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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.

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, specially 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).

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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 (37°23′7″N, 6° 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 × 1 m felt modules based on the Fytotextile® system (Terapia Urbana S.L., Seville, Spain), widely used in European countries (Fig. 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 as follows:

- 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 (Fig. 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) multistream 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 (Fig. 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 (Fig. 1).

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 300–1100 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 h of solar exposition) and then immersed in water for 30 min. 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

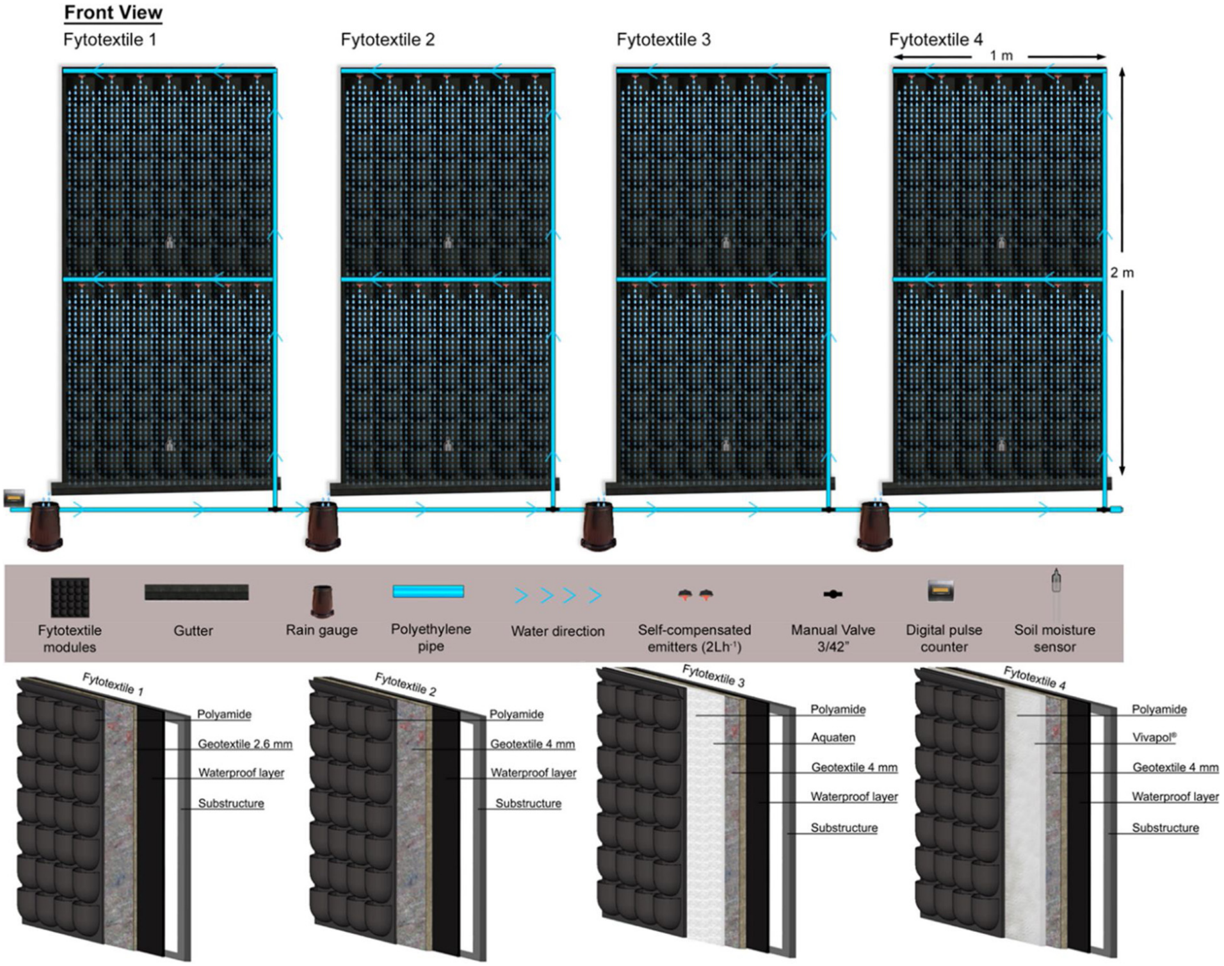

Fig. 1. Schematic layout of the irrigation system and drainage collectors. 3D details of each Fytotextile system.

