

Article

The Effect of Irrigation Treatment on the Growth of Lavender Species in an Extensive Green Roof System

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Received: 30 January 2020; Accepted: 17 March 2020; Published: 19 March 2020



Abstract: In green roofs, the use of plant species that withstand dry arid environmental conditions and have reduced water requirements is recommended. The current study presents the effect of irrigation amount on the growth of four different species of lavender; *Lavandula angustifolia*, *Lavandula dentata* var. *candicans*, *Lavandula dentata* var. *dentata*, and *Lavandula stoechas* established on an extensive green roof system and used in urban agriculture. Two irrigation treatments (high and low) determined by the substrate hydraulic properties were applied. Plant growth studied at regular intervals included measurements of plant height, shoot canopy diameter, plant growth index, shoot dry weight and stomatal conductance. The results were consistent and showed that low irrigation reduced plant growth. With the exception of *L. stoechas*, the appearance of plants watered with the low irrigation treatment was satisfactory, and their use under low water amount irrigation is supported. Interspecies differences among lavender species were present in both irrigation treatments. Overall, *L. dentata* var. *candicans* showed the greatest growth, followed in descending order by *L. dentata* var. *dentata* and *L. angustifolia*. In parallel, for stomatal conductance, *L. dentata* var. *candicans* showed the lowest value, similar to *L. dentata* var. *dentata*, and *L. angustifolia* the largest. Differences in plant characteristics and size among the latter three species can be considered in the design of extensive green roof systems. The use of substrate hydraulic properties was shown to be important for irrigation management on extensive green roof systems.

Keywords: drought tolerance; substrate hydraulic properties; substrate available water; ornamental; aromatic; urban agriculture; green infrastructures

1. Introduction

There is increasing interest in urban agriculture due to the related economic, social and environmental functions contributing to the sustainability of cities [1]. Though urban agriculture usually highlights food production, it includes the cultivation of other plants such as ornamentals [2], as well as agricultural systems that relate to recreation and leisure [3]. However, within cities, land and soil are limited resources [4]. Generally, cities are characterised by dense buildings, green spaces which are limited in number and size and large impervious paved areas. These characteristics have contributed to creating adverse environmental conditions within the cities such as the heat island effect, restricted air flows, human discomfort and poor health caused by heat stress and poor air

quality [5]. Roof greening (the development of planting on buildings, i.e., green roofs) is one means by which urban agriculture may be realized [1,6]; it has the potential to contribute to mitigating the problems caused by urbanisation on an individual scale, and when applied broadly, could improve the environment of a city [5].

Green roofs are generally classified into three categories depending on weight, substrate layer, maintenance, cost, plant community, and irrigation, i.e., extensive, semi-intensive and intensive roofs [7]. Within cities, the load-bearing capacity of many buildings, particularly older ones, is limited; hence, only extensive green roof systems can be applied on these buildings due to their smaller weight load in comparison to other green roof systems. Extensive green roofs are characterised by shallow depths and reduced water availability. Water is an additional limited natural resource within many cities, particularly in semiarid and arid locations such as the Mediterranean, and especially during the summer months [8]. Furthermore, in Mediterranean regions, high temperatures make the development of green roofs more difficult [9]. Under the increasing threat of climate change, water conservation is a priority. Therefore, it is critical in extensive green roofs to use plant species that withstand dry heat and water-deficits [10]. In recent years, research on the growth of shrubs in extensive green roofs is increasing [8,11–16]. Plant growth in extensive green roofs with limited irrigation was found to be satisfactory for *Artemisia absinthium* L., *Helichrysum italicum* Roth., *Helichrysum orientale* L. [11,12], *Origanum majorana* L., and *Santolina chamaecyparissus* L. [12] at a substrate depth of 7.5 cm, and for *Arthrocnemum macrostachyum*, *Halimione portulacoides* [8], *Convolvulus cneorum* L. [13,14], *Origanum dictamnus* L. [14], *Atriplex halimus* [16], and *Pallenis maritima* [15] at a substrate depth of 10 cm.

Generally, the literature on drought-resistant plants for use in agriculture and landscape architecture is extensive [17]. On the other hand, there is a need to study the survival of shrubs on green roofs in hot and dry climates [10]. The amount of water loss in extensive green roofs is a function of three properties of the green roof system, i.e., plant water uptake and transpiration, shading of substrate by vegetation that might reduce the substrate surface evaporation rate and greater water holding capacity of the substrates containing plant roots [18]. A balance among species of water and substrate is needed to address the adverse environmental conditions of green roofs and the effect of temperature extremes [19]. Therefore, plant selection and the improvement of the available amount of water to plants are key research aims [9]. Plant survival on green roofs with shallow substrates and low water availability is not easily understood, and is determined by a combination of drought avoidance physiological processes [10] such as the decline of stomatal conductance, and hydraulic conductivity [20] expressed by species in various ways that include dormancy, drought deciduousness and stomatal regulation [10]. Several authors believe that the first response of plants to severe drought is the closure of their stomata to prevent transpiration water loss [21–23]. Species that are well adapted to drought, such as *Olea europaea* L., decrease water loss through stomatal closure from early in the morning [24]. Stomatal conductance plays an essential role in regulating plant water balance and may reduce plant transpiration [23]; however, it may also concomitantly reduce cell expansion and growth rate, leading to reduced biomass and yield [22,25].

In accordance with De Boodt and Verdonck [26], plant growth decreases when water retention in substrates occurs at negative pressure heads greater than -100 cm, and inadequate substrate aeration conditions for plant growth are created when negative pressure heads are less than -10 cm. Therefore, retaining substrate water content within the available water range defined by negative pressure heads between -10 and -100 cm during irrigation ensures substrate water availability and plant water uptake, thereby reducing the effect of water stress. A comparative study for investigating plant growth among different lavender species (family: Lamiaceae) on a simulated extensive green system and under different irrigation treatments determined by the hydraulic properties of the substrate has not been undertaken before. Lamiaceae is characterised by numerous aromatic species of arid and warm climates. The *Lavandula* genus includes 47 species and many varieties [27]. The qualitative characteristics of the different species such as the habit and morphological characteristics of the flowers and foliage vary [28,29], and are of interest to both landscape and urban agriculture. In this study,

the hydraulic properties of an extensive green roof system substrate were used to determine different amounts of irrigation within the available water range defined by negative pressure heads between -10 and -100 cm. The objective of this study was to investigate the effect of irrigation amount on the growth of 4 lavender species, i.e., *Lavandula angustifolia*, *Lavandula dentata* var. *candicans*, *Lavandula dentata* var. *dentata* and *Lavandula stoechas* on an extensive green roof system under two irrigation treatments (high and low) in the aforementioned available water range to support the creation of aesthetically-pleasing green roofs for urban agriculture.

