74.2	78.9	34.0
	Up	1.9	2.9	2.2	38.3	73.8	44.1
2	Mid	0.6	0.7	1.2	26.0	52.7	32.3
	Down	0.4	0.3	0.8	19.2	19.9	20.4

Both the illuminance received and the PPFD depend, among other factors, on the distance to the light source. Figure 4 shows the different values of these two factors according to the distance from the LW to the different lamps tested. In the first metre, the values severely decrease, while this decrease is observed to be less intense as the distance increases.

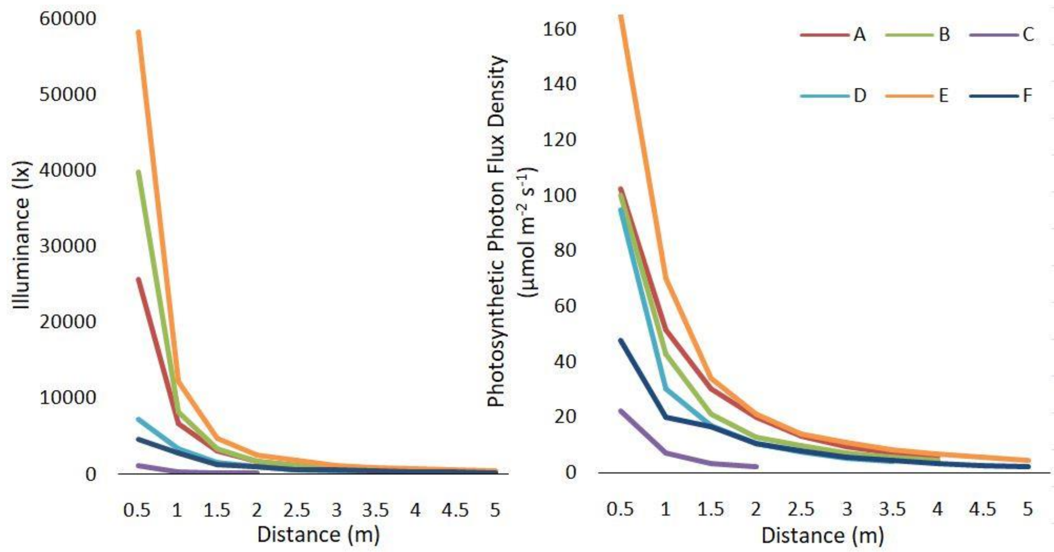


Figure 4. Illuminance (left) and Photosynthetic Photon Flux Density (right) at different distances from the light source for each lamp.

Figure 5 represents the relation between the measured values of illuminance vs the PPFD for the different lamps, hence obtaining the conversion equations between both factors, which are distinct for each lamp. Lamp A exhibited a good relation, comparing to the rest lamps, where then minimum illuminance of 420 lx corresponds to 5.8 μmol m^{-2} s^{-1} and a 1048 lx corresponds to 13.2 μmol m^{-2} s^{-1}. Lamp C presented the most elevated PPFD value (22.2 μmol m^{-2} s^{-1}) in 1136 lx, though, to be achieved, a short distance of 0.5 m is required (Figure 4). Lamp D had the highest PPFD value (94.8 μmol m^{-2} s^{-1}) when illuminance reaches 7204 lx. Lamp E showed a good relation between PPFD and illuminance.

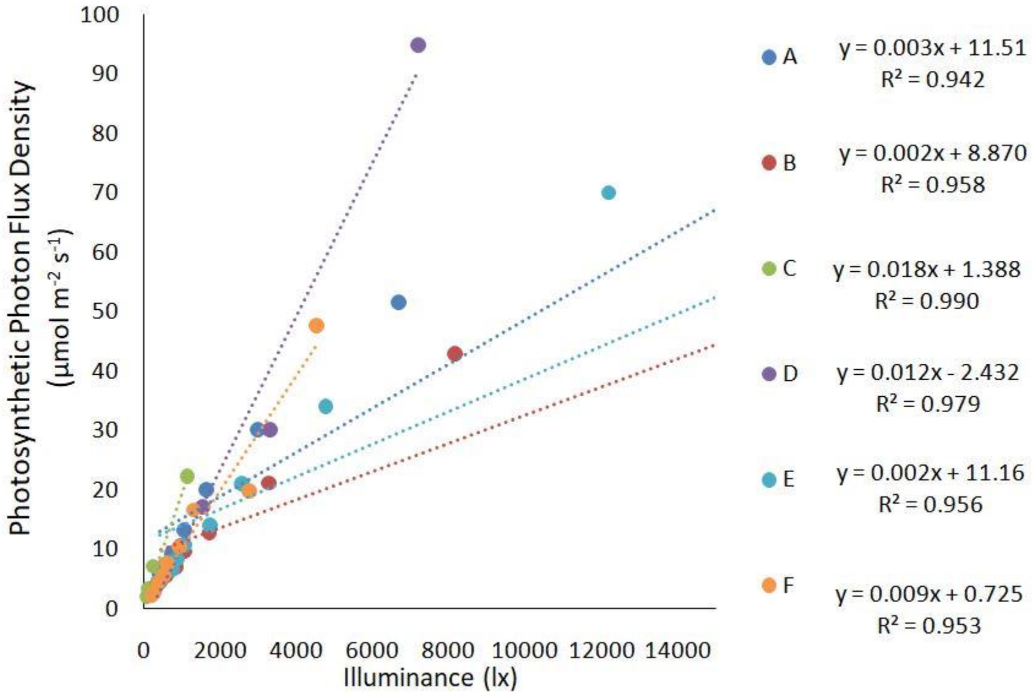


Figure 5. Relation between illuminance (lx) and Photosynthetic Photon Flux Density.