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

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 min/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 (Fig. 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.

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 min from May 27th to June 19th and 10 min 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 (Fig. 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 (Fig. 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.

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

Fig. 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 min (6 h and 35 min) after the beginning of the drying phase. However, Fytotextile 3 and 4 kept much water after 10 h, still showing water content values of 0.79 L m^{-2} and 4.16 L m^{-2}, respectively.

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).

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

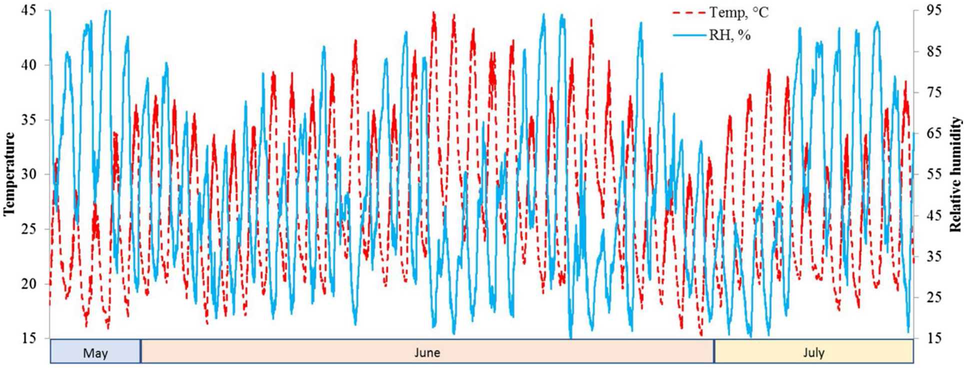

Fig. 3. Temperature (Temp, ºC) and Relative Humidity (RH, %) during the vegetation performance test.

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

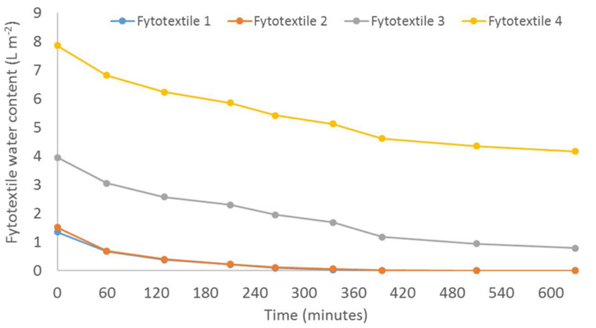

Fig. 4. Evolution of the Fytotextile (1, 2, 3, 4) water content (L m^{-2}) over 10 h (drying curve).

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

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.

The volumes of accumulated drainage water recovered from the four living walls tested throughout a day are depicted in Fig. 5 for irrigation schedules 1–4. 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.

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 (Fig. 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 (Fig. 6b).

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.

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 (Fig. 7).

In terms of the moisture of the substrate inside the pockets, differences can be appreciated between the different systems tested (Fig. 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 %).