2. Materials and Methods

2.1. Experimental Setup

Four popular lavender species were selected for study, *Lavandula angustifolia*, *Lavandula dentata* var. *dentata*, *Lavandula dentata* var. *candicans* and *Lavandula stoechas*. Uniform, 9 cm size pot lavender plants were supplied by the Kalantzis Plants (Marathonas, Greece) nursery. Plants were individually transplanted on 1 March 2016 in rectangular shaped 60 cm \times 40 cm plastic containers (1 plant per container), simulating an extensive green roof system comprised bottom-up from a water retention and protection layer, a drainage layer, a filter layer, and 10 cm deep substrate [8]. The substrate used was S₁₅:Pum₇₀:C₁₅ and consisted of soil (S), pumice (Pum) and grape marc compost (C) in a volumetric ratio of 15:70:15. Containers were positioned on metal benches (0.80 m height) on the roof of the main building of the Agricultural University of Athens (lat. 37°58'57" N, long. 23°42'17" E, alt. 30 m) to avoid the effect of shading from the perimeter walls of the roof. After transplanting, plants were left to grow and establish for 3 months (1 March—30 May 2016). An automated irrigation system was applied using a drip system with two emitters of 2L h⁻¹ per plant spaced at 10 cm on either side of the plant and a total irrigation water application rate of approximately 16.6 mm h⁻¹. Throughout the study period on a monthly basis, 1.2 g L⁻¹ H₂O Nutri-Leaf 20–20–20 (Miller Chemical and Fertilizer Corporation, U.S.A.) of fertilizer was applied to all plants. During the experiment, there was no leaching from the applied fertilizer, as the water application rate was gradual and the applied irrigation amount produced no water excess (see 2.3. *Experimental Design and Irrigation Treatments*). The duration of the experiment was 4 months and took place mainly over the summer months, from 31 May (day 1) to 30 September 2016 (day 123).

2.2. Physical-Hydraulic Properties of Substrate

The S₁₅:Pum₇₀:C₁₅ substrate had a bulk density $\rho_p = 1.035$ g cm⁻³, pH = 7.8 and EC = 1.33 dS m⁻¹ (the latter two measurements were made in 1:1 solution extract). The soil used was sandy loam/loam (53.62% sand, 30.82% silt, 15.56% clay, 0.7% organic matter), the pumice contained particles of diameter size 0.06–8 mm (LAVA, Mining & Quarrying A.D, Athens, Greece) and the grape marc compost (i.e., a waste product of wine production) was composted for 20 months and used as a sustainable alternative to peat. The particle size distribution of the substrates was determined with screen analysis. Weighed substrate samples were placed in the top sieve of a column of sieves arranged from top to bottom in descending order of screen mesh size (>20.00, 16.00, 10.00, 8.00, 4.00, 2.00, 1.00, 0.50, 0.25, 0.106, and <0.053 mm) resting on a sieve shaker for 3 min at 30 shakes per minute.

A tension plate apparatus in a Haines-type assembly [30], with an air-entry value of -180 cm of a water column was employed to define the substrate water retention curve. The substrate sample of 3 cm in height and 10.2 cm in diameter was positioned on the vibrating porous plate of a Buchner filter funnel to achieve satisfactory packing. It was then subjected to gradual wetting from the bottom of the plate until saturation (for 48 h). Measurements of the water content at different pressure heads were taken to obtain the water retention curve. The retention curve was the mean of three substrate samples ($n = 3$).

The RETC program [31] was used to calculate the fitting hydraulic parameters of the widely used Mualem-van Genuchten model [32,33] on the experimental water retention data. Van Genuchten [33] described the water retention curve as

$$\theta(H) = (\theta_s - \theta_r) \left(\frac{1}{1 + (\alpha|H|)^n} \right)^m + \theta_r, \quad (1)$$

where θ denotes the soil water content ($\text{cm}^3 \text{cm}^{-3}$), subscripts s and r denote the saturated and residual values of water content, α is the curve-fitting parameter inversely proportional to the mean pore diameter (cm^{-1}), and both m , n are dimensionless shape curve-fitting parameters, $m = 1 - 1/n$ and $0 < m < 1$.

Combining Equation (1) with the model developed by Mualem [32], the relationship between hydraulic conductivity and soil water content, $K(\theta)$, can be calculated as

$$K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{0.5} \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right]^m \right\}^2, \quad (2)$$

The model fitting parameters described above were evaluated by the RETC program using the measured water retention and saturated hydraulic conductivity data. The unknown parameters of the Mualem-van Genuchten model in the parameter optimization process to fit the water retention function were α , n and θ_r .

The saturated hydraulic conductivity, K_s , was determined by the constant-head method [34].

2.3. Experimental Design and Irrigation Treatments

The effect of the amount of irrigation water on the plant growth of the four selected lavender species (*Lavandula angustifolia*, *Lavandula dentata* var. *dentata*, *Lavandula dentata* var. *candicans* and *Lavandula stoechas*) was studied. The plant containers were arranged in a randomised design with 6 replicates per species. The amount of irrigation water was based on the substrate available water defined by the water retention curve of the substrate (i.e., water content released between -10 and -100 cm pressure head). Two irrigation treatments, i.e., high and low amounts of water, were applied through the automated irrigation system using two irrigation 9001 controllers (Galgon, Kfar Blum, Israel). Plants irrigated with a high amount of water were not subjected to water stress and served as the control. The above irrigation treatments were applied for 4 months from day 1 of the experiment (31 May 2016) until day 123 (30 September 2016). Substrate water content was measured daily using a handheld Frequency Domain Reflectometry (FDR) soil moisture sensor (HH2, Delta-T Devise, Cambridge, U.K.; WET Sensor type WET-2, Delta-T Devise, Cambridge, U.K.) set at the 'mineral' setting and calibrated to the used substrate. The sensor was fully inserted into the substrate with the central rod positioned 5 cm away from the plant centre. During the high irrigation treatment, when the FDR sensor showed a water content value of approximately $0.31 \text{ cm}^3 \text{ cm}^{-3}$ (at corresponding pressure head -50 cm), the plants were irrigated with 1.95 L, ensuring water availability within the easily available water (EAW) area. In the case of the low irrigation treatment, plants were irrigated with half the amount of the high irrigation treatment, i.e., 0.975 L, when the FDR sensor showed a water content value of approximately $0.29 \text{ cm}^3 \text{ cm}^{-3}$ (at corresponding pressure head -100 cm).

2.4. Plant Growth Biometrics

On day 1, plant size (height and shoot canopy diameter) was similar among species. Plant height (determined from the pot rim of the substrate surface), shoot canopy diameter (average of the widest and perpendicular to the widest plant diameter), and growth index [(height + widest width + perpendicular width)/3] were measured at monthly intervals. In all plants, at the end of the experiment (30 September/ day 123), stomatal conductance was recorded on the abaxial surface of the third or

fourth fully expanded leaf from the stem base on the exterior of the plant using the AP4 Porometer (Delta-T Devices, Cambridge UK). Measurements were taken between 13:00–14:00 h and three readings were recorded per plant and averaged. Next, in all plants, shoots were individually harvested at the end of the experiment (day 123). In all species and both irrigation treatments, plant roots penetrated the substrate and could not be separated from the substrate without partial loss of the fine root system; therefore, it was decided that the plant roots would not be harvested. The harvested shoots were dried in an oven at 70 °C for 48 h, and their dry weights were determined. Finally, in all plants, the percentage increase in plant height, shoot canopy diameter and growth index (GI) was calculated by dividing the difference between the last and first corresponding measurement with the first corresponding measurement and then multiplying by a hundred. Weekly recordings of observations for potential signs of water stress were undertaken throughout the duration of the experiment. In plants, the onset of visual symptoms induced by drought (leaf and stem chlorosis and necrosis) was recorded during the experiment and assessed at the end (on day 123). Visual symptoms induced by irrigation treatments were assessed on a 6-point scale from 0–5, where 0: plant mortality, 1: very severe leaf rolling and chlorosis >75%, 2: severe leaf rolling and chlorosis 50–75% approximately, 3: moderate leaf rolling and chlorosis 25–50% approximately, 4: mild leaf rolling and chlorosis <25%, 5: no leaf injury.