Finally, an illuminance simulation of both tests was performed in DIALux evo (Figure 6), showing a very similar pattern of lux levels to that depicted in Figure 3. The Pearson correlation coefficients results (0.95, 0.98, 0.92, 0.89, 0.95, 0.88, 0.79, 0.77 and 0.98 for modules A, B, C, D1, D2, E1, E2, F1 and F2, respectively) exhibited that the correlation between the simulations (Figure 6) and the actual measured values (Figure 3) was high, being slightly inferior for the lower modules.).

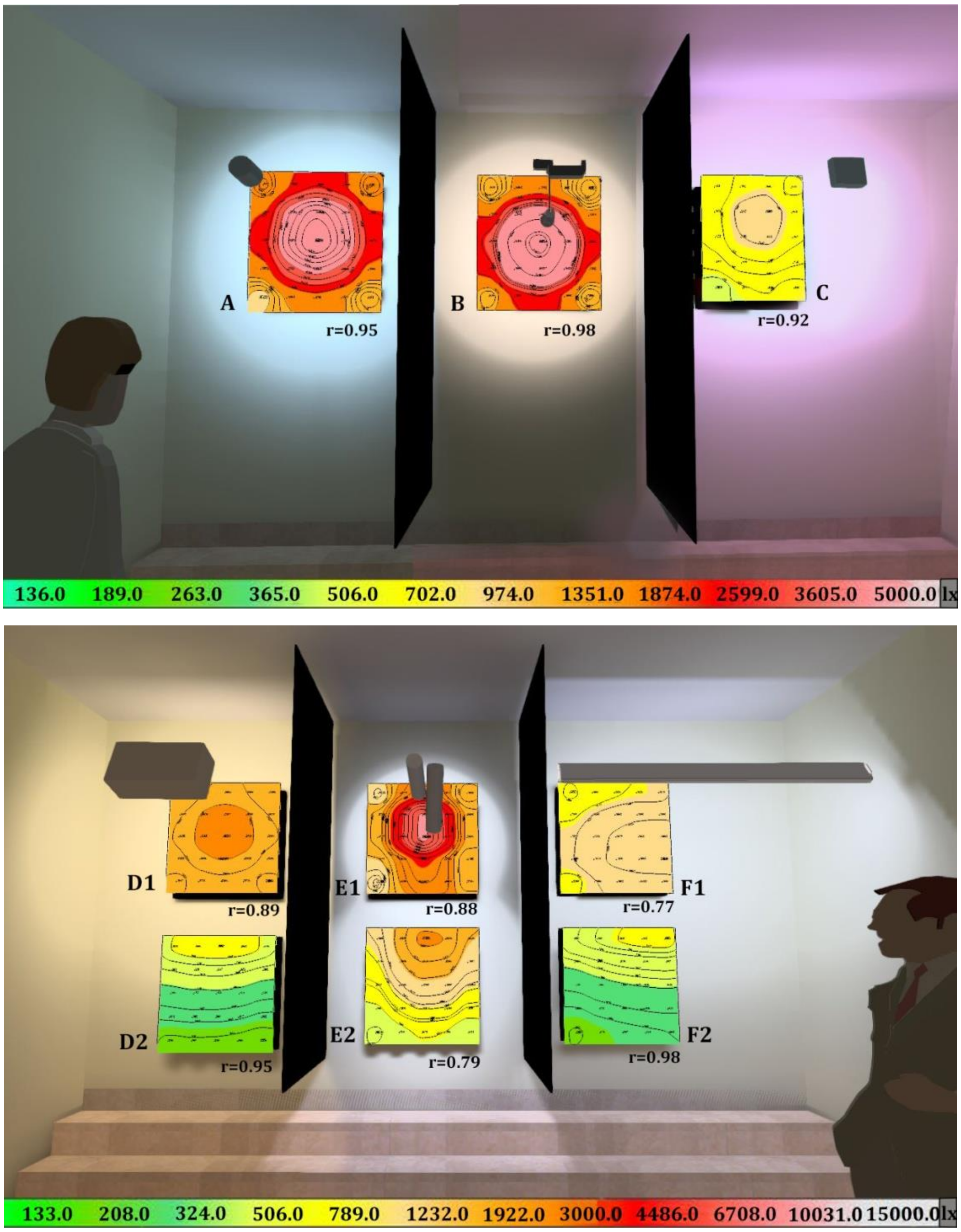


Figure 6. Simulation of illuminance levels for Test 1 (up) and Test 2 (down) using DIALux evo software and Pearson correlation coefficients (r) between the simulation and the measured illuminance values (lx).

Temperature and water consumption

The evolution of the temperature (T) close to each module is depicted, for both tests, in Figure 7. Variations in T were within 5ºC even between tests. The average T of test 1 and test 2 differed by 3ºC. During test 2, a difference of 1ºC on average was observed between the upper and lower modules except for D1 and D2 which did not differ. RH ranged between 50 % and 70 %. The average values were higher for the first test. In the second test, the RH was lower in the upper modules compared to the lower ones.