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 h 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 (Fig. 4) and the substrate moisture evolution (Fig. 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

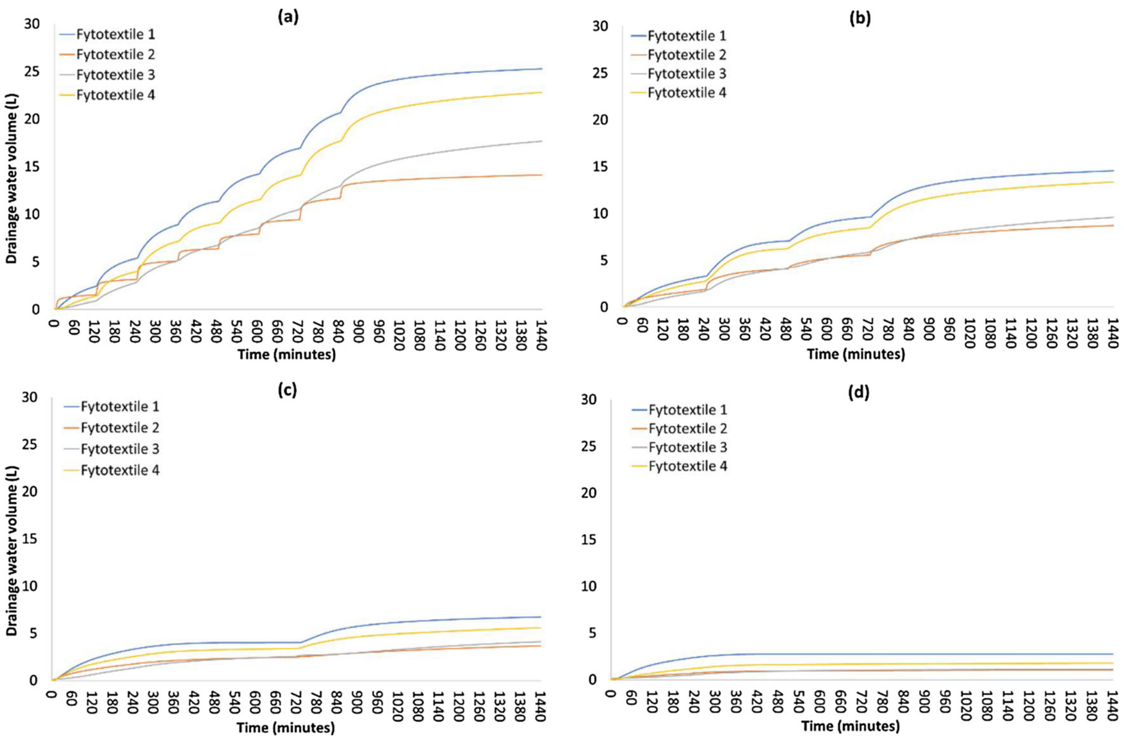

Fig. 5. Evolution of the average cumulative drainage water volume (L) during a day in the four tested Fytotextile systems for 8 (a), 4 (b), 2 (c) and 1 (d) irrigation events of 5 min.

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.

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

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

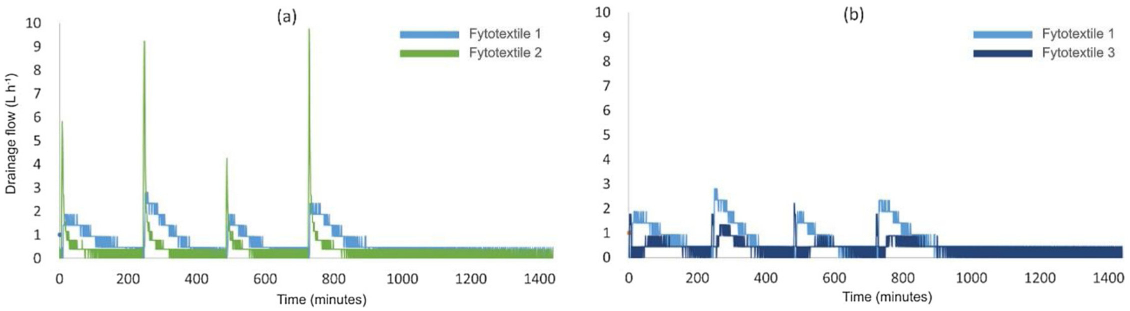

Fig. 6. Distribution of drainage water flows (L h^{-1}) recorded during an average day for irrigation schedule S2. Comparison between Fytotextile 1 and 2 (a) and Fytotextile 1 and 3 (b). Fytotextile 1 is represented in light blue, Fytotextile 2 in green and 3 in dark blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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

