Urban Ecosyst (2017) 20:1347–1357
DOI 10.1007/s11252-017-0687-9

Substrate influence on aromatic plant growth in extensive green roofs in a Mediterranean climate

Cristina M. Monteiro[1] · Cristina S. C. Calheiros[1] · João P. Martins[1] · Francisco M. Costa[1] · Paulo Palha[2] · Sara de Freitas[3] · Nuno M. M. Ramos[3] · Paula M. L. Castro[1]

Published online: 13 June 2017

Abstract Green roofs have been described as technical solutions to overcome urban environmental problems, such as decrease of vegetation and stormwater management. In the present study, two pilot 20 m^2 extensive green roofs were implemented in an urban Mediterranean region, at a 1st storey on a warehouse building structure, in order to test the adequacy of different substrates for supporting aromatic plants (*Lavandula dentata*, *Helichrysum italicum*, *Satureja montana*, *Thymus caespititius* and *Thymus pseudolanuginosus*). Experimental substrates included expanded clay and granulated cork as main components, supplemented with organic matter and crushed egg shell. A commercial substrate that obeys to FLL guidelines was also tested. Plant growth was assessed and compared within each platform. All experimental substrates proved to be adequate for vegetation growth, with the combination of 70% expanded clay, 15% organic matter and 15% crushed egg shell showing the best results regarding plant establishment and growth over time. Water runoff quality parameters - turbidity, pH, conductivity, NH_4^+, NO_3^-, PO_4^{3-} - met standard values required for water reuse for non-potable purposes, such as toilet flushing or irrigation. Preliminary qualitative thermographic measurements comparing surface temperature of different plant species and the substrate showed that temperature of vegetation surface was lower than substrate, reinforcing green roofs benefits of lowering air temperature in their surroundings. The present research shows that aromatic vegetation combined with clay substrates are suitable for green roofs located in countries of the Mediterranean region.

Keywords Extensive green roof · Substrates · Aromatic vegetation · Infrared thermography · Water runoff

Introduction

Nowadays, 54% of the world's population inhabit urban areas. By 2050, 66% of world population is expected to be urban, being Europe in the third position of the most urbanized regions with 73% of population living in urban areas (United

✉ Cristina M. Monteiro
cmonteiro@porto.ucp.pt

Cristina S. C. Calheiros
cristina@calheiros.org

João P. Martins
jprito87@gmail.com

Francisco M. Costa
frmachadoecosta@gmail.com

Paulo Palha
paulopalha@neoturf.pt

Sara de Freitas
sarafreitas@fe.up.pt

Nuno M. M. Ramos
nmmr@fe.up.pt

Paula M. L. Castro
plcastro@porto.ucp.pt

1 CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Rua Arquiteto Lobão Vital, Universidade Católica Portuguesa, Apartado 2511, 4202-401 Porto, Portugal

2 Neoturf - Rua das Amoreiras, 155, 4460-227 Senhora da Hora, Portugal

3 CONSTRUCT-LFC, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal

Nations 2014). This increase leads to a rapid replacement of vegetation for impervious surfaces, with the negative consequences to the environment, such as the rise in urban temperatures, higher risk of urban floods, decrease in wildlife in urban centres and increasing air pollution. Such transformation of the urban scenario accounts for an important challenge of sustainable urban development (Razzaghmanesh et al. 2014). In most developed cities, roofs account for 40–50% of the impervious urban surface area (Stovin et al. 2013), providing an alternative for installing vegetation namely as a green roof structure. Although green roofs technology, a type of construction where a building roof top is covered with vegetation in a substrate, is a long practice in Northern-European countries, it has received renewed interest since the 70's for retrofitting the traditional roofs with vegetation due to their ecological and environmental benefits (Mickovski et al. 2013; Nardini et al. 2012).

Green roofs are becoming an increasingly common component of sustainable urban landscape planning strategies to mitigate the consequences of climate change. Among the benefits of this ecotechnology on urban areas air pollutants removal, urban cooling through evapotranspiration, reduction of stormwater runoff, creation of habitat for wildlife and aesthetic improvement are most sought (Mickovski et al. 2013; Susca et al. 2011). Also, positive effects to buildings may include an increase in the lifespan of building materials and a decrease in building energy needs (Susca et al. 2011). However, the strength of these environmental benefits is quite dependent on the design, substrate and vegetation used on the green roof structure, which calls for more research regarding these topics in order to fully comply with such benefits.

Green roofs can be classified as extensive, semi-intensive or intensive depending on some characteristics regarding substrate depth, maintenance and type of vegetation. Extensive green roofs are chosen more frequently for retrofitting traditional existing roofs because of their minimal structural load (due to growing medium depth of less than 20 cm), less maintenance and cost effectiveness. In order to be functional and to prevent any damages to the building structure, green roofs must obey to a multilayer construction according to the FLL guidelines (the German Landscape Developing and Landscape Construction Research Society – FLL 2008). Besides that, green roof substrate must be lightweight, porous and must be able to support and supply the necessary nutrients to vegetation development.

The most common vegetation used in green roofs constructions are sedum or other succulent species (Rayner et al. 2016), applied in pre-vegetated mats, because of their tolerance to harsh climatic conditions, namely heat and drought conditions. However, alternative solutions regarding different substrates and vegetation to the existing commercial ones bring added value to the field. Additionally, solutions adapted to a specific climate are an advantage to the establishment and long life span of these structures. Among the endemic species of the Mediterranean region, aromatic plants gather characteristics that make them suitable to be used as an alternative to succulent species in green roofs structure, such as low maintenance and water needs, high resistance to roof top adverse conditions, low root extension, besides the aesthetical appearance and applications in several areas with economic human interest.

Support materials for plant growth are another component of considerable importance for green roofs construction and sustainable development, and different growing substrates using recycled and waste materials should be considered (e.g. crushed brick, expanded clay, volcanic materials) (Bates et al. 2015; Lee et al. 2015).

