

Growing substrates for aromatic plant species in green roofs and water runoff quality: pilot experiments in a Mediterranean climate

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ABSTRACT

Green roof technology has evolved in recent years as a potential solution to promote vegetation in urban areas. Green roof studies for Mediterranean climates, where extended drought periods in summer contrast with cold and rainy periods in winter, are still scarce. The present research study assesses the use of substrates with different compositions for the growth of six aromatic plant species – *Lavandula dentata*, *Pelargonium odoratissimum*, *Helichrysum italicum*, *Satureja montana*, *Thymus caespitius* and *T. pseudolanuginosus*, during a 2-year period, and the monitoring of water runoff quality. Growing substrates encompassed expanded clay and granulated cork, in combination with organic matter and crushed eggshell. These combinations were adequate for the establishment of all aromatic plants, allowing their propagation in the extensive system located on the 5th storey. The substrate composed of 70% expanded clay and 30% organic matter was the most suitable, and crushed eggshell incorporation improved the initial plant establishment. Water runoff quality parameters – turbidity, pH, conductivity, NH_4^+ , NO_3^- , PO_4^{3-} and chemical oxygen demand – showed that it could be reused for non-potable uses in buildings. The present study shows that selected aromatic plant species could be successfully used in green roofs in a Mediterranean climate.

Key words | aromatic vegetation, green roofs, growing substrates, sustainable drainage systems, water runoff

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INTRODUCTION

Green areas being replaced by an increasing quantity of hard and impermeable surfaces in the urban environment brings numerous problems for infrastructures of stormwater management, due to the runoff generated by those impervious surfaces, with flooding of drainage systems being more frequent. Following the need to find efficient stormwater management systems, sustainable urban drainage systems (SUDS) are a solution to stormwater management by controlling both the quantity and quality of the runoff. This approach is based on evapotranspiration and stormwater infiltration on-site, through natural or ecological constructions, to reduce the overflow (e.g. permeable pavings, raingardens, green roofs) (Brandão *et al.* 2017). Green roofs thus appear as a solution to support a sustainable stormwater management and being aligned with the SUDS approach.

In recent years, policy makers, urban planners and landscape architects, facing the challenges of sustainable development and improvement of human life in urban areas, have begun to look for ecological construction solutions. Green roofs in urban settings have the ability to manage stormwater runoff (by attenuating flood peaks), and improve the runoff quality, remove CO_2 and air pollutants, reduce the urban heat island effect, reduce building heat flux and consequently energy consumption with energy savings, and create habitats for wildlife (increasing urban biodiversity) (Vijayaraghavan *et al.* 2012; Beecham & Razzaghmanesh 2015).

Plant species selection and the growing substrate are two important items that should be carefully designed and selected, taking into consideration the climate of the region and the functional objectives of the green roof

structure. In the Mediterranean region, there has been a growing interest in this type of construction, although research and installation efforts are still limited due to specific characteristics of the Mediterranean climate (characterized by high summer temperatures and prolonged drought seasons), which is a challenge for vegetation survival on rooftops (Savi *et al.* 2014).

Sedum is the most common choice of plant species on green roof constructions (Papafotiou *et al.* 2013). However, their lower evapotranspiration capacity counteracts the desired effect in reducing the amount of water runoff (Nagase & Dunnet 2012). There is a growing interest in species other than *Sedum*. Studies developed in the Mediterranean countries started to use native aromatic vegetation, more adapted to the local climate variations and with lower maintenance needs (Savi *et al.* 2014; Raimondo *et al.* 2015; Van Mechelen *et al.* 2015). More studies encompassing the use of aromatic vegetation adapted to Mediterranean climate are needed.

The growing substrate is one major component of the green roof implementation. There is not a universal growing substrate for extensive green roof systems, but an adequate mixture of mineral and organic components adapted to local climate conditions, and allowing the adequate support and nutrition of target plants, is needed (Ampim *et al.* 2010; Raimondo *et al.* 2015). Components commonly used in green roof growing media include: perlite, vermiculite, volcanic pumice, sand, expanded shale, clay and slate (as natural mineral components), and peat or compost (as organic components) (Ampim *et al.* 2010; Nagase & Dunnet 2011). There are also several green roof substrates commercially available, with no disclosed formulation. However, alternative substrates made from recycled or waste materials should be investigated, in order to promote the sustainable development of green roof technology construction systems.