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

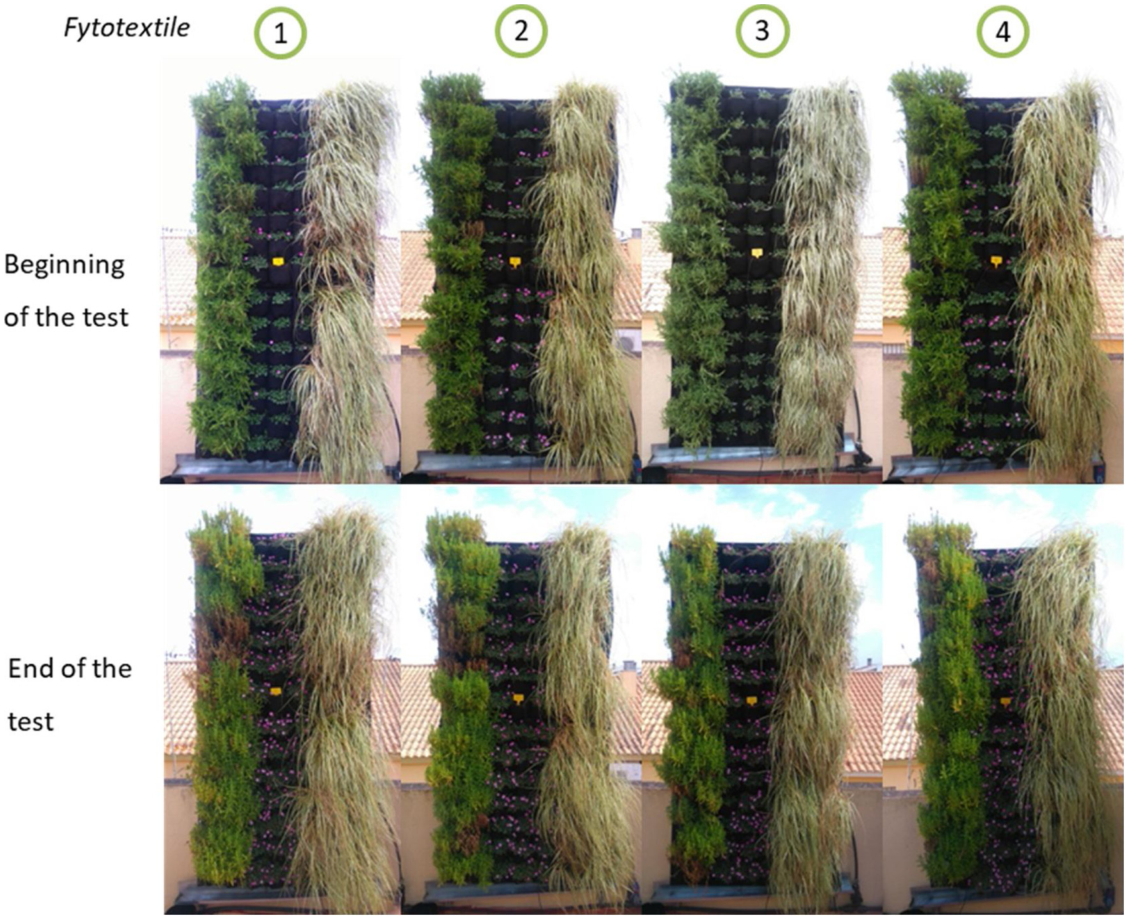

Fig. 7. Visual evolution of the plants in the different Fytotextile systems (1 to 4) tested at the beginning and end of the vegetation performance test.