2.5. Meteorological Conditions

Meteorological data were obtained by the nearby meteorological station at Thissio (lat. 38°0.00' N long. 23°43.48' E, alt. 110m) of the National Observatory of Athens, located 1.8 km away from the experimental site [35]. In 2016, the average daily temperatures ranged between 19.9 °C on 25 September, and 32.8 °C on 21 June, while the absolute maximum and minimum air temperature values of 39.9 °C and of 16.5 °C were recorded on 21 June and 26 September, respectively (Figure 1). Diurnal temperature range ($T_{\max} - T_{\min}$) fluctuated between 4.4–14.1 °C with an average of 8.8 °C. In more detail, during the initial period of the experiment, i.e., 31 May (day 1) until 30 June (day 31), warm thermal conditions dominated, ranging from 17.3 °C to 39.8 °C. In August, air temperature continued to fluctuate from 21.8 °C to 38.5 °C. A decrease in air temperature was observed during the end of the experimental period—from 1 September (day 94) to 30 September (day 123)—with fluctuations from 16.5 °C to 32.9 °C. Overall, July (day 32–62) and August (day 63–93) were the hottest months during the experiment.

Throughout the experiment period, there was very little precipitation concentrated near the start (4 days in June) and end (6 days in September) (Figure 1). More specifically, on 7 and 28 June, 2016 precipitation was approximately 7.6 and 9.6 mm, respectively, and on all the other rainy days, the precipitation was <2 mm. Furthermore, there was no rainfall in either July or August 2016. During the experiment, both July and August showed the least relative humidity (Figure 1). Hence, the hottest and least humid period of the experiment took place during days 33–93 (1 July and 31 August 2016). Furthermore, the air temperature values were higher, while the precipitation and relative humidity values were less than the corresponding climatic (normal) values (reference period 1961–1990). Therefore, during the time of the experiment, more hot and dry conditions than the climatic values prevailed [35]. Furthermore, measurements of meteorological stations are typically representative within a 10 km radius [36]. In the current study, the experimental site was located 1.8 km away from the meteorological station; therefore, the obtained meteorological data are representative. Microclimate conditions of the experimental site were not recorded, however, due to the adverse environmental conditions of the extensive green roofs [22], and it is likely that the ambient temperature and relative humidity levels were greater and less than the corresponding data obtained from the meteorological station.

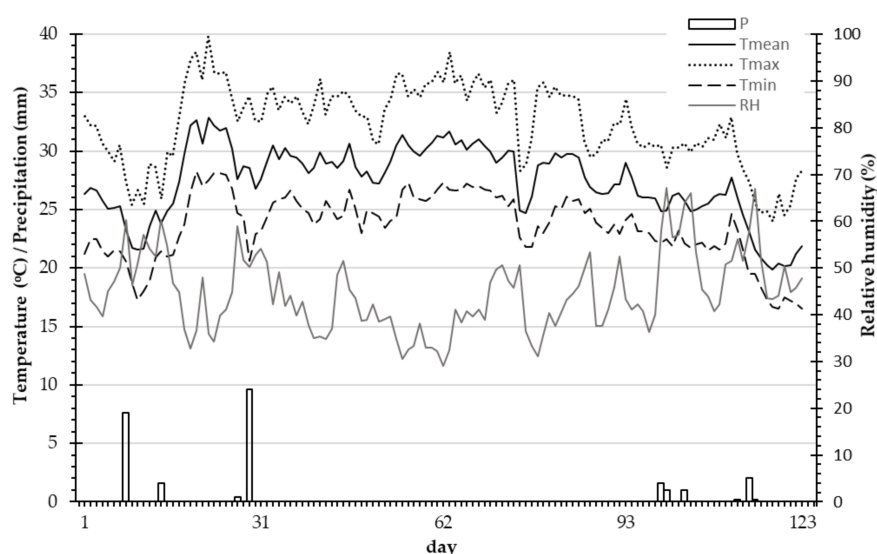


Figure 1. Diurnal mean, maximum and minimum air temperatures, precipitation and relative humidity during the simulated extensive green roof experiment on the main building of the Agricultural University of Athens from 31 May (day 1) to 30 September (day 123) in 2016. P: precipitation (mm); T_{mean} , T_{max} and T_{min} : mean, maximum and minimum temperature ($^{\circ}\text{C}$), respectively; RH: relative humidity (%) [35].

2.6. Experimental Design and Statistical Analysis

The experiment followed a completely randomized design with four lavender species and two irrigation treatments, with six replicates per species and irrigation treatment combination. A two-way analysis of variance of the experimental data was performed using SPSS Statistical Software v. 17.0 (SPSS Inc., Chicago, U.S.A.) and treatment means were compared using Tukey HSD test at a probability level $p < 0.05$.

3. Results and Discussion

3.1. Physical-Hydraulic Properties of Substrate

Particle size distribution affects the aeration and water retention properties of substrates [37,38]. The particle size distribution of the substrate used is presented in Table 1.

Table 1. Particle size distribution of $S_{15}:P_{um70}:C_{15}$ substrate (subscripts show volumetric proportions of S:soil, Pum: pumice and C: grape marc compost).

Particle Size (mm)	Particle Size Distribution (% by wt)
>10	0.00
10–8	0.34
8–4	13.55
4–2	23.16
2–1	12.49
1–0.5	8.98
0.5–0.25	12.25
0.25–0.106	23.34
0.106–0.053	4.54
<0.053	1.35

Knowledge of both basic hydraulic properties of substrates, $\theta(H)$ and $K(\theta)$ is essential for irrigation management [39–41]. The measured and predicted water retention data of the substrate used are

presented in Figure 2. As shown, there was a very good agreement between the experimental and predicted values of the water retention curve, indicating that the Mualem-van Genuchten model fitting parameters α , n and θ_r provide an adequate description of $\theta(H)$ with a high value of the coefficient of determination R^2 (0.9977).