The challenge of constructing a sustainable green roof structure is to find a combination of vegetation and growing substrate that functions properly, and is suitable for a specific climate region. Vegetation should survive extended drought periods in summer, in contrast with cold and rainy periods in winter, while a proper growing substrate should be light, well drained and with an adequate water and nutrient absorption capacity, supporting vegetation growth and not breaking down when exposed to harsh climatic conditions (see Forschungsgesellschaft Landschaftsentwicklung Landschaftshaue (FLL) guidelines (FLL 2008)).

The aim of the present work was to investigate the adequacy of different substrate compositions for the growth of six aromatic plant species, using pilot green roof structures, divided into two groups according to their growth characteristics:

evergreen shrubs – *Lavandula dentata*, *Pelargonium odoratissimum*, *Helichrysum italicum*, *Satureja montana* and mat forming species *Thymus caespititius* and *T. pseudolanuginosus*. Additionally, water runoff quality was assessed.

MATERIAL AND METHODS

Green roof experimental set-up

The experiments were conducted in an urban area in northern Portugal – Porto, a Mediterranean region. This has a warm temperate and dry summer climate (Csb) according to the Köppen Geiger climate classification (Kottek *et al.* 2006), recording an annual average temperature of 15.3 °C in the years preceding the experiment (2000–2013), and of 15.7 °C in the years of the experiments (2013–2015) (www.pordata.pt).

Experimental plots (Figure 1) were located on a roof top (5th storey) 129 m above sea level (Latitude 41.18 N; Longitude –8.61 W), exposed to local ambient conditions. The experimental green roof multilayer plot systems were set according to the European Standards FLL guidelines (FLL 2008). The structure of the plot units was made of propylene with the following design characteristics: surface area, $A = 1.2 \text{ m}^2$, effective depth of the substrate, $h_s = 0.17 \text{ m}$, depth of drainage layer, $h_d = 0.02 \text{ m}$ (composed of expanded clay Leca® L (Weber SaintGobain®, Aveiro, Portugal) of 10–20 mm granulometry). The experiment was conducted in six pilot-scale green roof systems, five vegetated and one non-vegetated, in a combination of different substrate compositions and/or aromatic plant species. The experiments were monitored from March 2013 to April 2015.

Plant material

Aromatic species, endemic to the Mediterranean region, were chosen for the extensive green roof plot experiments based on characteristics such as low maintenance, low



Figure 1 | Extensive green roofs plots.

water needs, and resistance to adverse conditions and the climate of the region. The selected aromatic plants can be divided in two groups according to their growth characteristics: evergreen shrubs (*L. dentata*, *H. italicum*, *P. odoratissimum*, *S. montana*) and mat forming (*T. pseudolanuginosus*, *T. caespititius*). All the plants were propagated in organic farming mode at Cantinho das Aromaticas – Viveiros, Lda, and then transplanted to our system by hand (four plants from each species), in a juvenile growing state. Seeds of clover (*Trifolium repens* ronny species, provided by A Sementeira - Alípio Dias & Irmão, Lda) were added to two experimental plots due to their capacity to host nitrogen fixing bacteria, and thus contribute to the natural fertilization of the plots.

Table 1 shows the distribution of the vegetation species in the experimental plots. Plant development was evaluated through growth measurements (height for evergreen shrubs and length for mat forming aromatic plants), once a month. Growth was assessed during the experimental period relative to the initial plant size and presented as a growth increment.

Growing substrate

Six plots were set up with different compositions of growing substrate (Table 1). A control, with substrate but without vegetation, was also established to monitor the runoff water quality. Substrate components used in the experimental plots had the following characteristics: (1) expanded clay – Leca® Hydro, with particle size ranging from 4–10 mm was provided by Weber SaintGobain®, Aveiro, Portugal; (2) granulated cork ADT, with particle size ranging from 2–7 mm was provided by Corticeira Amorim SGPS, SA, Santa Maria de Lamas, Portugal; (3) crushed egg shell supplied by DerOvo Group, Pombal, Portugal; and (4) organic matter (soil – collected at a private garden).