A great advantage of green roofs in urban areas it is the hability to help the decrease of the air temperature near the vegetated construction, due to the evapotranspiration capacity of the plants. Infrared thermography has been applied to building diagnosis for some decades to detect moisture, air leaks, zones of insufficient insulation, detachments, among others (Hart 2001; Meola and Carlomagno 2004; Barreira and Freitas 2007). The process of thermal imaging was simplified over the years with the availability of efficient, high resolution infrared cameras that convert the infrared radiation emitted from bodies into thermal images. However, the use of the rapid non-contact technology for the plant surface assessment has been a focus of only a few studies (Karachaliou et al. 2016; Zheng et al. 2013).

In the present work, two pilot extensive green roofs with different substrates have been set up in order to find which experimental combination is more proper to be used on green roof systems. Establishment and development of five aromatic species native from Mediterranean climate have been assessed on both platforms: *Lavandula dentata*, *Satureja montana* and *Helichrysum italicum* as shrub species and *Thymus pseudolanuginosus* and *Thymus caespititius* as mat forming species, in order to select which aromatic species would be more appropriated to be used in green roofs systems.

Water runoff quality and quantity was assessed in order to evaluate the potential for its later use in non-potable practices and preliminary thermography measurements were performed in order to detect the temperature differences between the different aromatic plants and the substrates.

Material and methods

Green roof testing platforms

Two extensive 20 m^2 pilot green roofs have been established on a roof top of a warehouse, in an urban area, at Escola Superior de Biotecnologia – Universidade Católica Portuguesa, Porto-Portugal (Fig. 1). Green roof platforms, installed at a 1st storey

Fig. 1 Urban roof top for green roof establishment (A- experimental platform; B- commercial platform)

(Latitude 41.18 N; Longitude −8.61 W; 108.95 m above sea level), had direct sunlight after 2 pm. The pilot systems have been set up following the guidelines for green roofs structure (FLL 2008), comprising a multilayer construction for a safe and functional technical system. The experimental design of our green roof systems have been decided based on other green roof studies already published, considering real roof structures and taking full advantage of using a real roof construction, to have the maximum combinations possible regarding roof substrates and vegetation species. The two platforms experiments were physically independent. Green roofs pilot platforms were set up in June 2013 and were monitored till April 2015.

Green roof experimental platform characteristics

The extensive green roof experimental platform was constructed including the following layers (from bottom to top – Fig. 2): a geotextile membrane of 200 g/m^2 for protection and absorption of water; a water retention layer of expanded clay of 2 cm height– Leca® L (Weber SaintGobain® - Portugal) of 10–20 mm granulometry for water retention; a geotextile membrane of 120 g/m^2 to prevent clogging of drainage layer; selected substrates and aromatic vegetation. Four different experimental substrates, with 15 cm height, in several combinations were tested. The substrates mixtures included expanded clay - Leca® Hydro (with particle size ranging from 4 to10 mm and pH between 8 and 9 – Weber SaintGobain® - Portugal), granulated cork (with particle size ranging from 10 to 20 mm – Corticeira Amorim SGPS, SA - Portugal), organic matter from urban solid waste compost (with the following characteristics: pH 5.5–8.5, organic matter 45%, total nitrogen 7200 mg/kg, total phosphorous 8080 mg/kg and total potassium 8960 mg/kg – provided by Suldouro- Valorização e Tratamento de Resíduos Sólidos Urbanos – Portugal) and crushed egg shell (DerOvo Group - Portugal). Growth of four different aromatic plant species – *L. dentata*, *S. montana, T. pseudolanuginosus* and *T. caespititius*- was assessed once a month. Sixteen plants were planted at regular space intervals in each square (with 5 m^2 each) with 4 rows of 4 plants of each species.

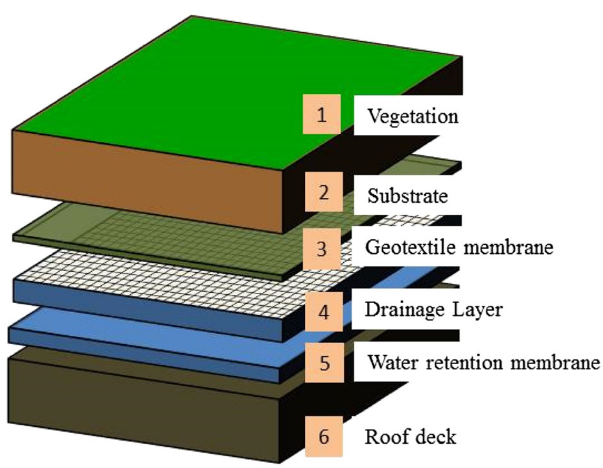

Fig. 2 Schematic representation of general green roof layers (not to scale)

Expanded clay and granulated cork were selected as main components of the substrate since they are characterized for having simultaneously a low weight and a good capacity of water adsorption that is then available for plant use. These two main substrate components have been selected in order to test substrate formulas different from those already commercially available for green roofs systems and find alternative solutions. Expanded clay has long been used to support plant growth in constructed wetlands systems treating different types of water streams (Dordio and Carvalho 2013; Calheiros et al. 2014; Calheiros et al. 2015). Organic aromatic plants have been purchased at Cantinho das Aromáticas – Viveiros, Lda, and young plants were then transplanted to the green roof systems. The green roof characteristics for each zone are set in Table 1.