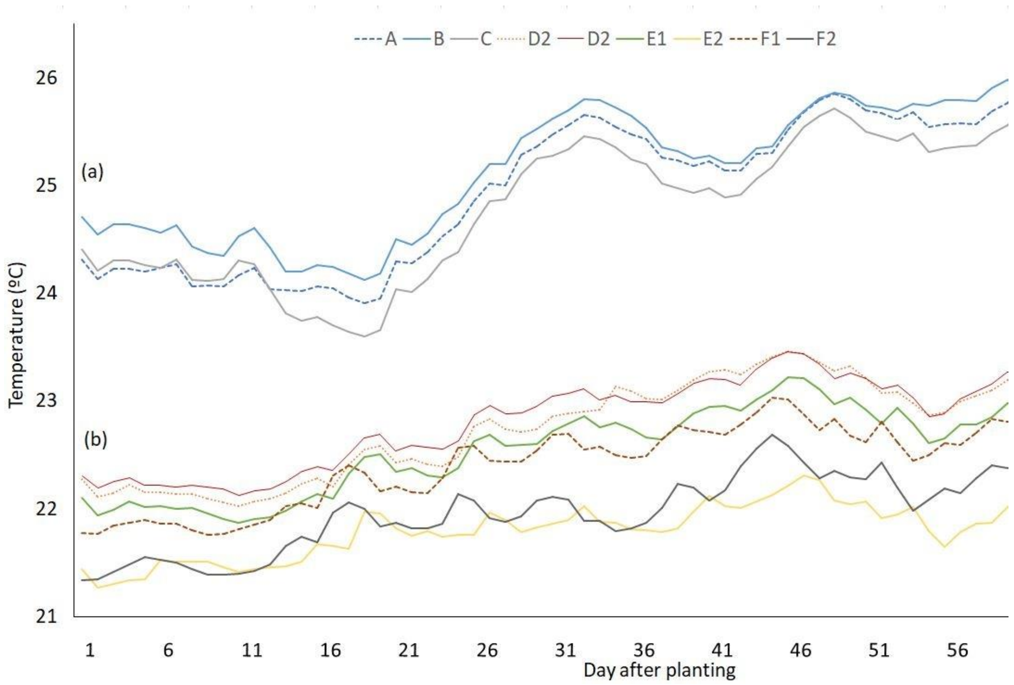


Figure 7. Evolution of the mean daily temperature near each living wall module during both tests

The average daily water consumption ranged between 1 and 1.5 L m^{-2} d^{-1} (Figure 8), resulting in more water consumed in module D2 (50.4 L) compared to B (35.2 L). Statistically significant differences (F = 2.834198; P-value = 0.00617977) in the average daily water consumption values were observed.

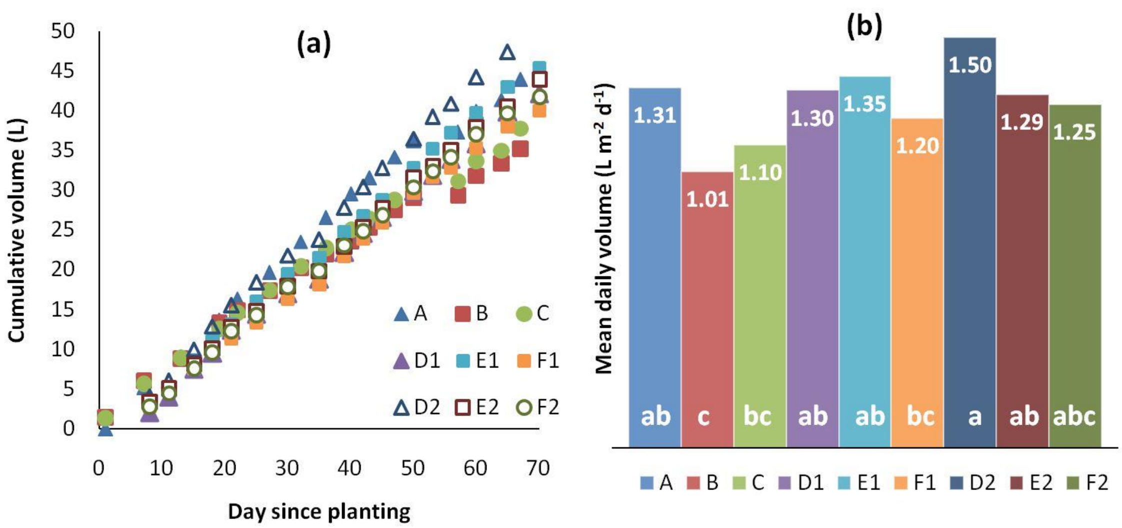


Figure 8. Water consumption in the different living wall modules: (a) Cumulative evolution during the tests (L) and (b) mean daily values (L m^{-2} d^{-1}). Different letters at the bottom of the bars indicate significant differences following Duncan's multiple range test ($P < 0.05$)

Vegetation performance

Plant biomass produced in each of the LW modules was calculated at the end of the tests. Both fresh and dry weights per plant were measured for the aerial and root parts. Total leaf area (TLA) was also obtained only for *Spathiphyllum*.

In the case of *Spathiphyllum* (Table 3), differences in fresh weight were more significant in the aerial part,while significant differences were exhibited only in the root system of module A. Module A had the higher fresh weights, while E2 presented the lowest. No differences were observed in fresh weight within modules lighted by lamps D, E and F. However, looking into their dry weights, the only significant difference occurred in the aerial part between E1 and D2. Even though no significant differences between upper and lower modules were observed, dry biomass in lower modules was 82.2 % of the average observed in the upper ones. Plants in module D2 had the lowest dry biomass, being 57 % of the obtained in module A, which produced the highest value (significantly different to the rest, excepting modules B and E1). There were no significant differences in leaf area.