Physical and chemical characteristics of each component of the growing substrates were determined: pH and conductivity (Houba et al. 1995), dry mass percentage, porosity and bulk density (Tan 1995) and water holding capacity (European Standard EN 1097-6:2000).

Water runoff sampling and analysis

Samples of the water runoff from each plot were collected for analysis of water quality (Tables 4 and 5), from multiple natural rainfall events within 1 year of the experimental period from December 2013 to November 2014. Two types of water runoff sample have been taken: (1) grab water runoff samples directly from the plots and (2) samples

Table 1 | Growing substrate composition of the green roof plots

	Control	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Substrate composition	30% organic matter + 70% expanded clay	30% organic matter + 70% expanded clay	30% organic matter + 70% expanded clay	30% organic matter + 70% expanded clay	15% organic matter + 15% crushed eggshell + 70% Expanded clay	30% organic matter + 70% granulated cork
Clover	Absent	Present	Present	Absent	Absent	Absent
Plant species	Without vegetation	<i>L. dentata</i> <i>P. odoratissimum</i> <i>H. italicum</i>	<i>T. pseudolanuginosus</i> <i>T. caespititius</i> <i>S. montana</i>			

of the water runoff from the system (composed of the total accumulated water runoff), hereby designated as cumulative samples, collected in a jerrycan placed at the outlet of the drainpipe of the plots between time periods of 3 h and 96 h. Rainwater was also collected.

The following parameters were determined, based on *Standard Methods* (APHA/AWWA/WEF 1998): pH, conductivity, turbidity and chemical oxygen demand (COD). The concentration of phosphorus, ammonium and nitrate (PO_4^{3-} , NH_4^+ and NO_3^-) was determined with photometric test kits (Spectroquant[®], Merck, Darmstadt, Germany), using a Photometer NOVA 60 Spectroquant[®] (Darmstadt, Germany).

Statistical analysis

Statistical analysis was performed using the software SPSS (SPSS Inc., Chicago, IL, USA; Version 12.0). Data were analysed through one-way analysis of variance to compare the volume of water runoff between vegetated plots (1–5). To detect the statistical significance of differences ($p < 0.05$) between means of observation, the Duncan test was performed.

RESULTS AND DISCUSSION

Characterization of the different growing substrates

The properties of substrate components tested in this study are presented in Table 2. Organic matter (soil) used in the present studies had a pH value of 6.70.

Substrate pH is a parameter that influences nutrient availability and absorption – a lower value may contribute to an excess of nutrients in the substrate, increasing phytotoxicity, whereas a higher pH may make nutrients unavailable for plant use, due to their precipitation (Brito & Mourão 2012). According to the recommendations of the FLL guidelines (FLL 2008), engineered substrates for

extensive green roofs should present pH and water storage ability/maximum water holding capacity between 6.0–8.5 and $\geq 35\%$ volume, respectively. Among our substrate components, only granulated cork presented an acidic pH value (4.33–4.97), below the recommended value from FLL guidelines. However, the selected aromatic plants grow on a wide range of pH values (5.5–8.0) (Skinner 2005) and consequently substrate pH should not be a limiting factor in this case. Regarding water holding capacity, only granulated cork (ADT 2–3 mm) presented values higher (70%) than those recommended by FLL guidelines, while expanded clay was very near the minimum value recommended (30%). All the other substrate constituents presented lower values of water holding capacity than those suggested by FLL guidelines. Note that the expanded clay was the major component present in the substrate layer (70% total volume), thus being the largest contributor for this characteristic in the global substrate mixture, and thus the recommended FLL value of 35% water storage ability for extensive multilayer green roof systems is not compromised.

Concerning the other analysed parameters (total pore volume – related to air content, and bulk density), no recommendations were found in the literature or technical guides. However, these parameters were analysed in order to sustain the characterization of the used substrate. Higher density than 0.67 g/cm^3 is not suitable for green roofs, since it usually implies reduced water infiltration rates, poor drainage and limited plant growth (Skinner 2005), which is not the case for the green roof components used in the present study, and so they can be considered adequate substrate components.