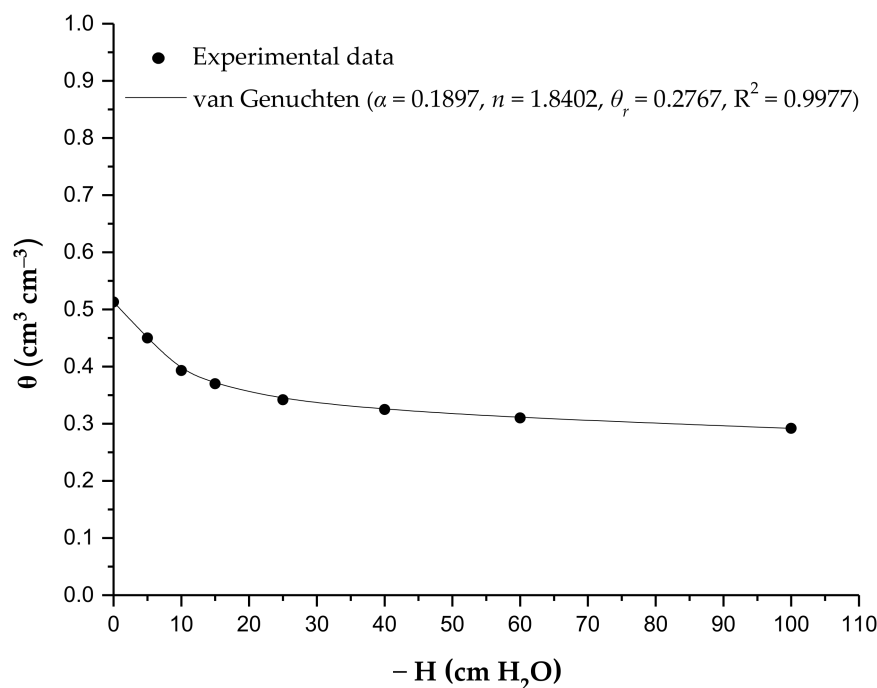


Figure 2. Experimental water retention data (symbol) and predicted curve (line) obtained by the Mualem-van Genuchten model using the RETC program for the substrate S₁₅:Pum₇₀:C₁₅ (subscripts show volumetric proportions of S:soil, Pum: pumice and C: grape marc compost). Values are the means of three replicates (n = 3).

The hydraulic characteristics derived from the water retention curve provide important information concerning plant growth and irrigation management. The main substrate hydraulic characteristics are presented in Table 2. Specifically, the total porosity (water content at 0 cm pressure head), the water content at -50 and -100 cm, as well as the easily available water (the amount of water released between -10 and -50 cm) and the air-filled porosity at -50 cm are given. Also, the measured value of hydraulic conductivity at saturation is presented.

Table 2. Hydraulic characteristics of the substrate S₁₅:Pum₇₀:C₁₅ (subscripts show volumetric proportions of S:soil, Pum: pumice and C: grape marc compost).

Total Porosity ¹ (cm ³ cm ⁻³)	Water Content at -50 cm (cm ³ cm ⁻³)	Water Content at -100 cm (cm ³ cm ⁻³)	Easily Available Water (EAW) ² (cm ³ cm ⁻³)	Air-Filled Porosity at -50 cm (cm ³ cm ⁻³)	K _s ³ (cm min ⁻¹)
0.513	0.3120	0.2920	0.081	0.201	0.547

¹ water content at 0 cm pressure head (saturation); ² the amount of water released between pressure heads of -10 and -50 cm; ³ the value of hydraulic conductivity at saturation.

In the high irrigation treatment, with the aim of retaining the substrate water content in the easily available water range, when the FDR reading reached approximately $0.31 \text{ cm}^3 \text{ cm}^{-3}$ (water content at -50 cm), plants were irrigated with the corresponding amount of water providing 100% EAW, i.e., $8.1 \text{ mm H}_2\text{O}$ or $1.95 \text{ L H}_2\text{O}$. On the other hand, in the low irrigation treatment, with the aim of stressing plants, when the FDR reading reached approximately $0.29 \text{ cm}^3 \text{ cm}^{-3}$ (water content at -100 cm), plants

were irrigated with half of the amount of the high irrigation treatment, i.e., 4.05 mm H₂O or 0.975 L H₂O, raising the substrate water content to approximately 0.33 cm³ cm⁻³ (water content at -30 cm) and within the EAW range.

The unsaturated hydraulic conductivity values provide information of fundamental importance, because the rate of evapotranspiration is directly correlated to hydraulic conductivity, i.e., the water flow rate of the substrate has the ability to replace the water loss caused by evapotranspiration. In Figure 3, the measured value of hydraulic conductivity at saturation, as well as the predicted values of unsaturated hydraulic conductivity obtained by the Mualem–van Genuchten model within the range of water content between 0.513 and 0.292 cm³ cm⁻³ (at corresponding pressure heads between 0 and -100 cm, respectively) are presented. As shown, between two successive irrigations, a sharp decrease of the unsaturated hydraulic conductivity was observed within this range. Similar results have been reported by other researchers on growth substrates used for plant production [39,42]. Londra [39] found a decrease of five to six orders of magnitude in unsaturated hydraulic conductivity for peat and both mixtures of peat-perlite and coir-perlite, respectively, for a pressure heads range from 0 to -70 cm. Also, Da Silva et al. [42] reported a decrease of three orders of magnitude for peat for a range from 0 to -25 cm.

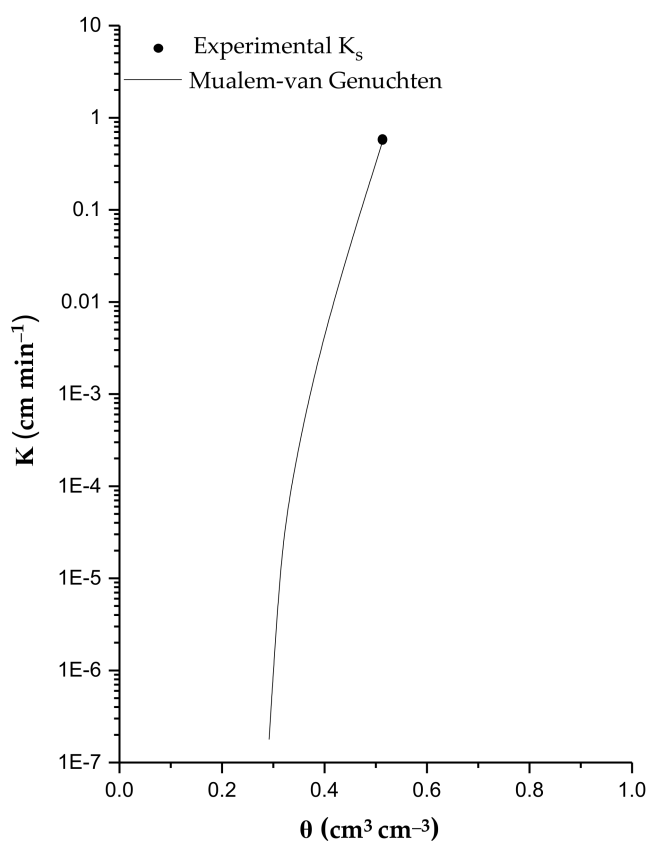


Figure 3. Experimental hydraulic conductivity at saturation (symbol) and predicted relationship between unsaturated hydraulic conductivity and water content (line) obtained by the Mualem–van Genuchten model using the RETC program for the substrate S₁₅:Pum₇₀:C₁₅ (subscripts show volumetric proportions of S:soil, Pum: pumice and C: grape marc compost).