Table 4 shows the biomass production for *Soleirolia* plants. In this case, a much lower weight per plant was obtained in module C (especially regarding the aerial part), followed by F2.The total dry weight of plants in module C was 35 % of that obtained in D1 and E1. Plants grown in lower modules had, on average, 66 % of the dry weight of the plants in the upper modules. However, lamps D and F showed significant differences between the upper and lower modules only due to the root part, and no differences were found for lamp E. Precisely, lamp F was the one with a lower biomass production in the lower modules, as the average total dry weigh of plants in module F2 was 57 % of that observed in E2 (though no statistically significant differences were found between both).

Table 3. Weights and leaf area of *Spathiphyllum* plants. TFW: total fresh weight; RFW: root fresh weight; AFW: aerial fresh weight; TDW: total dry weight; RDW: root dry weight; ADW: aerial dry weight; LA: mean leaf area.

Measured variables	LW module									*P-value*
	A	B	C	D1	E1	F1	D2	E2	F2	
TFW (g $plant^{-1}$)	170.5a	134.9b	112.8bc	94.4cd	102.0cd	97.8cd	88.7cd	82.5d	93.5cd	0.0000
RFW (g $plant^{-1}$)	43.50a	30.04b	21.30b	22.53b	26.82b	26.94b	23.18b	26.08b	24.43b	0.0005
AFW (g $plant^{-1}$)	126.9a	104.82b	91.47bc	71.84d	75.22cd	70.91d	65.53d	56.41d	69.05d	0.0000
TDW (g $plant^{-1}$)	14.89a	12.29ab	10.71bc	11.29bc	12.53ab	10.94bc	8.50c	9.95bc	10.12bc	0.0150
RDW (g $plant^{-1}$)	3.94a	2.65abc	1.41c	2.60abc	3.55ab	2.92abc	2.05abc	3.06abc	2.39abc	0.0478
ADW (g $plant^{-1}$)	10.94a	9.64ab	9.31ab	8.70bc	8.98abc	8.02bcd	6.44d	6.89cd	7.73abc	0.0014
ADW / RDW	2.78	3.64	6.60	3.35	2.53	2.75	3.14	2.25	3.23	-
TFW / TDW	11.5	11.0	10.5	8.4	8.1	8.9	10.4	8.3	9.2	-
LA ($cm^2 leave^{-1}$)	15.73bc	14.27c	14.70bc	15.07bc	14.10c	13.28c	17.53b	14.20c	13.13c	0.0768

For each row, mean values followed by different letters indicate significant differences following Duncan's multiple range test ($P< 0.05$) and each value is the mean of six replicates (n=6) per experimental unit (A, B, C, D1, E1, F1, D2, E2, and F2).

Table 4. Weights determined for *Soleirolia* plants. TFW: total fresh weight; RFW: root fresh weight; AFW: aerial fresh weight; TDW: total dry weight; RDW: root dry weight; ADW: aerial dry weight.

Measured variables	LW module									*P-value*
	A	B	C	D1	E1	F1	D2	E2	F2	
TFW (g $plant^{-1}$)	65.3bcd	61.0cde	36.1e	92.2ab	104.1a	70.2bcd	77.4abcd	84.4abc	51.4de	0.0001
RFW (g $plant^{-1}$)	10.5e	10.3e	11.6de	29.4ab	32.7a	24.4bc	19.1cd	21.2bc	8.1e	0.0000
AFW (g $plant^{-1}$)	54.8ab	50.6ab	24.5c	62.8ab	71.4a	45.8bc	58.2ab	63.2ab	43.4bc	0.004
TDW (g $plant^{-1}$)	9.73ab	8.83ab	3.93d	11.14a	11.20a	7.75abc	7.00bcd	8.12ab	4.67cd	0.0000
RDW (g $plant^{-1}$)	1.52cd	1.28cd	1.32cd	3.92a	3.73ab	2.59bc	1.74cd	1.74cd	0.74d	0.0000
ADW (g $plant^{-1}$)	8.21a	7.56ab	2.62d	7.22ab	7.47ab	5.16bcd	5.26ab	6.38abc	3.92cd	0.0002
ADW / RDW	5.40	5.91	1.98	1.84	2.00	1.99	3.02	3.67	5.30	-
TFW / TDW	6.7	6.9	9.2	8.3	9.3	9.1	11.1	10.4	11.0	-

For each row, mean values followed by different letters indicate significant differences following Duncan's multiple range test ($P < 0.05$) and each value is the mean of seven replicates(n=7) per experimental unit (A, B, C, D1, E1, F1, D2, E2, and F2)..

The evolution of the green cover expressed by the % of the LW module covered by vegetation is shown in Figure 9. The vegetation initially covered around 28 % of the LW modules and differences were already appreciated from the first week after planting. In general, the upper modules showed a higher green cover, exceeding 80 % of the LW module covered by vegetation at the end of the test in A, B and D1. E1 and F1 reached 79 % and 73 %, respectively. Module C, however, presented a much lower coverage (64 %), similar to that obtained in the lower modules of the second test (67 %, 65 % and 71 % for D2, E2 and F2, respectively).