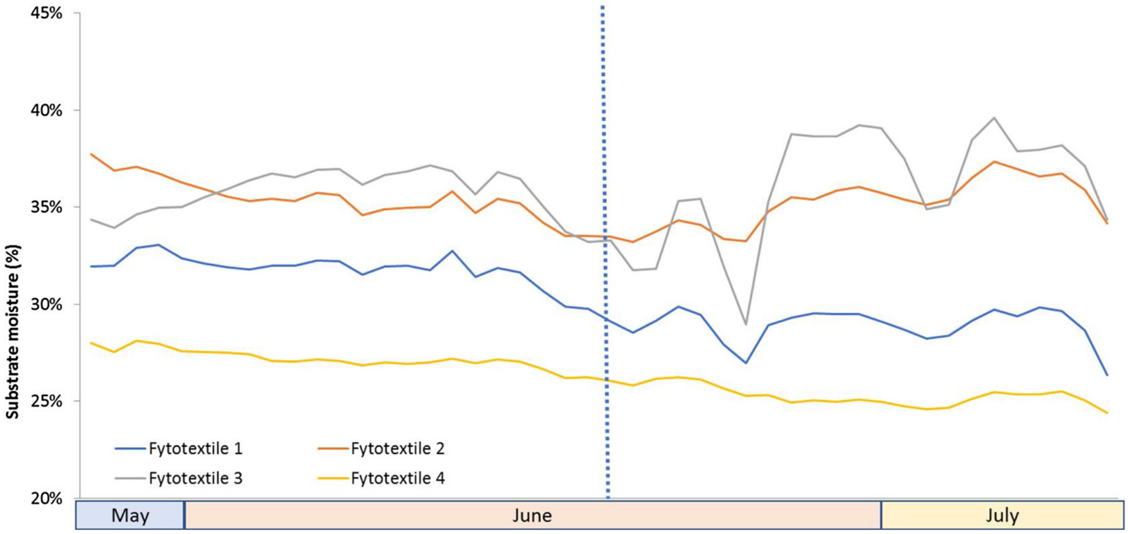

Fig. 8. Evolution of the average daily substrate moisture (%) in the pockets throughout the test. The dotted vertical blue line denotes the moment when the irrigation duration changed from 15 to 10 min. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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.

CRediT authorship contribution statement

Maria P. Kaltsidi: Formal analysis, Writing - original draft, Writing - review & editing. **Rafael Fernández-Cañero:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Antonio Franco-Salas:** Conceptualization, Methodology, Investigation. **Luis Pérez-Urrestarazu:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare not to have any conflict of interest

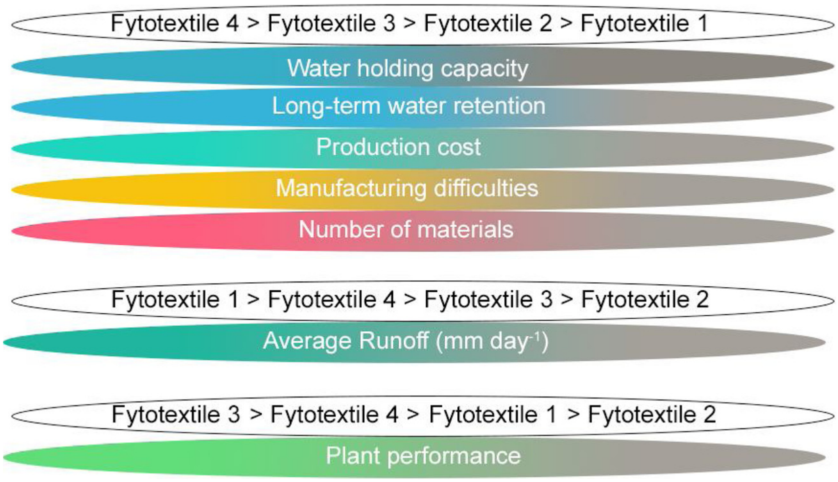

Fig. 9. Comparative summary of results for each type of Fytotextile system. The ‘ > ’ sign indicates a higher value in the attributes described below.