Growing substrates suitable for all vegetation species and climate conditions are not available. Therefore, alternative growing substrates, adapted to local conditions, should be surveyed. Studies using other experimental mixtures, composed of recycled and waste materials, have begun to appear in the literature (Bates *et al.* 2015). Mickovski *et al.*

Table 2 | Physico-chemical characterization of substrate components

	Chemical characteristics		Physical characteristics			
	pH	Conductivity ($\mu\text{S/cm}$)	Porosity (%)	Bulk density (g/mL)	Dry mass (%)	Water holding capacity (%)
Expanded clay (Leca [®] Hydro)	8.83	210	50	0.2	14.2	30.1
Granulated cork (ADT 2–3 mm)	4.33	457	39	0.2	1.9	70.3
Granulated cork (ADT 3–7 mm)	4.97	171	36	0.1	3.9	22.4
Crushed eggshell	7.89	581	70	0.6	5.8	19.9

(2013) used a green roof substrate mixture composed of recycled inert construction waste (20%), inert loam (65%) and compost (15%), which has been proven to be adequate for plant growth (grass mix and sedum), besides being resistant to erosion and allowing water drainage. Following the same trend, Molineux et al. (2009) tested three experimental green roof media composed of recycled materials (clay pellets, paper ash pellets and carbonated limestone), in comparison to the UK standard substrate for green roofs (crushed red brick).

On the other hand, the amount of organic matter in the total substrate mixture is an issue of concern. High amounts of organic matter lead to higher plant and biomass growth, which could be harmful in terms of plant survival when drought conditions occur (Rowe et al. 2006), besides encouraging weed growth. Studies described by Nagase & Dunnet (2011) reported that 10% of organic matter by volume in the form of compost, in a mixture with crushed brick, provided optimal growth for the plant species tested – *Allium schoenoprasum*, *Limonium latifolium*, *Melica ciliate* and *Nepeta × faassenii*. Nevertheless, Beattie & Bergharge (2004) suggested that 10–25% organic matter content in green roof substrates would be the ideal for extensive systems.

Plant growth on different growing substrates

Plant growth in the various experimental plots with different growing substrates was measured once a month from March 2013 until April 2015, and vegetation growth is presented in Table 3.

Concerning growth of plant species tested in plot 1, no differences in growth could be observed by the end of the experiment, and all plants survived until the end of the experiment. Among the three species tested, *P. odoratissimum* was shown to be more sensitive, since 1 month after

planting and during the following 6 months it dried out (losing leaves), after which time it began to sprout. The other two species maintained their viability, and *L. dentata* kept its flowers during all the experimental period.

Seeds of clover were added to plot 2 (at 10 g per plot, 1 month after aromatic planting). Clover is known to have the capability to form a symbiotic association with rhizobia (soil bacteria), which in turn absorb nitrogen from the atmosphere. This could influence and encourage plant growth, since nitrogen is an essential micronutrient for this. Plots 2 and 3 have been compared, and differences in growth increment were only detected for *Thymus* species, showing a higher growth increment in the plot with clover seeds (plot 2), and no differences were detected for *S. montana* between plots 2 and 3. Although clover seeds had grown in both plots, their influence on aromatic growth was not very evident in these specific conditions.

Growth of *Thymus* species and *S. montana* were compared at the end of the experiment, between plots 3, 4 and 5, which are composed of different growing substrates. *Thymus* species had a high mortality in plot 4, and *S. montana* kept its initial height in plot 5. The growing substrate of plot 4 included crushed eggshell, a residue from the egg industry composed of calcium carbonate. It was incorporated in the growing substrate in order to analyse its influence on vegetation development. A qualitative survey of aromatic species planted in plots 3 and 4, during the first 5 months of plant establishment, allowed us to conclude that plants supplemented with crushed eggshell presented an initial faster establishment and development after planting when compared to the substrate without crushed eggshell. Growth measurements confirmed this observation: comparing the growth of vegetation between plots 3 (without crushed eggshell) and 4 (supplemented with crushed eggshell), 5 months after planting plot 4 showed a greater increase in all aromatic species tested: 19% against 52%, for

Table 3 | Aromatic plant species growth increment (%) at the end of the experimental period (April 2015)