Green roof commercial platform characteristics

The commercial green roof structure was set by Neoturf- Construção e Manutenção de Espaços Verdes, Lda, a green roof specialized company, which works according to the FLL standards. All the needed materials were supported by LANDLAB, that represents ZinCo (manufacturers materials

Table 1 Green roof sections composition at Universidade Católica Portuguesa facility: experimental vs commercial pilot tests

	Substrate components (%)					Plant species					
	Expanded clay	Granulated Cork	Organic matter	Crushed Egg shell	Substrate granulometry	*Lavandula dentata*	*Satureja montana*	*Thymus pseudolanuginosus*	*Thymus caespititius*	*Helichrysum italicum*	Sedum carpet
Experimental Green Roof											
Section 1	70		30		nd	+	+	+	+	–	–
Section 2	70		15	15	nd	+	+	+	+	–	–
Section 3		70	15	15	nd	+	+	+	+	–	–
Section 4		70	30		nd	+	+	+	+	–	–
Commercial Green Roof											
Section 1	–	–	–	–	Higher	+	+	–	–	+	+
Section 2	–	–	–	–	Lower	+	+	–	–	+	+
Section 3	–	–	–	–	Lower	+	+	–	–	+	+
Section 4	–	–	–	–	Higher	+	+	–	–	+	+

(−) absent; (+) present; nd = not determined

for green roofs) for Portugal. The multilayer construction was (from bottom to top – Fig. 2): a geotextile membrane of 470 g/m^2 for water retention (ZinCo SSM45); an alveolar drainage layer of recycled polyethylene of 2.5 cm height for water retention (Floradrain FD 25/25-E); a geotextile membrane of 100 g/m^2 to prevent clogging of drainage layer (SF ZinCO); coverage with two commercial substrate mixtures (LANDLAB) and vegetation. Substrate mixtures have been set at depths between 12 cm and 15 cm combining different granulometries (identified as higher vs. lower): expanded clay (20% 0.6–1 mm vs. 60% 0.6–1 mm), fermented pine bark humus (25% 1–2 mm vs. 20% 1–2 mm), selected blonde peat (5% 3–8 mm vs. 20% 3–8 mm) and special volcanic rock (50% 8–16 mm). The substrate is an exclusive mixture of the company with the following characteristics: pH corrected to 5.5–6.5, dry weight 750–850 kg/m^3; saturated weight 900–1000 kg/m^3; natural humidity 50–60%; air capacity 37.3% *v*/v; organic matter 13.8% and water easily used taxa 6.8% *v*/v. Also, an access/control box has been placed on the draining zone. Aromatic species (*L. dentata*, *S. montana* and *H. italicum)* were planted as above and a carpet of a mixture of several succulent species (eleven *Sedum* sp.) was placed as vegetation control. Nine plants were planted at regular space intervals in each square (with 4 m^2 each) with 3 rows of 3 plants of each species (Fig. 1).

Platforms monitoring and substrate characterization

Plant growth was monitored monthly through height measurements for *L. dentata*, *S. montana* and *H. italicum*, and length measurements for *Thymus* species (considering always the highest length). Aromatic plant growth at the end of experiment was expressed in growth increment (percentage) relatively to the initial plant size. Green roof platforms were checked for weeds appearance and cleaned whenever required. Irrigation was performed 1–2 times a week during the first 3–4 months after plantation.

The substrate mixtures tested in the experimental green roof platform were analysed for 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) at the beginning of the experiment.

Water runoff from several natural rain events during the experimental time period has been collected for analysis and characterization. The following parameters were determined based on Standard Methods (APHA 1998): pH, conductivity and turbidity. The concentration of phosphorous, ammonium and nitrate (PO_4^{3-}, NH_4^+ and NO_3^-) were determined with Photometric test kits (Spectroquant®). The analyses were done immediately after sample collection. Two different types of samples were collected: (i) grab runoff samples were collected in a short time period (5 min) until the necessary volume of 50 mL for sample analysis was reached, and (ii) cumulative samples (samples of the water runoff from the system composed of the total accumulated water runoff), were collected for a larger time period (minimum 90 min).

Thermographic analysis

At the end of the experimental period, infrared measurements with a thermographic camera were performed as a preliminary means to assess surface temperature. The tests involved an outdoor analysis of the surface temperature of the two green roofs during a sunny afternoon in April 2015. Given the difficulty of controlling all the parameters involved in the measurements, especially in field conditions, a qualitative analysis was adopted, which consists in obtaining the temperature differences between the different aromatic plants and the substrate. The thermographic camera was a Thermo Tracer TH 7800 from NEC AVIO with the following basic properties: measurement accuracy ±2% or ±2 °C; resolution 0.05 °C to 0.1 °C for a range of −20 °C to 100 °C; 752 (H) × 480 (V) pixels and a spectral band of 8 to 14 μm.

Statistical analysis

Statistical analyses were performed using the SPSS software (IBM Corp., Released 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.). The Student's t-test was applied to compare growth increment of *Lavandula dentata* between section 1 and 2 of experimental platform.

One-way ANOVA was used to detect significance differences between the growth increment of each plant species concerning each section (1, 2, 3 and 4) for experimental platform and for commercial platform. Multiple pairwise differences of means were posteriorly evaluated using Duncan's test. The significance level assumed was 5% in all tests performed.

Results and discussion

Aromatic plants establishment on experimental and commercial platforms

The establishment and growth of the aromatic vegetation tested on both green roof platforms (experimental and commercial), was in general successful on most of the tested substrates, with survival of almost all the plants (Tables 2 and 3).

Regarding the experimental platform, substrates composed of expanded clay proved to be more effective for the establishment and long term growth and survival of vegetation, in opposition to substrates composed with granulated cork. This observation could be explained due to the good capacity of expanded clay to adsorb water onto its structure which is then available for plant use over time (Ampim et al. 2010; Molineux et al. 2009). Regarding shrubs species (*L. dentata* and *S. montana*), no significant differences between section 1 and 2 have been detected for *L. dentata*, and between section 2 and 3 for *S. montana*. However, *S. montana* growth increment was significantly different between sections 1 and 4, with section 1 showing higher growth increment than the section 4. Regarding mat forming species (*T. pseudolanuginosus* and *T. caespititius*), the statistical analysis performed revealed significant differences between sections 1 and 4 for *T. caespititius* although no significant differences were seen between section 1 and 2, and between section 2 and 4. Concerning *T. pseudolanuginosus* there were no significant differences between section 1, 2 and 4, and between section 1 and 3, but the growth increment was significantly higher in section 3 than in sections 2 and 4.