During plant growth in this study, the pressure heads varied from -10 to -50 cm between two successive irrigations in the high irrigation treatment (100% EAW) and from -30 to -100 cm in the low irrigation treatment. In the case of the high irrigation treatment, hydraulic conductivity decreased by approximately two orders of magnitude (ranged from 4.06×10^{-3} to 1.07×10^{-5} cm min⁻¹). On the other hand, in the case of the low irrigation treatment, hydraulic conductivity decreased by approximately

two and a half orders of magnitude, ranging from 8.16×10^{-5} to 1.78×10^{-7} (Table 3). However, it is worth noting that the K values observed with the low irrigation treatment were much lower than those observed with the high irrigation treatment, confirming the presence of plant water stress.

Table 3. Measured values of water content (θ) and hydraulic conductivity (K) at saturation ($H = 0$ cm) and predicted ones obtained by the Mualem–van Genuchten model at water pressure heads $H = -10$, -30 , and -50 cm for the substrate S₁₅:Pum₇₀:C₁₅ (subscripts show volumetric proportions of S: soil, Pum: pumice and C: grape marc compost).

H (cm)	θ (cm ³ cm ⁻³)	K (cm min ⁻¹)
0	0.513	0.547
-10	0.393	4.06×10^{-3}
-30	0.330	8.16×10^{-5}
-50	0.312	1.07×10^{-5}
-100	0.292	1.78×10^{-7}

Nevertheless, it should be noted that in some cases, the predicted $K(\theta)$ values using the water retention curve data and the saturated hydraulic conductivity may deviate significantly from the actual $K(\theta)$ values [43–47].

3.2. Symptoms Induced by Water Stress

Schroll et al. [48] mention that it is possible for shrubs that are drought tolerant in their natural habitat to be unable to use their drought tolerance mechanisms properly in the shallow, nonnative soil of an extensive green roof system. The best indicator of the effect of drought is the visible symptoms of induced damage in plants (such as leaf chlorosis, browning, and necrosis) that affects the landscape visual quality [49,50]. With the exception of *L. stoechas*, all species appeared to be healthy and demonstrated no visual signs such as chlorosis or necrosis. *L. stoechas* started to demonstrate mild leaf rolling and chlorosis of the leaves in the low irrigated water treatment approximately two months after the start of the experiment (day 62), followed one month later by *L. stoechas* irrigated with the high water treatment (day 93) (data not shown). At the end of the experiment (day 123), only *L. stoechas* demonstrated moderate leaf rolling and chlorosis of the leaves in plants irrigated with the high water treatment and severe leaf rolling and chlorosis in plants irrigated with the low water treatment (Table 4). Concerning the control (high water treatment), leaf rolling is a drought response [48]. Plants watered with the low irrigation treatment showed more intense symptoms of chlorosis compared to the corresponding plants watered with the high irrigation treatment, suggesting that the smaller amount of irrigation contributed to increasing the intensity of leaf roll and chlorosis in the plant leaves. Similar research in an extensive green roof found that *Cistus creticus* spp. *creticus* under low irrigation demonstrated brown leaves that dropped and left the branch-ends bare, which was not aesthetically-pleasing and additionally created a fire hazard due to the presence of dried leaves [48]. The presence of water stress in the low irrigation treatment was determined (see Section 3.1).

Table 4. Assessment of visual symptoms of lavender plants under different irrigation treatments at the end of the experiment (day 123), based on a 6-point scale (0–5). Differences between means shown with different letters (Tukey HSD, $p < 0.05$).

Species	Irrigation Treatment	
	High	Low
<i>L. angustifolia</i>	5 a	5 a
<i>L. stoechas</i>	3 b	2 c
<i>L. dentata</i> var. <i>candicans</i>	5 a	5 a
<i>L. dentata</i> var. <i>dentata</i>	5 a	5 a

where 0: plant mortality, 1: very severe leaf rolling and chlorosis >75%, 2: severe leaf rolling and chlorosis 50–75% approximately, 3: moderate leaf rolling and chlorosis 25–50% approximately, 4: mild leaf rolling and chlorosis <25%, 5: no leaf injury.

Furthermore, green roofs, and particularly extensive green roof systems, are characterized by the additive effect of both water deficits (water stress) and high air and substrate temperatures (heat stress) [51,52]. During warm periods, the relationship between air temperature and water in a substrate of an extensive green roof strongly influences plant growth. High substrate temperatures can limit root nutrient and water uptake and transport to leaves [53–56]. Also, the water in the substrate is susceptible to rapid evaporation [9]. In the current study, for all species and both irrigation treatments, the substrate cover from the vegetation within the surface area of each simulated extensive green roof system container was not complete (data not shown), and the meteorological data confirmed the presence of high air temperatures and moderate relative humidity (Figure 1). Further research considering substrate temperature (surface and inside) in relation to vegetation cover is necessary to study the effect of water stress on lavender species in more detail.

3.3. Plant Growth

Two-way ANOVA for data concerning the various plant growth biometrics measured throughout the duration of the experiment showed no significant interactions of the main experimental factors, i.e., among different lavender species and irrigation treatments. On the other hand, differences were shown within the experimental factors. Irrespective of lavender species, the percentage increase in height, shoot canopy diameter and growth index of plants watered with the low irrigation treatment showed smaller corresponding values than the plants watered with the high irrigation treatment ($p < 0.05$) (Table 5). Many wild plant species ceased growth due to adverse environmental conditions [57]. More specifically, during water stress, plants reduced their water requirements for the maintenance of high biomass by limiting their growth [58]. The greatest decrease in percentage increase was shown for the shoot canopy diameter. More specific, shoot canopy diameter percentage increase was reduced by 53% in plants watered with the low irrigation treatment, as opposed to plants watered with the high irrigation treatment (Table 5). Growth index percentage increase was reduced by 40% in plants watered with the low irrigation treatment, as opposed to plants watered with the high irrigation treatment. Finally, plant height percentage increase was reduced by 29% in plants watered with the low irrigation treatment, as opposed to plants watered with the high irrigation treatment. Despite the reduced percentage increase, all lavender species with the exception of *L. stoechas*, had a “healthy” appearance (i.e., without signs of leaf roll, chlorosis or necrosis). Therefore, the lavender species that showed satisfactory growth (*L. dentata* var. *candicans*, *L. dentata* var. *dentata* and *L. angustifolia*) when watered with the low irrigation treatment should be considered in the design of extensive green roof systems to create aesthetically-pleasing green roofs for urban agriculture under conditions of water stress. Note that the water content of the substrate in the low irrigation treatment remained within the substrate’s available water range (see 3.2. *Symptoms Induced by Water Stress*), and could contribute to conserving water resources without affecting the appearance of *L. dentata* var. *candicans*, *L. dentata* var. *dentata* and *L. angustifolia*. Further research is necessary to determine the effect of low irrigation

defined by the substrate hydraulic properties of other ornamental plant species which could be grown on extensive green roofs.

Table 5. Interspecies differences and the effect of different irrigation amounts in the percentage increase in plant height (H), shoot canopy diameter (D) and growth index (GI) ($n = 12$, $p < 0.05$) of lavender species. Differences between means \pm S.E. shown in columns with different letters (Tukey HSD, $p < 0.05$).