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References

Collins, R., Schaafsma, M., Hudson, M.D., 2017. The value of green walls to urban biodiversity. Land Use Policy 64, 114–123.

Cortês, A., Almeida, J., de Brito, J., Tadeu, A., 2019. Water retention and drainage capability of expanded cork agglomerate boards intended for application in green vertical systems. Constr. Build. Mater. 224, 439–446. https://doi.org/10.1016/j.conbuildmat.2019.07.030.

Ghazalli, A.J., Brack, C., Bai, X., Said, I., 2019. Physical and non-physical benefits of vertical greenery systems: a review. J. Urban Technol. 1–26. https://doi.org/10.1080/10630732.2019.1637694.

Larcher, F., Battisti, L., Bianco, L., Giordano, R., Montacchini, E., Serra, V., Tedesco, S., 2018. Sustainability of living wall systems through an ecosystem services lens. Urban Horticulture. pp. 31–51. https://doi.org/10.1007/978-3-319-67017-1_2.

Manso, M., Castro-gomes, J., 2015. Green wall systems: a review of their characteristics. Renewable Sustainable Energy Rev. 41, 863–871. https://doi.org/10.1016/j.rser.2014.07.203.

Medl, A., Stangl, R., Florineth, F., 2017. Vertical greening systems – a review on recent technologies and research advancement. Build. Environ. 125, 227–239. https://doi.org/10.1016/j.buildenv.2017.08.054.

Medl, A., Florineth, F., Kikuta, S.B., Mayr, S., 2018. Irrigation of 'Green walls' is necessary to avoid drought stress of grass vegetation (Phleum pratense L.). Ecol. Eng. 113, 21–26. https://doi.org/10.1016/J.ECOLENG.2018.01.007.

Pallardy, S.G., 2008. Enzymes, energetics, and respiration. Physiology of Woody Plants. Elsevier, pp. 169–197. https://doi.org/10.1016/B978-012088765-1.50007-5.

Pérez, G., Coma, J., Barreneche, C., De Gracia, A., Urrestarazu, M., Burés, S., Cabeza, L.F., 2016. Acoustic insulation capacity of Vertical Greenery Systems for buildings. Appl. Acoust. 110, 218–226. https://doi.org/10.1016/j.apacoust.2016.03.040.

Pérez-Urrestarazu, L., Urrestarazu, M., 2018. Vertical greening systems: irrigation and maintenance. In: Pérez, G., Perini, K. (Eds.), Nature Based Strategies for Urban and Building Sustainability. Elsevier, Butterworth-Heinemann, pp. 55–63. https://doi.org/10.1016/B978-0-12-812150-4.00005-7.

Pérez-Urrestarazu, L., Egea, G., Franco-Salas, A., Fernández-Cañero, R., 2014. Irrigation systems evaluation for living walls. J. Irrig. Drain. Eng. 140, 04013024. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000702.

Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco-Salas, A., Egea, G., 2015. Vertical greening systems and sustainable cities. J. Urban Technol. 22, 65–85. https://doi.org/10.1080/10630732.2015.1073900.

Riley, B., 2017. The state of the art of living walls: lessons learned. Build. Environ. 114, 219–232. https://doi.org/10.1016/j.buildenv.2016.12.016.

Segovia-Cardozo, D.A., Rodríguez-Sinobas, L., Zubelzu, S., 2019. Living green walls: estimation of water requirements and assessment of irrigation management. Urban For. Urban Green. 46, 126458. https://doi.org/10.1016/j.ufug.2019.126458.

Weinmaster, M., 2009. Are green walls as "green" as they look? an introduction to the various technologies and ecological benefits of green walls. J. Green Build. 4, 1–18. https://doi.org/10.3992/jgb.4.4.3.