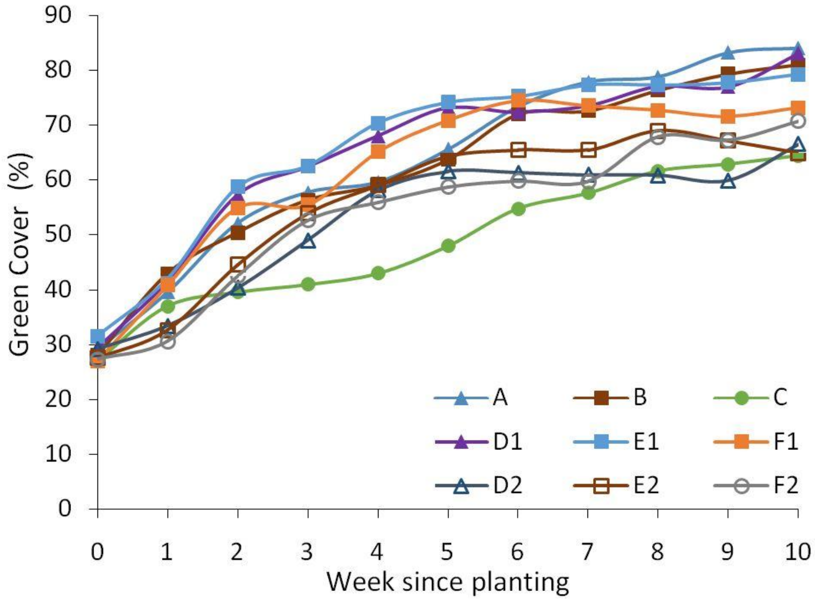


Figure 9. Evolution of the green cover (GC, %) in the different living wall modules

The number of *Spathiphyllum* white flowers in each LW module is shown in Figure 10 on a weekly basis. There was a big difference between tests, but not as much between the lamps used. In the first one, the average number of flowers was 11, 18 and 12 for modules A, B and C, respectively. In contrast, an average of 43, 50, 45, 46, 44 and 43 flowers were observed in D1, E1, F1, D2, E2 and F2, respectively.

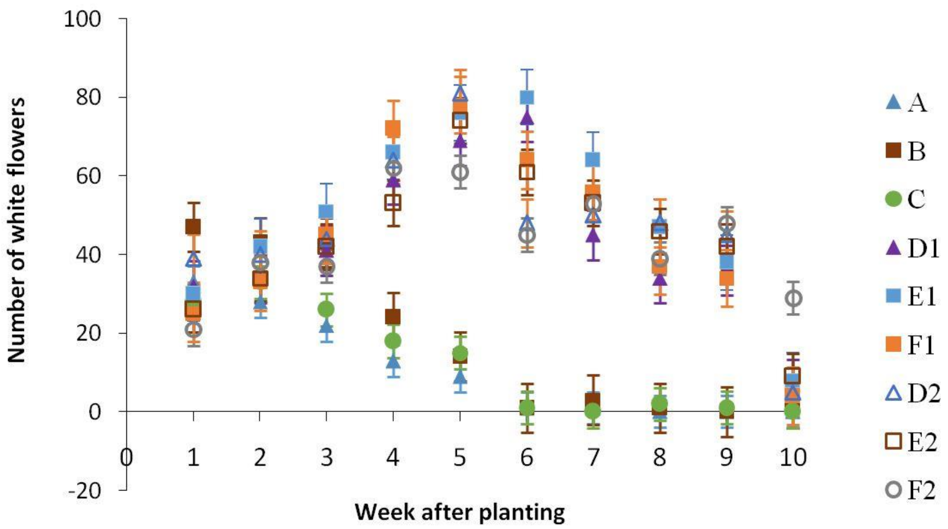


Figure 10. Evolution of the number of *Spathiphyllum* white flowers in the different modules

Table 5 shows the mean NDVI values obtained at the middle and end of each test. All the values ranged between 0.68 (C and E1) and 0.91 (D2). After four weeks since planting, all the values were fairly similar, though C already showed the lowest NDVI value. Modules A, B, C and F2 maintained or a slightly increased NDVI at the end of the tests. However, the NDVI decreased in D1, E1 and F1, showing lower values than the rest of the modules (even C). Conversely, the NDVI was considerably higher for D2 and E2 at the end of the test. Only module B did not show significant differences between weeks 4 and 10.

Table 5. Mean Normalized Difference Vegetation Index (NDVI) values taken for each living wall module four and ten weeks after planting

	Module								
Week	A	B	C	D1	E1	F1	D2	E2	F2
4	0.75de*	0.79c	0.68f*	0.82ab*	0.77cd*	0.79bc*	0.83a*	0.74e*	0.79c*
10	0.77d	0.79c	0.71e	0.69ef	0.68f	0.70e	0.91a	0.84b	0.82b

Different letters in a row show statistically significant differences among the treatments of each week (week 4th and week 10th) and the asterisk (*) indicates the statistically significant differences between the treatments in both weeks (e.g. module A week 4 compared to module A week 10).

The chlorophyll content in *Spathiphyllum* leaves in each module was measured at the end of the tests and the average SPAD values are presented in Figure 11. The lowest values were observed in the upper modules in the second test (D1, E1 and F1), ranging between 41.4 and 44.1. D2 and F2 had the highest values 54.9 and 54.1, respectively).