Species	Percentage Increase (%)			
	H	D	GI	
<i>L. dentata</i> var. <i>candicans</i>	157 \pm 7.305 a	335 \pm 3.554 a	235 \pm 3.669 a	
<i>L. dentata</i> var. <i>dentata</i>	79 \pm 7.305 b	277 \pm 3.554 b	173 \pm 3.669 b	
<i>L. angustifolia</i>	48 \pm 7.305 c	178 \pm 3.554 c	107 \pm 3.669 c	
<i>L. stoechas</i>	42 \pm 7.305 c	53 \pm 3.554 d	38 \pm 3.669 d	
Irrigation treatment				
high	96 \pm 5.165 a	237 \pm 2.513 a	158 \pm 2.595 a	
low	67 \pm 5.165 b	184 \pm 2.513 b	118 \pm 2.595 b	
Interaction (species \times irrigation treatment)				
<i>L. dentata</i> var. <i>candicans</i>	\times high	179 \pm 10.331	358 \pm 5.025	256 \pm 5.189
	\times low	135 \pm 10.331	313 \pm 5.025	214 \pm 5.189
<i>L. dentata</i> var. <i>dentata</i>	\times high	94 \pm 10.331	299 \pm 5.025	191 \pm 5.189
	\times low	64 \pm 10.331	254 \pm 5.025	154 \pm 5.189
<i>L. angustifolia</i>	\times high	60 \pm 10.331	213 \pm 5.025	131 \pm 5.189
	\times low	36 \pm 10.331	143 \pm 5.025	84 \pm 5.189
<i>L. stoechas</i>	\times high	51 \pm 10.331	78 \pm 5.025	56 \pm 5.189
	\times low	32 \pm 10.331	27 \pm 5.025	21 \pm 5.189
$F_{\text{species/sig.}}$	*	*	*	
$F_{\text{irrigation/sig.}}$	*	*	*	
$F_{\text{interaction/sig.}}$	ns	ns	ns	

ns: nonsignificant; * denotes significant differences between means at $p < 0.05$, shown with different letters within columns.

Differences in the percentage increase among lavender species are likely due to interspecies variations. Overall, among the different lavender species, *L. dentata* var. *candicans* showed the greatest increase in plant height, shoot canopy diameter and growth index, followed in descending order by *L. dentata* var. *dentata*, *L. angustifolia* and *L. stoechas* with the lowest value ($p < 0.05$) (Table 5). However, *L. stoechas* showed signs of stress even under the high irrigation treatment due to the additional stress induced under the extensive green roof system (see Section 3.2); therefore is not recommended that it be used in extensive green roofs. Interspecies differences in growth provide opportunities for combining the other three lavender species in various ways and creating aesthetically-pleasing planting schemes.

On day 123, the results obtained for the shoot dry weights were consistent with the results discussed above, due to interspecies differences ($p < 0.05$). Throughout the experiment, the shoot dry weights of *L. dentata* var. *candicans* showed the greatest value, followed in descending order by *L. dentata* var. *dentata*, *L. angustifolia* and *L. stoechas* with the lowest value ($p < 0.05$) (Table 6).

Table 6. Interspecies differences and the effect of different irrigation amounts in the dry weight (DW) and stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$) ($n = 12, p < 0.05$) of lavender species. Differences between means \pm S.E. shown in columns with different letters (Tukey HSD, $p < 0.05$).

Species		Shoot Dry Weight (g)	Stomatal Conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)
<i>L. dentata</i> var. <i>candicans</i>		188 \pm 3.165 a	44 \pm 1.123 c
<i>L. dentata</i> var. <i>dentata</i>		126 \pm 3.165 b	47 \pm 1.123 bc
<i>L. angustifolia</i>		76 \pm 3.165 c	64 \pm 1.123 b
<i>L. stoechas</i>		35 \pm 3.165 d	50 \pm 1.123 a
Irrigation Treatment			
	high	120 \pm 2.238 a	54 \pm 0.794 a
	low	92 \pm 2.238 b	49 \pm 0.794 b
Interaction (species \times irrigation treatment)			
<i>L. dentata</i> var. <i>candicans</i>	\times high	205 \pm 4.477	49 \pm 1.589
	\times low	171 \pm 4.477	45 \pm 1.589
<i>L. dentata</i> var. <i>dentata</i>	\times high	141 \pm 4.477	45 \pm 1.589
	\times low	111 \pm 4.477	43 \pm 1.589
<i>L. angustifolia</i>	\times high	86 \pm 4.477	68 \pm 1.589
	\times low	65 \pm 4.477	60 \pm 1.589
<i>L. stoechas</i>	\times high	49 \pm 4.477	53 \pm 1.589
	\times low	21 \pm 4.477	48 \pm 1.589
$F_{\text{species/sig.}}$		*	*
$F_{\text{irrigation/sig.}}$		*	*
$F_{\text{interaction/sig.}}$		ns	ns

ns: nonsignificant; * denotes significant differences between means at $p < 0.05$, shown with different letters within columns.

Drought avoidance physiological processes [10,20] are expressed by species in various ways, such as stomatal regulation [10]. Stomatal conductance for both species and irrigation treatments on day 123 was significant ($p < 0.05$). Among lavender species, *L. dentata* var. *candicans* showed the least stomatal conductance; this was not significantly different from the stomatal conductance of *L. dentata* var. *dentata*, followed by *L. stoechas* and *L. angustifolia*, which had the largest stomatal conductance ($p < 0.05$) (Table 6). Additionally, all lavender species showed smaller stomatal conductance values under the low irrigation treatment ($p < 0.05$) (Table 6), suggesting that the plants were being subjected to stress. As mentioned, the presence of water stress was determined (see Section 3.2). However, the stomatal conductance values in all species watered with the high irrigation treatment ($\cong 49\text{--}68 \text{ mmol m}^{-2} \text{ s}^{-1}$) suggests that all species had undergone additional stress, possibly due to the additive effect of the adverse environmental conditions on the green roof (mainly by temperature) and potential root vulnerability to high substrate temperatures [18]. Substrate temperature in relation to air temperature was not studied in the present study; however, plants were exposed to high temperatures during the summer, i.e., ranging between 32.7–34.3 °C (Figure 1), and therefore, in accordance with the findings of Vestrella et al. [19], substrate temperatures may have risen by 6 °C, reaching 38.7–40.3 °C or even higher if the absolute maximum daily temperatures were considered (often above 35 °C; see Figure 1).