By the end of the experiment, both shrubs species (*L. dentata* and *S. montana*) proved to be more robust over time, with a more sustainable growth and survival than mat forming species *T. pseudolanuginosus* and *T. caespititius*. These observations could be explained due to the specific characteristics of the aromatic plant species used. The shrub species used have low water needs and higher tolerance to temperature variations when compared to mat forming ones. A study conducted by Nektarios et al. (2011), reporting the effect substrate on growth of native species in green roofs, has shown that the Mediterranean xerophyte *Dianthus fruticosus* survived through the hot season in Athens, Greece, with minimum irrigation (15% of pan evaporation). Raimondo et al. (2015) also described that both shrub species *Arbutus unedo* L. and *Salvia officinalis* L., were suitable species for green roofs in the Mediterranean area, although with different drought tolerance mechanisms.

The commercial substrate, approved for green roof construction, was effective for establishment and growth of aromatic species, allowing 100% survival of all plants. Three different aromatic shrub species have been tested, with *L. dentata* showing the highest growth increment percentage by the end of experimental trial. Statistical analysis used to compare the growth increment of each species between the four sections tested, revealed that *L. dentata* had significant higher growth increment in section 4 when compared with sections 1, 2 and 3; for *H. italicum* – section 1 has shown significant higher growth increment than section 2 and 4, although there were no significant differences between section 1 and 3, and between sections 2, 3 and 4. Concerning *S. montana* no significant differences on plant growth increment between sections have been detected.

At the same time, a sedum carpet has been placed on the commercial substrate, in order to serve as a control of the suitability and capacity of the substrate to support vegetation growth, showing a normal development of this mat forming species. Also, and comparing both platforms, it was noticed (by visual inspection) that in the platform with the

Table 2 Aromatic plants growth increment (%) from experimental platform at the end of study. Results are expressed as means±SD

	Plant growth increment (%)															
	Section 1				Section 2				Section 3				Section 4			
	Average	±	SD	*n*	Average	±	SD	*n*	Average	±	SD	*n*	Average	±	SD	*n*
L. dentata	223.7	±	41.0	*4*	255.4	±	78.2	*4*	313.7	±	32.9	*3*	275.7	±	169.0	*2*
S. montana	122.9	±	15.2	*3*	62.7	±	5.0	*3*	44.5	±	35.8	*4*	26.9	±	54.5	*4*
T. pseudolanuginosus	558.8	±	208.7	*4*	315.7	±	70.8	*4*	627.2	±	211.0	*3*	310.2	±	158.2	*4*
T. caespititius	663.0	±	317.8	*4*	390.5	±	127.2	*4*	190.0	±	-	*1*	294.1	±	32.4	*4*

experimental substrate, aromatic vegetation had a fast initial establishment and growth when compared to the commercial one. This result might be justified due to the composition and richness on nutrients of the organic matter used which contained 45% of organic matter (dry weight) against 14% of organic matter on the commercial substrate.

The majority of literature on green roofs studies use succulent species, such as sedum, due to their characteristics of resistance to extreme environmental conditions and low maintenance (Farrell et al. 2012; Oberndorfer et al. 2007). However, aromatic vegetation also presents resistance to adverse conditions (e.g. temperature), reduced irrigation needs and low maintenance needs. Nevertheless, literature regarding the use of aromatic plants on green roofs construction is scarce, and vegetation species adapted to local conditions should be found in alternative to the succulents species frequently used in these structures worldwide. Therefore, we have selected five different autochthonous aromatic species (which are adapted to Mediterranean climate of the region) and tested them in different mixtures, since it has been described that plant combinations in green roofs systems are more effective due to their associations and use of different resources (Nagase and Dunnett 2010; Van Mechelen et al. 2015). For instance, *Helichrysum italicum*, *Helichrysum orientale* and *Artemisia absinthium L.* have been used in two different substrates (one containing grape marc compost and other composed by peat) and two depths with a suitable growth on this type of construction (Papafotiou et al. 2013).

Substrate characteristics

The available characteristics of the commercial substrate have been described on the materials and methods section, and of the experimental substrate are described in Table 4.

There is not a general composition for green roof substrates. However, some basic characteristics should be fulfilled in order to attain an adequate mixture for green roof systems, and to allow good support and nutrition supply for vegetation (Latshaw et al. 2009). Green roofs substrates should be lightweight enough (in order not to overload building structure), but at the same time, they should hold the nutrients for plants needs and allow a good aeration and drainage ability (Ampim et al. 2010). Regarding specific substrate characteristics, FLL recommendations (2008) advise a pH between 6.0–8.5 and water holding capacity ≥35% volume. Substrates mixtures used in the current study present pH and water holding capacity values according to these recommendations. The substrate characteristics used on green roofs are a key factor for the system's capacity to retain rainwater, and consequently the management and delay of stormwater runoff. Substrate depth is one of the major characteristics of the green roof system influencing rainwater retention, with higher moisture content levels in systems with deeper substrate layer (Berreta et al. 2014). The amount of water that the system could retain is influenced by the climate of the region and evapotranspiration processes both by plants and substrate exposed surface (Palla et al. 2010). According to Stovin (2010),

Table 3 Aromatic plants growth increment (%) from commercial platform at the end of study. Results are expressed as means ±SD

	Plant growth increment (%)															
	Section 1				Section 2				Section 3				Section 4			
	Average	±	SD	*n*	Average	±	SD	*n*	Average	±	SD	*n*	Average	±	SD	*n*
L. dentata	257.3	±	64.9	*3*	207.6	±	39.1	*3*	213.3	±	92.3	*3*	480.4	±	38.5	*3*
S. montana	54.3	±	21.7	*3*	89.0	±	112.0	*3*	65.5	±	9.3	*3*	56.9	±	16.6	*3*
H. italicum	60.1	±	24.8	*3*	85.9	±	39.8	*3*	87.4	±	35.9	*3*	150.6	±	96.2	*3*