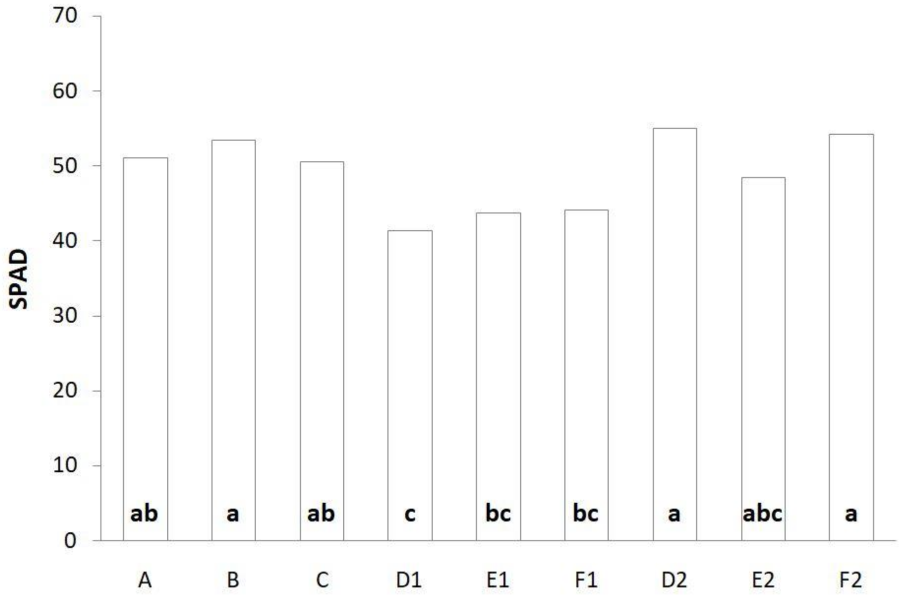


Figure 11. Average SPAD values measured in *Spathiphyllum* at the end of each test. Different letters indicate significant differences according to Duncan's Multiple Range test ($P < 0.05$) and each value is the mean of three replicates per experimental unit (A, B, C, D1, E1, F1, D2, E2, and F2).

Observers' perception

In order to assess the visual quality, the observers were asked if the lights (Figure 12) produced attractive colours and a natural appearance of the plants (Table 5). Lamps D and F were the ones with the highest scores in both questions, followed by E. Lamps A and C got the lowest values. In fact, when the participants were asked to rank the lamps in order of preference, lamp D was chosen in the first position by 54.4 % of the respondents and as second by 30.4 % of them. Lamp F was the one preferred by 36.7 % of the observers and chosen as the second by 44.3 %. 86.8 % of the participants selected lamp C as the least preferable. Lamp B was mainly chosen in the third (29 %) and fourth (38 %) place. Lamp A was chosen in the fifth place by 52.8 % and in the last place by 13.2 %.

Table 6. Average value for each lamp of the responses obtained to the question posed (1 -do not agree- to 5 -totally agree)

Question	A	B	C	D	E	F
Colours under this light are attractive	2.56	3.02	1.64	4.38	3.46	4.35
Plants have a natural appearance under this light	2.76	3.15	1.47	4.4	3.65	4.39

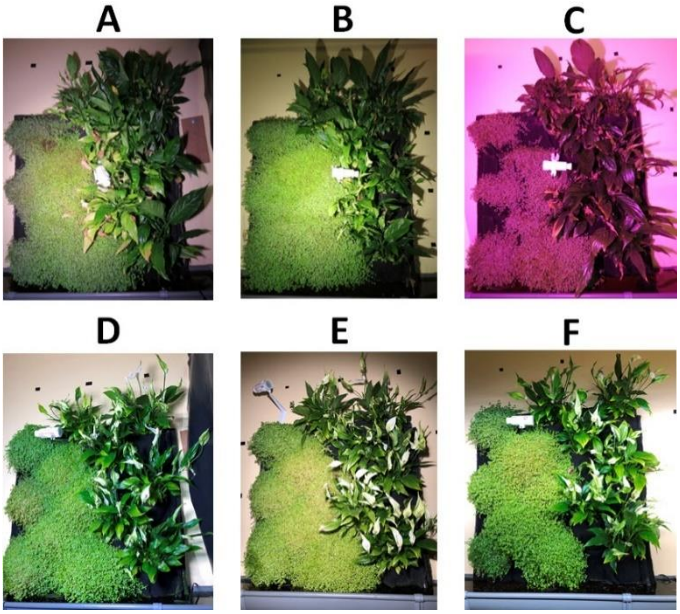


Figure 12. Photographs of the living wall modules illuminated by each lamp at the end of the trials

Discussion

Including ornamental greenery indoors often requires auxiliary illumination when not enough natural light is available increasing the energy consumption. In this regard, specific lighting requirements for indoor ornamental plants is necessary in order to optimise the programming of the lighting and minimise the occurrence of over-compensation (Tan et al., 2017). It is also important to select lamps that, producing a good result in terms of vegetation development and appearance, do not have excessive energy consumption and do not produce too much heat. Even when the above fact is precisely the advantage of LED lamps the choice of the one with the least wattage does not guarantee the effectiveness of the lamp. In fact, there are some lamps that use the energy to produce more light in the PAR spectrum, hence being more effective.

In the current study, as observed in Figure 5, lamp C is the one with a higher illuminance/PPFD relation, exhibiting a higher luminous flux within PAR wavelengths (high slope of the lx-PPFD conversion equation). Lamps D and F also have a high ratio, while the worst performance in these terms is showed by lamp B. Conversely, observing the efficacy values in terms of photosynthetic photons received in average per m^2 per energy unit (PPDE, derived from the photosynthetic photon efficacy (PPE) described in (Park and Runkle, 2018), lamp C shows an amazingly poor value (0.04 μmol m^{-2} J^{-1}), compared with the highest PPDE observed (0.68 μmol m^{-2} J^{-1} for lamp E). Lamp B produces a low value (0.38 μmol m^{-2} J^{-1}), while A, D and F exhibit intermediate values (0.46, 0.45 and 0.56 μmol m^{-2} J^{-1}, respectively).