Low stomatal conductance values in all lavender species also suggest the presence of a drought defense strategy. Our results agree with the findings of Sendo et al. [59] that on hot summer days, in an extensive green roof system with plants not being subjected to water stress, the drought-tolerant species *Fragaria \times ananassa*, *Thymus serpyllum*, *Evolvulus pilosus*, *Ophiopogon japonicus*, *Vinca major* and *Hedera helix* had significantly lower stomatal conductance than the nondrought tolerant species *Pelargonium \times hortorum*, *Verbena \times hybrida* and *Petunia \times hybrida*. In northeast Italy (Trieste), *Salvia officinalis* grown in 14 cm deep substrate of an extensive green roof system that received natural

precipitation and irrigated only during prolonged drought periods showed a stomatal conductance value of $15.1 \text{ mmol m}^{-2} \text{ s}^{-1}$ and 83% desiccation of the shoots in August that recovered by 40% after autumn rains [60]. However, *L. stoechas*, with the least stomatal conductance ($p < 0.05$) (Table 6), had symptoms of chlorosis in the leaves. The effect of water stress on the growth of the lavender species is not straightforward due to the additive effect of air and substrate temperature mentioned above. Based on the findings of Huang et al. [53] that high substrate temperatures limit root uptake, and the findings of Theodosiou [56] that plant dimensions (height and shoot canopy diameter) can reduce substrate temperature through shading, it seems that the smaller percentage increase of *L. stoechas* in relation to the other species may have led to the occurrence of chlorosis in the leaves, i.e., *L. stoechas* created less shade on the substrate surface, causing greater substrate temperature and reduced nutrient uptake. Further research is necessary to determine the effect of irrigation in relation to both air and substrate temperature. However, potential carry-over effects from year to year due to water stress need to be studied in long-lived species, such as shrubs, as the induced stress may determine plant physiological and molecular changes [61].

Throughout the experiment, the biometrics (i.e., height, shoot canopy diameter and growth index) of plants watered with the high irrigation treatment showed greater values than plants watered with the low irrigation treatment ($p < 0.05$) (Figure 4). Similarly, in an extensive green roof, *Cistus creticus* spp. *creticus* showed reduced growth index when irrigated with low amount of water compared to nonwater stress irrigated plants [48]. With the exception of *L. stoechas*, despite the smaller biometric values, the other lavender species did not demonstrate visible symptoms of induced damage by water stress. Although the low irrigation treatment produced overall smaller plants, if necessary, it could contribute to conserving water resources without affecting the appearance of *L. dentata* var. *candicans*, *L. dentata* var. *dentata* and *L. angustifolia*. As mentioned, additional research to determine the effect of low irrigation defined by the substrate hydraulic properties on the growth of other ornamental plant species of extensive green roofs is recommended.

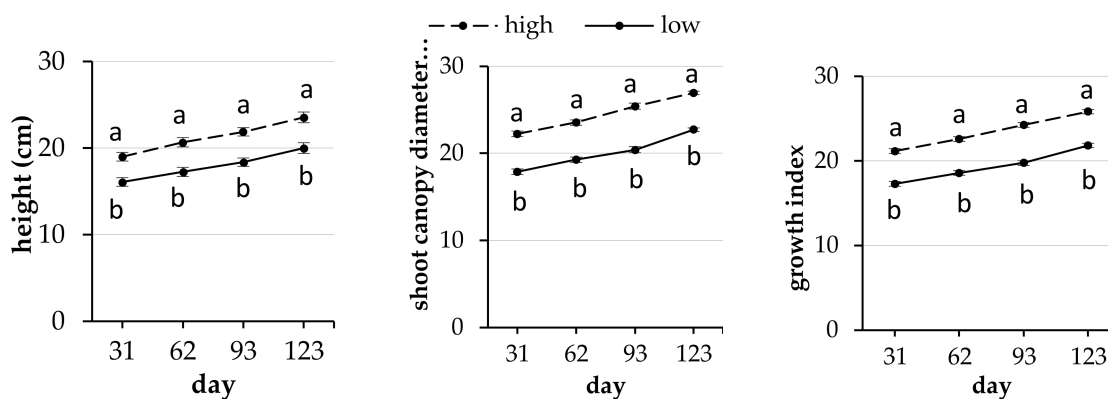


Figure 4. The effect of different irrigation amounts (high and low) on the biometrics (height, shoot canopy diameter and growth index) of *Lavandula* plants irrespective of species ($n = 24$, $p < 0.05$). Differences between means \pm S.E. shown with different letters (Tukey HSD, $p < 0.05$) for each individual biometric variable.

Significant differences ($p < 0.05$) were also shown among different lavender species in plant height, shoot canopy diameter and growth index. In the current study, the differences in plant height among the lavender species were likely due to interspecies variations. *L. dentata* var. *candicans* showed the greatest growth in height throughout the experiment, followed by *L. dentata* var. *dentata* ($p < 0.05$). The heights of both *L. stoechas* and *L. angustifolia* were similar but smaller than the corresponding heights of the other two lavender species ($p < 0.05$) (Figure 5). The differences in height among the lavender species that showed satisfactory growth (*L. dentata* var. *candicans*, *L. dentata* var. *dentata* and *L. angustifolia*) when watered with the low irrigation treatment should be considered in the design of

extensive green roof systems to create aesthetically-pleasing green roofs for urban agriculture under conditions of water stress.

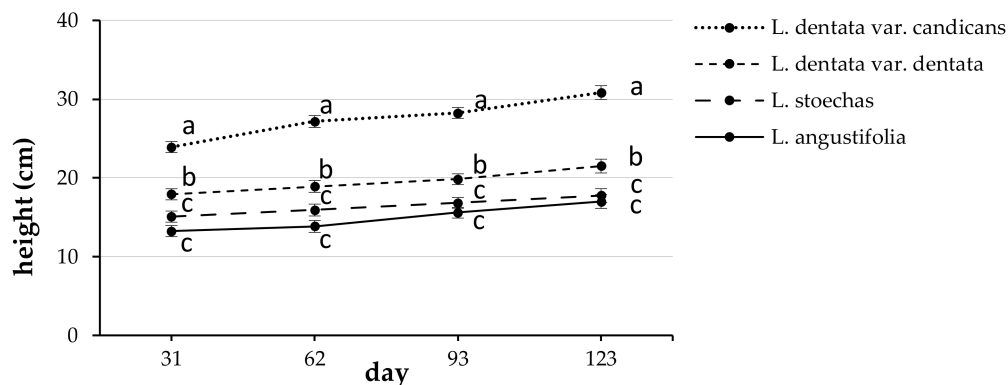


Figure 5. *Lavandula* interspecies differences in plant height ($n = 12$, $p < 0.05$). Differences between means \pm S.E. shown in columns with different letters (Tukey HSD, $p < 0.05$).

With regards to shoot canopy diameter throughout the experiment, *L. dentata* var. *candidans* showed the greatest value, followed in descending order by *L. dentata* var. *dentata*, *L. stoechas* and *L. angustifolia* with the lowest value ($p < 0.05$) (Figure 6). These differences were due to interspecies variations. Shoot canopy diameter is an important determinant of plant success on green roofs, especially in extensive green roofs, as it influences vegetation cover [62]; vegetation cover shades the substrate surface, and hence, reduces substrate evaporation rates [18]. Therefore, the greater shoot canopy diameter of both *L. dentata* var. *candidans* and *L. dentata* var. *dentata* compared to the other lavender species suggests that they are more suitable for use in extensive green roof systems in comparison to the other lavender species studied. However, between the other two lavender species, only *L. angustifolia* showed satisfactory growth, possibly due to its dense foliage or drought tolerance mechanism [48]. As such, it is recommended for use in extensive green roof systems.