Table 4 Physical and chemical characteristics of experimental substrates mixtures

	pH	Conductivity (µS/cm)	Porosity (%)	Bulk Density (× 10^6 mg/m^3)	Dry mass (%)	Water Holding capacity (%) Average ± SD		
Experimental substrate - section 1	7.24	3610	45.21	0.46	22.91	63.65	±	1.06
Experimental substrate - section 2	7.67	2350	62.95	0.51	19.36	25.28	±	0.48
Experimental substrate - section 3	nd	nd	nd	nd	nd	nd	±	nd
Experimental substrate - section 4	6.40	7100	55.11	0.33	25.69	35.29	±	7.73

nd = not determined

water retention on a green roof in Sheffield (UK) was of 34% during the spring season. On the other hand, Poë et al. (2015) described that evapotranspiration was affected by climate, showing higher values in summer when compared to spring season (3.4 mm/day vs 2.0 mm/day).

Also, growing substrates should be balanced in terms of porosity for water and air retention in equivalent amounts (Latshaw et al. 2009). For that reason, green roof substrates usually include in their composition expanded shale, perlite, sand and pumice as inorganic materials, since they create a lightweight supporting media, porous, less easily compacted, providing at the same time root support (Latshaw et al. 2009).

Regarding the other substrate parameters analysed, no guidelines are described in FLL standards nor recommendations have been found in literature for green roofs substrates. Nevertheless, their analysis have been performed as a support for substrates characterization. All the substrates have very similar characteristics, except for conductivity. Experimental substrates revealed much higher values for this parameter when compared to the commercial one. This could be justified by its origin on urban solid waste compost. Nevertheless, and in general, all the substrates used allowed suitable establishment of aromatic vegetation tested, showing thus a potential use on green roofs.

In the experimental platform, excess of weeds have been noticed in all sections with experimental substrates, due to the nature and high content of organic matter, which is originated from urban solid waste compost. This feature is not appropriate for an extensive green roof construction where low maintenance and attention should be paid.

Green roof substrates include perlite, vermiculite, volcanic rocks, expanded clay, crushed bricks, peat and compost (Ampim et al. 2010; Nagase and Dunnett 2011). However, substrates composed by waste materials should be tested in order to achieve sustainable formulas for green roofs systems. Several studies have been reported in literature regarding recycled materials such as clay, paper ash and limestone pellets (Molineux et al. 2009), scoria, crushed roof tiles and bottom ash (Farrell et al. 2012), presenting suitable results concerning vegetation growth. In the present study, besides the common used expanded clay, crushed egg shell and granulated cork residue which have not been found in green roof studies, have been tested, revealing good results in supporting aromatic vegetation growth.

Water runoff

Green roof water runoff has been collected for several natural rain events during the experimental period and data of water runoff quality for the two platforms are presented in Table 5.

Comparing the quality of the rainwater runoff between the two platforms and between grab and cumulative samples, no significant differences were detected for pH values, showing that the substrate components did not influence that parameter. On the other hand, conductivity, turbidity, NO_3^- and PO_4^{3-} of the water runoff presented higher maximum values in the experimental substrate, whereas NH_4^+ only presented higher maximum values for both substrates on grab samples, leading us to infer that experimental substrate leads to the release of higher amount of particles to the water that runoffs from the system compared to the commercial substrate.

The results obtained in the present study are in accordance with literature published, which describes that water runoff quality from green roofs is dependent on the growing substrate components used, with lower percentage of organic matter in growing substrates resulting in higher water runoff quality (Beecham and Razzaghmanesh 2015).

Several studies have analysed the influence of green roofs on water runoff quality. Zhang et al. (2014) compared the runoff water quality from four roof structures (concrete, asphalt, ceramic tile and green roof), showing that water runoff from the green roof presented significantly higher electrical conductivity (EC) and total nitrogen (TN) values (225 µS/cm and 18.3 mg/L, respectively) when compared to others tested, which are in accordance with the results obtained in the present study, where conductivity and turbidity of water runoff collected from the experimental substrates was higher than the commercial substrate, which occurs due to its higher content in organic substances and nutrients. The same trend has been described by Mendez et al. (2011) who reported that pH and conductivity from a rainwater harvested green roof sample were significantly higher than those obtained directly from rain events, and by Vijayaraghavan et al. (2012), where

Table 5 Green roof water runoff characterization

	Experimental Platform										Commercial Platform									
	Grab Samples					Cumulative Samples					Grab Samples					Cumulative Samples				
	Min-Max	Average	±	SD	*n*	Min-Max	Average	±	SD	*n*	Min-Max	Average	±	SD	*n*	Min-Max	Average	±	SD	*n*
pH	7.39–8.12	7.68	±	0.19	*17*	6.98–8.35	7.71	±	0.28	*23*	7.57–8.22	7.76	±	0.17	*18*	7.20–8.40	7.71	±	0.27	*25*
Conductivity (μS/cm)	196–364	272	±	53	*15*	213–391	279	±	48	*21*	77–218	177	±	34	*18*	127–330	179	±	42	*24*
Turbidity (NTU)	3.05–13.24	8.52	±	3.72	*13*	0.29–15.20	7.39	±	5.00	*18*	0.43–6.41	2.08	±	1.83	*13*	0.27–4.86	1.76	±	1.38	*18*
NH_4^+ (mg/L)	0.04–0.92	0.22	±	0.30	*12*	0.06–0.18	0.10	±	0.04	*11*	0.03–0.83	0.18	±	0.23	*13*	0.02–0.12	0.07	±	0.03	*14*
NO_3^- (mg/L)	0.95–7.80	4.92	±	2.27	*12*	1.70–7.75	5.46	±	1.85	*10*	0.60–2.60	1.54	±	0.62	*13*	0.50–4.40	1.77	±	1.07	*13*
PO_4^{3-} (mg/L)	1.28–2.72	2.03	±	0.50	*12*	0.88–2.60	1.72	±	0.52	*11*	0.21–1.73	0.56	±	0.44	*12*	0.20–0.67	0.35	±	0.14	*13*

green roofs runoff compared to real rain events contained significant higher amounts of PO_4^{3-}.