	Growth Increment (%) (Min–Max)					
	<i>Lavandula dentata</i>		<i>Pelargonium odoratissimum</i>		<i>Helichrysum italicum</i>	
Plot 1	56 (–3 to 94)	<i>n</i> = 4	74 (47–100)	<i>n</i> = 4	141 (26–300)	<i>n</i> = 4
	<i>Thymus pseudolanuginosus</i>		<i>Thymus caespitius</i>		<i>Satureja montana</i>	
Plot 2	165 (131–250)	<i>n</i> = 4	418 (360–475)	<i>n</i> = 2	288 (125–400)	<i>n</i> = 4
Plot 3	24 (–31 to 60)	<i>n</i> = 4	121 (–30 to 236)	<i>n</i> = 4	243 (57–340)	<i>n</i> = 4
Plot 4	dieback		288	<i>n</i> = 1	247 (178–340)	<i>n</i> = 4
Plot 5	141 (92–188)	<i>n</i> = 4	146 (92–254)	<i>n</i> = 4	N.G. (–21 to 31)	<i>n</i> = 4

N.G., no growth increment.

T. pseudolanuginosus, 67% against 100% for *T. caespititius* and 215% against 305% for *S. montana*, respectively.

Based on our experimental results, we could say that all experimental tested substrates are adequate for aromatic species establishment. The tested substrate used on plot 2 (a mixture of 70% expanded clay + 30% organic matter) was the most suitable for growth of the target species in the long term, since it presented the highest growth increment for the three species (when compared to plots 3, 4 and 5).

In order to benefit from all the advantages inherent to green roof installation, vegetation species adapted to the climate features of the Mediterranean should be found. Also, diverse plant mixes in green roof construction, with different functional diversity and complexity, are more advantageous than using plants of the same taxonomic group which can compete for the same resources (Van Mechelen et al. 2015). For that reason, in the present study, different aromatic species with different growing patterns (evergreen shrubs and mat forming) were chosen.

The use of aromatic vegetation in green roofs is not common in the literature. Among the aromatic plants previously studied in green roof systems (Papafotiou et al. 2013; Savi et al. 2014; Raimondo et al. 2015), only *Helichrysum italicum* has been used in our study, reaching a 100% survival of plants at the end of the experimental period, hence this being a good choice for green roof systems in the typical conditions of a Mediterranean climate.

The aromatic species selected are native from the Mediterranean region, and so are well adapted to the climate. On the other hand, aromatic species in green roofs have also been chosen not only due to their aesthetic landscape integration and contribution to the biodiversity of the surroundings, but also for economic exploitation (e.g. food, pharmaceutical or cosmetic industries), bringing added value to the green roof installation.

Water runoff quality

Water runoff quality from the experimental green roof plots and rainwater quality is presented in Tables 4 and 5.

Comparing rainwater runoff quality of experimental plots with the control, and concerning grab samples data, discharge from plots 4 and 5 presented higher values of conductivity, NH_4^+ , NO_3^- and PO_4^{3-} than the control. The water runoff from the other experimental plots showed similar values for all parameters in comparison with the unvegetated control, which led us to conclude that vegetation did not influence water runoff quality. In opposition to our results, Beecham & Razzaghmanesh (2015) described

Table 4 | Water runoff characterization of green roof plot experiments – grab samples

	Average results (min.–max.) for each experimental plot											
	Control	n	Plot 1	n	Plot 2	n	Plot 3	n	Plot 4	n	Plot 5	n
pH	7.95 (7.67–8.67)	5	7.82 (7.57–8.30)	5	8.11 (7.54–8.96)	10	7.79 (7.32–8.51)	11	7.70 (7.19–8.18)	11	7.49 (7.28–7.82)	7
Conductivity ($\mu\text{S}/\text{cm}$)	117 (104–129)	5	132 (123–157)	5	126 (100–142)	10	130 (98–162)	11	323 (227–637)	11	149 (115–168)	7
Turbidity (NTU)	2.5 (0.9–5.1)	5	1.8 (0.5–3.7)	5	1.9 (0.7–6.3)	7	2.0 (0.5–5.1)	8	3.3 (1.4–8.1)	8	12.7 (9.1–14.5)	6
NH_4^+ (mg $\text{NH}_4\text{-N}/\text{L}$)	0.06 (0.05–0.07)	4	0.06 (0.06–0.07)	3	0.08 (0.05–0.11)	7	0.08 (0.04–0.17)	9	0.11 (0.03–0.37)	9	0.11 (0.09–0.16)	5
NO_3^- (mg $\text{NO}_3\text{-N}/\text{L}$)	0.81 (0.60–1.15)	4	0.67 (0.60–0.80)	3	0.86 (0.50–1.20)	8	0.78 (0.30–1.50)	6	6.83 (0.20–16.70)	8	1.39 (0.75–2.90)	5
PO_4^{3-} (mg $\text{PO}_4\text{-P}/\text{L}$)	1.11 (0.91–1.50)	3	1.06 (0.77–1.87)	4	1.21 (0.76–1.84)	8	1.70 (0.80–4.65)	9	1.04 (0.62–1.94)	8	1.91 (1.46–2.16)	5
COD (mg/L)	38 (7–64)	4	27 (4–53)	4	26 (4–44)	6	27 (7–44)	6	50 (30–63)	5	64 (14–131)	6