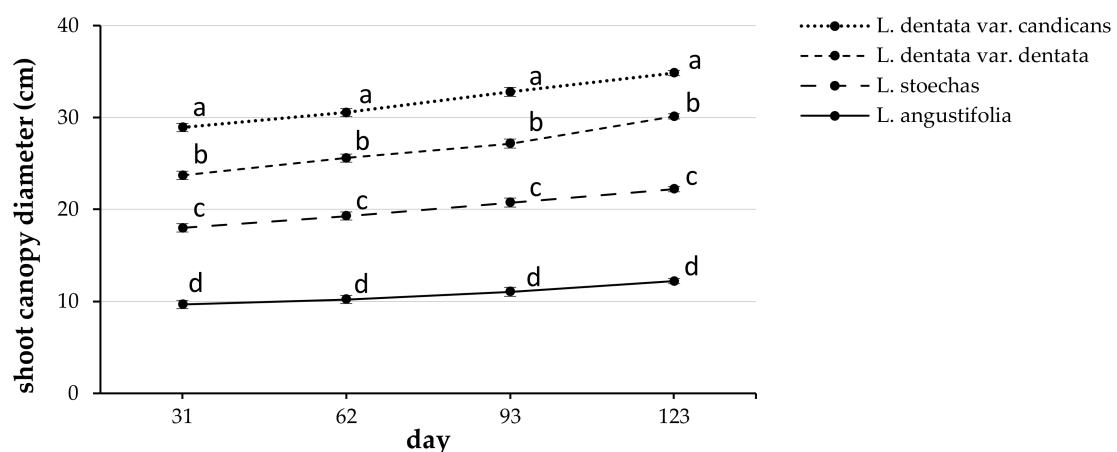


Figure 6. *Lavandula* interspecies differences in shoot canopy diameter ($n = 12$, $p < 0.05$). Differences between means \pm S.E. shown in columns with different letters (Tukey HSD, $p < 0.05$).

Similarly, regarding the growth index throughout the experiment, *L. dentata* var. *candidans* showed the greatest value, followed in descending order by *L. dentata* var. *dentata*, *L. stoechas* and *L. angustifolia* with the lowest value ($p < 0.05$) (Figure 7). The growth index results were consistent with both the plant height and shoot canopy diameter results discussed above, and are due to interspecies differences ($p < 0.05$).

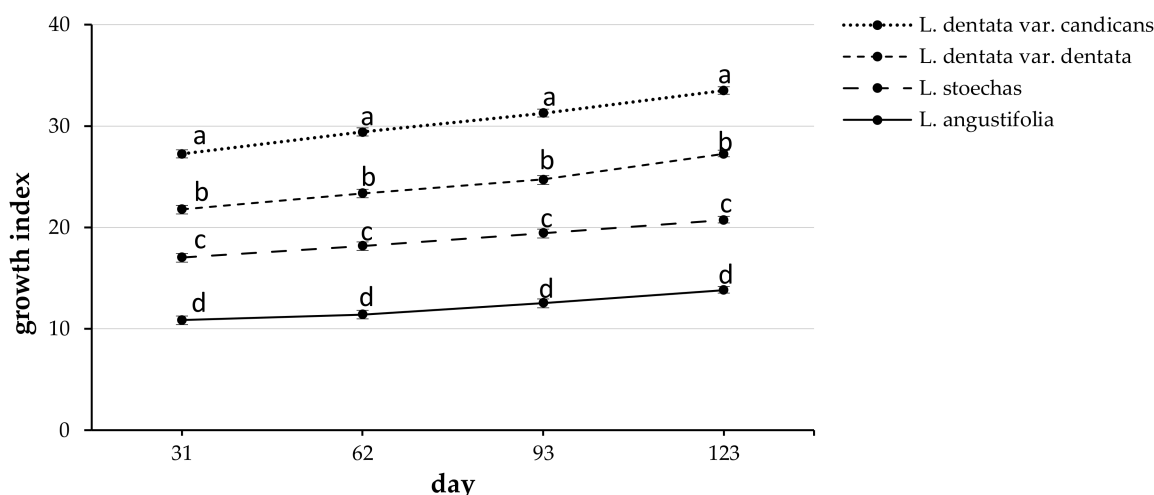


Figure 7. *Lavandula* interspecies differences in growth index ($n = 12$, $p < 0.05$). Differences between means \pm S.E. shown in columns with different letters (Tukey HSD, $p < 0.05$).

4. Conclusions

The hydraulic properties (e.g. water retention curve, hydraulic conductivity) of substrates affect water availability and provide important information for irrigation management. In the current study, two amounts of water irrigation treatments (high and low) were applied within an available water range of an extensive green roof substrate based on its hydraulic properties. In general, plant growth was reduced in the low irrigation treatment. Among the various lavender species studied, *L. dentata* var. *candidans* showed the greatest growth, while *L. angustifolia* showed the least. Overall, plant growth due to interspecies variation was as follows, in descending order: *L. dentata* var. *candidans*, *L. dentata* var. *dentata*, *L. stoechas* and *L. angustifolia*. All lavender species showed low stomatal conductance values, suggesting the presence of a drought defense strategy. *L. dentata* var. *candidans* showed the lowest stomatal conductance value, similar to those of *L. dentata* var. *dentata* and followed in ascending order by *L. stoechas* and *L. angustifolia*, with the greatest stomatal conductance.

On the other hand, with the exception of *L. stoechas*, the appearance of all species studied was satisfactory. Therefore, the use of *L. stoechas* is not proposed, as the visual quality of the plant was reduced due to leaf roll and chlorosis induced by stress. Despite the reduced growth of lavender species watered with the low irrigation treatment, the satisfactory appearance (i.e., lack of damage induced symptoms) of the plants supports the use of *L. dentata* var. *candidans*, *L. dentata* var. *dentata*, and *L. angustifolia* under low irrigation. Further study on the effect of low irrigation within the substrate available water range determined by the substrate hydraulic properties on the growth of other ornamental plant species on extensive green roofs is recommended.

The differences in plant characteristics and size among *L. dentata* var. *candidans*, *L. dentata* var. *dentata*, and *L. angustifolia* can be considered in the design of extensive green roof systems including amphitheatrical planting schemes to create aesthetically-pleasing green roofs for urban agriculture. The larger *L. dentata* var. *candidans* and *L. dentata* var. *dentata* varieties are recommended for extensive green roofs, as they provide greater vegetation cover in substrates, potentially reducing the effect of high substrate temperatures due to shading. Further research is recommended to determine the effect of irrigation in relation to drought tolerance mechanisms, as well as both air and substrate temperatures in extensive green roof systems.

Author Contributions: Conceptualization, A.T.P.; methodology, A.T.P. and P.A.L.; formal analysis, A.T.P., P.T., P.A.L. and A.P.K.; investigation, P.T. and A.P.; writing—original draft preparation, A.P.; writing—review and editing, A.T.P., P.A.L. and A.P.K.; supervision, A.T.P. and P.A.L.; project administration, A.P. and P.T. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: We would like to thank Kalantzis Plants for the free supply of lavender plants.

Conflicts of Interest: The authors declare no conflict of interest.

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