At the present, there is no Portuguese legislation for re-use of this water source in buildings and taking into consideration only physico-chemical parameters, the water runoff from both green roofs systems is suitable for non-potable uses such as toilet flushing or even irrigation (ETA 701– 2012). Rainwater reuse should be encouraged due to the water scarcity that already is felt due to the climate changes.

On the other hand, the amount of water that the system could retain delaying its release for public drainage systems is another important trait offered by green roofs systems in urban areas. A previous study, regarding rainwater harvesting in green roof systems, reported an amount of water retention of 30%, delaying its runoff to the public drainage urban systems; an expression to calculate the amount of water that would leave the system as runoff on a monthly base was developed (Monteiro et al. 2016). Regarding the amount of water that runoffs the platforms, we have observed that the experimental platform could harvest more rainwater than the commercial green roof tested, at the beginning of the rain events. The higher retention achieved on the experimental platform is due to the higher amount of water retained on the substrate and on the drainage layer, the latter composed of expanded clay. This is an important and useful characteristic of green roofs for urban areas, where vegetation areas were replaced for impervious surfaces, and are now facing problems of floods and stormwater management.

Thermographic studies

Figures 3 and 4 shows the thermograms (general and detailed view), and the respective photographies, of the two green roofs.

Surface temperature between plant species and between plants and substrate surface was compared within the same thermogram. Lower surface temperatures were found for the green roof plants compared to the substrate at the time of the thermograms. A difference among the several plants surface temperature was also observed. On experimental green roof platform (Fig. 3) the plant *T. caespititius,* with a lower height and leaf density, presented a higher surface temperature. On the other hand, on the commercial green roof (Fig. 4), the sedum carpet mixture, which can be seen on the middle of the platform, presented higher temperature than the other aromatic plants. Some details, such as the shadow effect, can be seen on the thermograms for the experimental green roof. Moreover, if the bare substrate is visible, the temperature rises significantly. Our preliminary results reveal the same trend reported by Susca et al. (2011), who found that green roofs thermal resistance and evapotranspiration given by the plants biomass and the substrate reduces the heat fluxes through the roof, contributing to the mitigation of the urban heat island

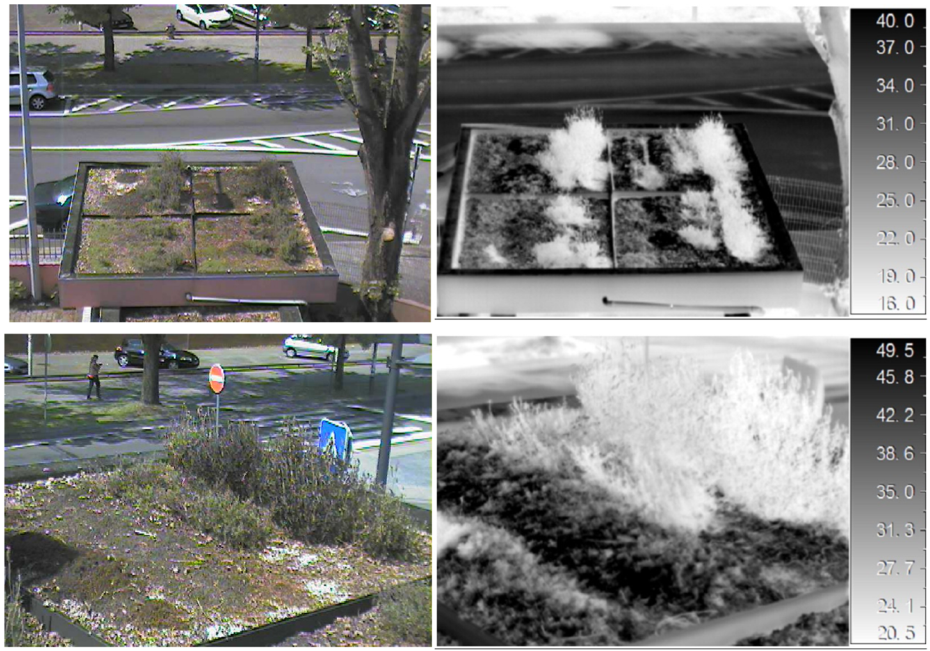

Fig. 3 Experimental platform, photography and thermogram (general view and detail)

(UHI) effect. They described that the evapotranspiration on the green roof dissipates heat and maintain the thermal variation on the soil bottom of less than 20 °C when compared to a black surface or a white roof, where the variations are of 60 °C and 30 °C, respectively.

There are three types of parameters related to the properties of the material, ambient conditions and characteristics of the camera that can influence the thermoghraphy measurements. The most important ones are the emissivity, which defines the material's capacity to emit energy (that is usually reported as 0.95 for the plants) (Tabares-Velasco and Srebric 2009), reflections, meteorological conditions (such as air temperature, precipitation, wind speed, cloud cover and direct sunlight), distance between the camera and the analyzed object and the characteristics of the camera (de Freitas et al. 2014). Nevertheless, the infrared thermography measurements are an interesting tool for capturing the effects of the green roof plant species and are an easy non-contact measurement technology for a not homogeneous surface like a plant.