Table 5 | Water runoff characterization of green roof plot experiments – cumulative samples

	Average results (min.–max.) for each experimental plot										
	Control	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	n	n	n	n	
pH	7.66 (7.12–8.89)	7.71 (7.21–8.38)	7.65 (7.32–8.24)	7.63 (7.21–8.29)	7.72 (7.36–8.67)	7.51 (7.19–7.89)	15	14	17	18	17
Conductivity ($\mu\text{S}/\text{cm}$)	125 (98–204)	137 (92–198)	152 (95–439)	128 (80–152)	324 (162–666)	157 (116–239)	15	14	17	18	17
Turbidity (NTU)	3.9 (0.8–9.7)	1.6 (0.5–6.3)	1.4 (0.2–6.2)	1.5 (0.3–4.1)	2.8 (0.4–8.8)	8.9 (0.9–15.5)	10	12	13	14	13
NH_4^+ (mg $\text{NH}_4\text{-N}/\text{L}$)	0.18 (0.05–0.45)	0.12 (0.05–0.24)	0.12 (0.08–0.20)	0.12 (0.05–0.28)	0.13 (0.07–0.24)	0.17 (0.06–0.35)	7	6	8	8	6
NO_3^- (mg $\text{NO}_3\text{-N}/\text{L}$)	1.77 (0.60–5.80)	0.59 (0.55–0.65)	1.15 (0.50–2.77)	0.69 (0.50–1.00)	10.78 (0.60–22.90)	2.13 (1.70–2.70)	6	6	5	5	5
PO_4^{3-} (mg $\text{PO}_4\text{-P}/\text{L}$)	1.29 (0.76–2.89)	0.89 (0.59–1.07)	1.00 (0.80–1.45)	1.63 (0.80–3.79)	0.69 (0.50–1.12)	1.70 (1.03–2.16)	6	7	8	8	6
COD (mg/L)	30 (7–89)	23 (5–53)	25 (16–37)	25 (8–48)	38 (8–80)	99 (32–207)	16	17	20	20	19

significant differences in water quality parameters (NO_2 , NO_3 , NH_4 , PO_4 , pH, EC, TDS and turbidity) between the outflows of vegetated and non-vegetated systems in the first operational year of the system. It has been described that water runoff quality is strongly dependent on the growing media used in vegetated structures (Vijayaraghavan *et al.* 2012), with rainwater passing through growing media with less organic matter presenting higher quality (Beecham & Razzaghmanesh 2015). Our results are in accordance with these observations.

Cumulative samples of rainwater have been collected, and its quality has been analysed, in terms of the following parameters: pH (4.77–7.45); conductivity (13–208 $\mu\text{S}/\text{cm}$); turbidity (0.4–2.6 NTU); NH_4^+ (0.04–0.56 mg $\text{NH}_4\text{-N}/\text{L}$); NO_3^- (0.70–3.80 mg $\text{NO}_3\text{-N}/\text{L}$); PO_4^{3-} (0.05–0.40 mg $\text{PO}_4\text{-P}/\text{L}$) and COD (<DL-79 mg/L). Rainwater quality has been compared with water runoff from experimental plots; for all the parameters tested, water runoff from green roof systems presented higher values than those for rainfall water.