Even when Lamp C is specifically designed for plant growth, it is the one which has the worst behaviour (low PPFD levels and the worst performance of vegetation). This happens because this type of lamps is prepared to be positioned very close to the vegetation (less than 0.5 m away). Therefore, they are not suitable for this use given that the lamps cannot be located right in front of the LW and at a short distance. However, in this study the vegetation cover survived and, though its development was not as adequate as with the other lamps, the plants maintained a fairly appropriate condition. As has been already stated, an added drawback of these lamps is the unnatural appearance and unpleasant view that they produce, resulting again in unsuitability for ornamental purposes.

The effectiveness of artificial lighting depends not only on the type of source, but also on several other factors such as the vertical gradient of illuminance (due to the distance from the vegetation to the light source) and the number of lamps and their position (Chen, 2005). In fact, it is well known that the illuminance is inversely proportional to the square of the distance from the source (inverse square law of light). For instance, Thiel et al. (1996) reported a vertical gradient of illuminance in which its value decreased between 25 % and 60 % per metre of distance to the light source. In our study, between 48 % (lamp F) and 64 % (lamp B) of illuminance was lost, in average, per metre of distance to the light source, depending on the lamp considered (excluding lamp C, with 78.6 % lost). Yet, in the first metre, between 71 % and 92 % of the illuminance was lost. However, the PPFD gradient observed is slightly lower as the photon flux is not reduced so quickly: between 46 % and 60 %of the PPFD lost in average per metre, losing between 65 % and 82 %in the first metre. This means that the light source cannot be placed too far away from the lower part of the LW, as the PPFD levels dramatically decrease in the first metres.

Precisely, this vertical gradient leads to a lack of illuminance uniformity. An idea of this uniformity can be gained dividing the minimum PPDF value obtained with each lamp by the average PPFD. Therefore, uniformities of 2, 3, 19, 38, 30, and 44 % (for lamps A, B, C, D, E and F, respectively) were achieved, though if only the upper modules were considered, those values were higher (64, 52, 85, 87, 71 and 56 %, respectively). This must be taken into account to make a sound species selection in which plants with lesser light requirements will be placed at the bottom. In some cases, when the height of the LW increases, lamps located at different elevations (or at the bottom of the LW) will be required.

The PPFD values obtained in our study show how the mid-section of the upper LW modules was always the one which receives more light. In the first test, the PPFD values measured right under the upper modules were below 5 μmol m^{-2} s^{-1} (too low for the plants to survive) for all the lamps tested (A, B and C). This means that for LW higher than 1 m, these lamps are of no use unless several lamps are placed at different heights. This is normally difficult given that the lamps cannot be located too far from the LW, so their placement is complicated. For this reason, other solutions using different lamps were sought in the second test.

The light intensity pattern is also affected by the lamp characteristics in terms of beam angle and shape. For example, given the configuration of lamp F and the angle used, the lower part of the upper module (F1) received less light than the upper part of the lower module (F2) (Table 1), as this area is partially shaded by a central structure of the lamp.

This should be considered in the planting design when using this lamp. On the other hand, lamp F (with a lineal configuration and 1.52 m long) offers the advantage of lighting a greater length of wall, hence requiring fewer lamps to cover the whole LW. As another example, lamp E produced a more concentrated light beam which produced high levels of illuminance especially at the centre of the module but lower values in the periphery (Figures 3 and 6). For that reason, two lamps instead of only one had to be employed. On the other hand, due to this same reason, the distance reached with reasonable levels of illuminance was higher for this lamp.

Not only the type of lamps and their number and configuration affect the vegetation performance. The number of hours of artificial lighting can also affect it. To take this into account, the photosynthetic daily light integral (DLI) is often employed, as it describes the cumulative amount of PAR delivered to a specific area over a 24-h period (Fausey et al., 2005). Species with a DLI requirement of 3 to 6 mol $m^{-2}d^{-1}$ are considered low-light(Torres and Lopez, 2010). Average PPFD values received in each of the modules (Table 1) can be easily converted to DLI knowing the number of hours of light received per day. Hence, mean DLI values in each module were 1.8 (A), 1.3 (B), 0.4 (C), 3.6 (D1), 4.2 (E1), 3.0 (F1), 1.4 (D2), 2.5(E2) and 1.6 (F2) mol $m^{-2}d^{-1}$.

Dry biomass is expected to be higher if DLI increases (Oh et al., 2009; Warner and Erwin, 2005). This was so in our study for *Soleirolia* but not for *Spathiphyllum* plants, in which a higher DLI (or PPFD) did not involve higher dry mass (Figure 13), presumably because *Spathiphyllum* is more adapted to receive less light. The vegetation cover did not have much relation with the PPFD levels either. Egea et al.(2014) reported a clearer relation between the dry mass and the PPFD, even for *Spathiphyllum*. Mattson and Erwin (2005) suggested that the photoperiod affected the dry weight gain per day more than increasing irradiance, but in their study 11 species out of 41 (none of them being *Spathiphyllum* nor *Soleirolia*) were not affected by any of them.