Vegetation on top of buildings in city centers help to attenuate the negative effects of massive construction and heat flux by two aspects: (1) by water storage in plant leaves and roots

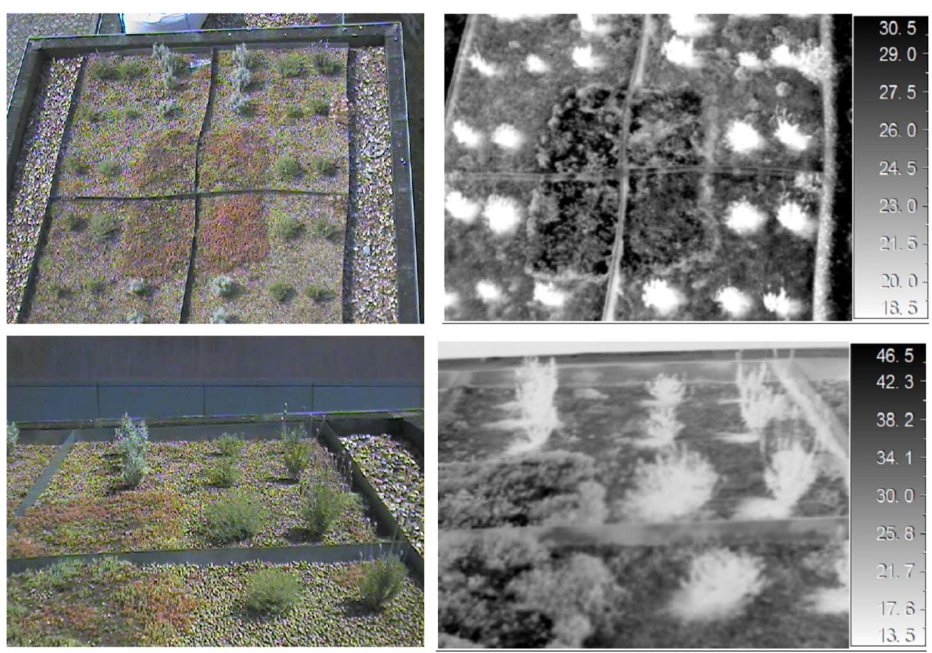

Fig. 4 Commercial platform, photography and thermogram (general view and detail)

and (2) by shadow provided by plant leaves (Tabares-Velasco and Srebric 2009). Additionally, the type of plants also influence the heat flux on the system (Susca et al. 2011). Del Barrio (1998) recommended using plants with mainly horizontal leaf distribution and large foliage in order to optimize green roof cooling.

Green roofs offer several environmental benefits, if they are properly constructed and successfully established. The aromatic species selected here could be used with success in green roof constructions on countries of the Mediterranean region since they could survive despite the adverse conditions on the rooftop environment.

Conclusions

The green roof substrates mixtures (experimental and commercial) tested in this study proved to be adequate for vegetation establishment on these type of structures. The mixture that allowed the best growing results for the aromatic species tested was that composed by 70% expanded clay, supplemented with 15% crushed egg shell and 15% urban solid waste compost. All aromatic plant species tested demonstrated to be suitable for green roofs structures, showing their resistance to the imposed conditions on roof tops, in Mediterranean region. Additionally, water runoff quality is in accordance with legislation as use for non-potable practices. Infrared thermography measurements performed revealed some differences in the surface temperature of the green roof, showing that the presence of dense vegetation decreases the temperature in the surroundings.

The present study allows the dissemination of green roofs construction technology adapted to the Mediterranean climate, and presents alternative materials to commercial solutions that are available in the market, regarding different substrates and vegetation used. These technical solutions are decisive for Mediterranean zones, especially urban areas that are facing climate changes.

Acknowledgements Cristina M. Monteiro (SFRH/BPD/80885/2011) and Cristina S. C. Calheiros (SFRH/BPD/63204/2009 and SFRH/BPD/109711/2015), thank the grants from Fundação para a Ciência e Tecnologia (FCT, Portugal) and Fundo Social Europeu through the program POPH – QREN. This work was supported by National Funds from FCT-Fundação para a Ciência e Tecnologia through project UID/Multi/50016/2013. Authors are also grateful to Saint-Gobain-Weber Portugal, Corticeira Amorim, DerOvo Group, Suldouro, LANDLAB and Neoturf, for the materials and services supplied. Also, authors would like to express their gratitude to the dedication and assistance of José Barros.

References

Ampim PAY, Sloan JJ, Cabrera RI, Harp DA, Jaber FH (2010) Green roof growing substrates: types, ingredients, composition and properties. J Environ Hortic 28:244–252

APHA - *Standard Methods for the Examination of Water and Wastewater* (1998) 20th edn. American Public Health Association/American Water Works Association/Water Environment Federation Washington DC

Barreira E, Freitas VP (2007) Evaluation of building materials using infrared thermography. Constr Build Mater 21:218–224

Bates AJ, Sadler JP, Greswell RB, Mackay R (2015) Effects of recycled aggregate growth substrate on green roof vegetation development: a six year experiment. Landsc Urban Plan 135:22–31

Beecham S, Razzaghmanesh M (2015) Water quality and quantity investigation of green roofs in a dry climate. Water Res 70:370–384

Berreta C, Poë S, Stovin V (2014) Moisture content behavior in extensive green roofs during dry periods: the influence of vegetation and substrate characteristics. J Hydrol 511:374–386

Calheiros CSC, Rangel AOSS, Castro PML (2014) Constructed wetlands for tannery wastewater treatment in Portugal: ten years of experience. Intern J Phytoremed 16:859–870

Calheiros CSC, Bessa VS, Mesquita RBR, Brix H, Rangel AOSS, Castro PML (2015) Constructed wetland with a polyculture of ornamental plants for wastewater treatment at a rural tourism facility. Ecol Eng 79:1–7

Del Barrio EP (1998) Analysis of the green roofs cooling potential in buildings. Energy Build 27:179–193

Dordio A, Carvalho AJ (2013) Constructed wetlands with light expanded clay aggregates for agricultural wastewater treatment. Sci Total Environ 463-464:454–461

European Standard EN 1097–6:2000. Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption

Farrell C, Mitchell RE, Szota C, Rayner JP, Williams NSG (2012) Green roofs for hot and dry climates: interacting effects of plant water use, succulence and substrate. Ecol Eng 49:270–276

FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftshaue) (2008) Guidelines for the planning, construction and maintenance of green roofing – green roofing guideline. Landscape Development and Landscape Research Society – Germany.

de Freitas SS, de Freitas VP, Barreira E (2014) Detection of façade plaster detachments using infrared thermography – a nondestructive technique. Constr Build Mater 70:80–87

Hart J (2001) A practical guide for infra-red thermography for building surveys. Garston, Watford, BRE, p 92

Houba VJG, Van Der Lee JJ, Novozamsky I (1995) Soil analysis procedures: other procedures (soil and plant analysis. Part 5B). In: a series of syllabi, 6th edn. Department of Soil Science and Plant Nutrition, Wageningen agricultural University, Wageningen

Karachaliou P, Santamouris M, Pangalou H (2016) Experimental and numerical analysis of the energy performance of a large scale intensive green roof system installed on an office building in Athens. Energy Build 114:256–264

Latshaw K, Fitzgerald J, Sutton R (2009) Analysis of green roof growing media porosity. Review of undergraduate research in agricultural and Life Sciences 4:article 2

Lee JY, Lee MJ, Han M (2015) A pilot study to evaluate runoff quantity from green roofs. J Environ Manag 152:171–176

Mendez CB, Klenzendorf JB, Afshar BR, Simmons MT, Barret ME, Kinney KA, Kirisits MJ (2011) The effect of roofing material on the quality of harvested rainwater. Water Res 45:2049–2059

Meola C, Carlomagno G (2004) Recent advances in the use of infrared thermography. Meas Sci Technol 15:R27–R58

Mickovski SB, Buss K, McKenzie BM, Sökmener B (2013) Laboratory study on the potential use of recycled inert construction waste material in the substrate mix for extensive green roofs. Ecol Eng 61P: 706–714

Molineux CJ, Fentiman CH, Gange AC (2009) Characterising alternative recycled waste materials for use as green roof growing media in the U.K. Ecol Eng 35:1507–1513

Monteiro CM, Calheiros CSC, Pimentel-Rodrigues C, Silva-Afonso A, Castro PML (2016) Contributions to the design of rainwater harvesting systems in buildings with green roofs in a Mediterranean climate. Water Sci Technol 73(8):1842–1847

Nagase A, Dunnett N (2010) Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity. Landsc Urban Plan 97:318–327

Nagase A, Dunnett N (2011) The relationship between percentage of organic matter in substrate and plant growth in extensive green roofs. Landsc Urban Plan 103:230–236

Nardini A, Andri S, Crasso M (2012) Influence of substrate depth and vegetation type on temperature and water runoff mitigation by extensive green roofs: shrubs versus herbaceous plants. Urban Ecossyst 15:697–708

Nektarios PA, Amountzias I, Kokkinou I, Ntoulas N (2011) Green roof substrate type and depth affect the growth of the native species *Dianthus fruticosus* under reduced irrigation regimens. Hortscience 46:1208–1216

Oberndorfer E, Lundholm J, Bass B, Coffman RR, Doshi H, Dunnett N, Gaffin S, Köhler M, Liu KKY, Rowe B (2007) Green roofs as urban ecosystems: ecological structures, functions, and services. Bioscience 57:823–833

Palla A, Gnecco I, Lanza LG (2010) Hydrologic restoration in the urban environment using green roofs. Water 2:140–154

Papafotiou M, Pergialioti N, Tassoula L, Massas I, Kargas G (2013) Growth of native aromatic xerophytes in an extensive Mediterranean green roof as affected by substrate type and depth and irrigation frequency. Hortscience 48:1327–1333

Poë S, Stovin V, Berreta C (2015) Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration. J Hydrol 523:356–367

Raimondo F, Trifilò P, Lo Gullo MA, Andri S, Savi T, Nardini A (2015) Plant performance on Mediterranean green roofs: interaction of species-specific hydraulic strategies and substrate water relations. AoB PLANTS 7: plv007.

Rayner JP, Farrell C, Raynor KJ, Murphy SM, Williams NSG (2016) Plant establishment on a green roof under extreme hot and dryconditions: the importance of leaf succulence in plant selection. Urban For Urban Green 15:6–14

Razzaghmanesh M, Beecham S, Brien CJ (2014) Developing resilient green roofs in a dry climate. Sci Total Environ 490:579–589

Stovin V (2010) The potential of green roofs to manage urban stormwater. Water Environ J 24:192–199

Stovin V, Poë S, Berreta C (2013) A modelling study of long term green roof retention performance. J Environ Manag 131:206–215

Susca T, Gaffin SR, Dell'Osso GR (2011) Positive effects of vegetation: urban heat island and green roofs. Environ Poll 159:2119–2126

Tabares-Velasco PC, Srebric J (2009) The role of plants in the reduction of heat flux through green roofs: laboratory experiments. ASHRAE Trans 115:793–802

Tan KH (1995) Soil sampling, preparation and analysis. The University of Georgia Athens, GA

Technical Specification ETA 0701 - *Rainwater harvesting systems in buildings (version 8)* (2012) ANQIP (Portuguese Association for Quality and Efficiency in Building Services)

United Nations (2014) World urbanization prospects – the 2014 revision. United Nations, New York

Van Mechelen C, Dutoit T, Hermy M (2015) Vegetation development on different extensive green roof types in a Mediterranean and temperate maritime climate. Ecol Eng 82:571–582

Vijayaraghavan K, Joshi UM, Balasubramanian R (2012) A field study to evaluate runoff quality from green roofs. Water Res 46:1337–1345

Zhang Q, Wang X, Hou P, Wan W, Li R, Ren Y, Ouyang Z (2014) Quality and seasonal variation of rainwater harvested from concrete, asphalt, ceramic tile and green roofs in Chongqing, China. J Environ Manag 132:178–187

Zheng X, Yang Z-j, B-h L, Zheng X-k, Fan W, Q-q G (2013) Study of roof greening's effect on thermal environment by using infrared thermography. Spectrosc Spectr Anal 33:1491–1495