In accordance to our results, Vijayaraghavan *et al.* (2012) showed that the runoff from their green roofs from simulated rain events contained significant amounts of PO_4^{3-} (42.8–66.0 mg/L) when compared to real rain events (19.8–40.0 mg/L). Nevertheless, the results obtained for water quality in our experiments should be taken with caution, since some cumulative samples included the initial runoff of a rain event (first flush), which is known to affect water quality (as has already been described in a previous study – Monteiro *et al.* 2016). It has been demonstrated in green roof experiments that the concentrations of most chemical components in runoff were highest during the beginning of rain events, and decreased with subsequent rain events (Vijayaraghavan *et al.* 2012).

Additionally, rainwater runoff quality from vegetated roofs is important when storage water is intended for later use. According to ETA 701-2012 (ANQIP 2012), our results indicate that the water runoff from the experimental green roofs could be stored for later non-potable uses, such as landscape irrigation and/or toilet flushing. At present, no Portuguese legislation is available for re-use of this water source in buildings. Therefore, research studies regarding the analysis of rainwater runoff from green roofs should be performed, in order to make it possible to use this potential alternative water source.

Green roof rainwater storage capacity

Another important feature of green roof systems in urban areas is the capacity that the substrate has to retain

rainwater and, therefore, delay the release of stormwater runoff to water management systems, preventing floods when severe rain events occur (Nagase & Dunnet 2012).

No significant differences regarding amount of water runoff were seen between vegetated plots (1–5) composed of different growing substrates. Also, no significant differences could be seen between control and vegetated roofs. The fact that no significant differences were found between the plots suggests that, besides the different experimental growing substrates tested, all compositions had similar retention capacity, and the presence of vegetation had no influence. According to Berndtsson (2010), green roof depth and type of substrate are the key factors that affect water retention capacity instead of vegetation type. An opposite observation has been described by Nagase & Dunnet (2012) and Vanuytrecht *et al.* (2014), reporting significant differences in amount of water runoff between vegetation types tested, where grasses (or grass-herb green roofs) were the most effective for reducing water runoff, followed by forbs (herbaceous flowering plants) and *Sedum*. Also in opposition to our observations, Beecham & Razzaghmanesh (2015) reported retentions between 52 and 95% in vegetated beds, while in non-vegetated beds the range was between 31 and 65%, which could be explained due to evapotranspiration, which in turn influences stormwater retention capacity.

Although it has been stated that water retention/runoff from green roofs depends not only on growing media composition and properties, but also on vegetation species used (Nagase & Dunnet 2012), the present research study does not reveal any difference in water runoff for the different combinations of tested substrates and vegetation used. These achievements could be justified if shoot and root systems of vegetation were not widely developed. According to Nagase & Dunnet (2012), taller-height plants, with larger diameters and root and shoot biomass, are more effective in reducing water runoff from green roofs, as opposed to plants with lower height and smaller diameters and root and shoot biomass. However, it also should be taken into consideration that the different drainage layer used in our study (expanded clay), when compared to the industrial material commonly used (a plastic with water retention channels), might influence the water retention by the system. Therefore, if the green roof is designed to mainly reduce stormwater runoff (to the detriment of the other benefits), the effectiveness of different vegetation species, focusing on plants with high evaporation rates and deep roots to absorb water, should be taken into consideration (Vanuytrecht *et al.* 2014).

CONCLUSIONS

The experimental growing substrate most suitable for the aromatic species tested was that composed of 70% expanded clay and 30% organic matter. Water runoff had a quality compatible with storage and reuse for non-potable purposes. The amount of water runoff from the vegetated and the non-vegetated plots was not significantly different, which may be attributed to the fact that plants did not achieve maturity since it is known that vegetation influences water runoff quality and quantity. The present study adds knowledge to potential substrate components and plant species (aromatic species) native to the region, which could be used in green roof structures in the Mediterranean climate, as an alternative to the common succulent ones. Moreover, the present study supports the importance of green roofs to the stormwater management in urban areas. They are one component of SUDS, due to their capacity to reduce and attenuate the amount of water runoff via their components (plants, substrate and drainage layer) for public drainage systems, and restoring pre-development hydrological conditions. Also, the presence of green roofs and the increase of vegetation in urban areas has a crucial impact on mitigating the effects of climate change in urban areas, such as the urban heat island effect. Besides that, in terms of stormwater management, the conjunction of green roofs and SUDS schemes is considered an interesting approach.

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