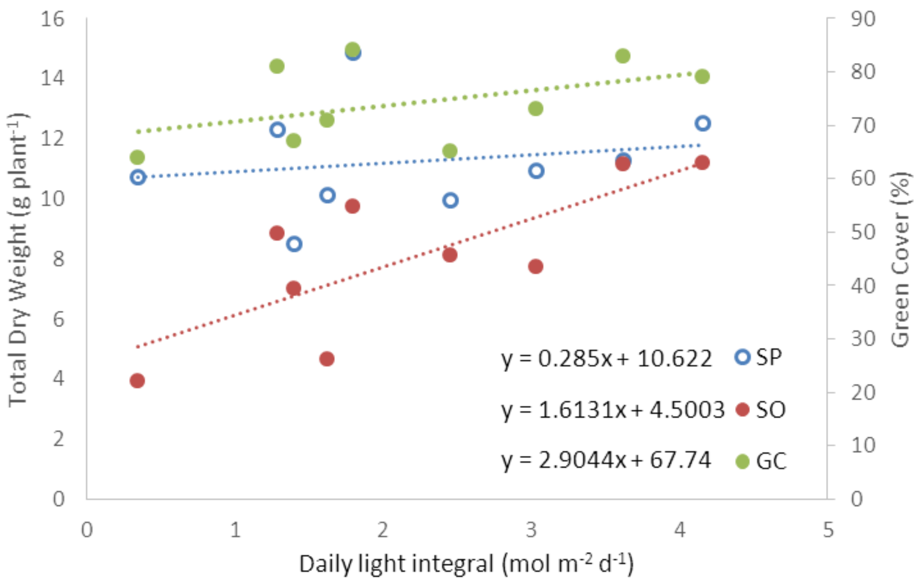


Figure 13. Relationship between the total dry weight (TDW) of *Spathiphyllum* (SP) and *Soleirolia* (SO), green cover (GC) and the mean daily light integral (DLI). The dotted lines denote the regression lines for each group of values.

The proposed optimum DLI value for *Spathiphyllum* is 4 mol $m^{-2}d^{-1}$(Faust, 2001), so following this recommendation, only E1 received an adequate DLI, being close in D1, but this did not have an influence on significant differences in the dry mass per *Spathiphyllum* plant obtained (for instance module A showed the highest dry biomass only receiving 1.8 mol $m^{-2}d^{-1}$).No proposed DLI values were found for *Soleirolia*, though Yue (2004) suggested a quite wide PAR scope for the growth of *Soleirolia*, in the range of 8.5 to 299 μmol m^{-2} s^{-1}. In any case, the differences in plant development between the lamp treatments found in our study, higher for *Soleirolia* than for *Spathiphyllum*, suggest that the former seems to be more sensitive to DLI variations.

A higher DLI can also increase flowering (Currey and Erwin, 2011; Oh et al., 2009). In our study, this did not happen as DLI for modules A and B were similar to D2 and F2 but there were far fewer flowers in the former. In this case, the mean daily temperature might have been a key factor. According to Meng and Runkle (2014), the mean daily temperature and the DLI can interact to influence the flowering time of various ornamental crops. Also, the previous growing conditions in the nursery before the transplant for the trials might have affected them as the differences in temperature between tests 1 and 2 were low (3-4 ºC), being higher for the first one (when, precisely, higher temperatures are supposed to induce flowering (Blanchard et al., 2011)).

The PPFD measured in our study was in general much higher than that reported by Egea et al.(2014) (excluding lamp C). Biomass production in the present study was also higher, especially for *Soleirolia* plants, except for module C, which produced similar values to those observed by Egea et al.(2014).
The use of LED lamps also had implications on the water consumption. For instance, the daily water volume consumed was slightly higher in the lower modules than in the upper ones (for the same lamp) though the differences were not statistically significant. In contrast, the results provided by Egea et al. (2014)denoted a bigger influence of the type of lamp and the distance to the light source, as the heat produced by the lamps was an issue. In fact, the water consumed in that study ranged between 2.1 and 5 L m^{-2} d^{-1}, while in the present work the values were between 1 and 1.5 L m^{-2} d^{-1}.

As LW have a marked ornamental purpose, the healthy appearance of the plants and a good vegetation cover are rather more important than the growth of the plants. In this regard, even when there were few significant differences found in the generated plant biomass, the vegetation cover was higher in the modules close to the light source. Conversely, for lamps D, E and F (with a higher light intensity), the appearance of the plants in the modules closer to the lamp became worse with the course of time (especially in *Soleirolia*).

In this regard, it is interesting to note that in terms of the NDVI and the SPAD, those modules specifically receiving a lower PPFD showed higher values. Receiving an excessive luminous flux sometimes results in a decrease in the chlorophyll content of leaves and vice versa (Dibenedetto, 1991; Zhang et al., 2016). Krause and Winter (1996) even reported a certain photoinhibition of photosynthesis in species growing in a Tropical forest when subjected to a highlight intensity exposure. Differences in the NDVI can be associated with changes in pigment composition and protective mechanisms against excess light (Mielke and Schaffer, 2010).

In spite of this, the participants in the perception analyses preferred lamps D and F over the rest. The colour composition and temperature often have an influence on these decisions (Jost-Boissard et al., 2009), but it seems that the lamps producing a homogeneous distribution of light were also preferred over those creating a beam of light.

Conclusions

When artificial lighting is required for indoor greenery, selecting the most efficient lamps is very important, as the wrong choice may be crucial for the survival of a green wall. All the commercial LED lamps tested in this study, except for lamp C which was precisely the one designed for crop production, are apt for LW lighting. However, their placement (the distance from the LW, the beam angle, the lamp orientation) should be based on the lamp characteristics and plays an important role in obtaining a proper result. Energy consumption should also be considered, as some lamps use the energy more efficiently to produce light in the spectrum which is more usable by the plants. Lastly, the visual quality of the light in terms of producing a natural appearance of the vegetation is important in order to be pleasant for observers.

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