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Plant Growth on a Mediterranean Green Roof: A Pilot Study on Influence of Substrate Depth, Substrate Composition, and Type of Green Roof

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Green roofs have been proposed as a significant method of "renaturing" the city, mitigating the urban heat island effect and controlling storm water movement. Plant growth on green roofs affects the environmental performance of the roof. Thus, it is important to examine which parameters influence this growth. Green roofs in the Mediterranean region, due to the climatic specificities of the area, have been a challenge. What types of plants are appropriate, how green roofs should be constructed and other related topics have concerned scientists in the recent years. The aim of this pilot study was to explore the growth of five plants—*Sedum sediforme, Drosanthemum floribundum* and *Lampranthus spectabilis, Medicago arborea,* and *Lavandula angustifolia*—on a pilot Mediterranean green roof in relation to substrate depth, organic content of substrate and type of green roof (open and modular). Data were analyzed using multiple regression with Analysis of Variance. The results indicated that substrate depth, type of green roof and substrate organic content are not significantly important parameters affecting the growth of plants and cannot predict plant performance by themselves. A main insight arising from this study is that plant communities and interspecies relations should be examined more closely in future green roof research as they may affect the impact of selected parameters on plant growth on Mediterranean green roofs. Furthermore, although the type of the green roof—open or modular—could not be directly associated with plant performance, it may be worth examining its impact on plant community performance in future studies.

Keywords: Mediterranean green roof, plant growth, substrate depth, organic content, modular and open system, sustainable cities, succulents

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INTRODUCTION

Cities continue to grow and to attract an increasing number of people; at present, cities house more than half of the global human population. Contemporary cities violate nature and its laws, as they are made of concrete, are designed around the use of private cars and fossil fuels, with a high density of human population and human activities, importing resources for inhabitants' needs and used with a linear logic, generating much waste. The need to "renature" cities, find nature-based solutions to urban problems, and thus, make cities greener and more respectful of natural laws, has been recognized (e.g., European Commission, 2021). The concept of "biophilia" (Farr, 2008; Rogers, 2019)—love and contact with nature—is now considered a basic element of sustainable cities. Reconciliation ecology also promotes the idea of co-existence of humans with other species and anthropogenic habitats that support the existence of other species too (Francis, 2011).

Installing green roofs is a method for reintroducing nature into the cities and supporting the provision of its invaluable ecosystem services, as well as providing landscapes that are amenable to both humans and other species. The environmental benefits of green roofs have been the focus of many studies in the last decades (indicatively see Oberndorfer et al., 2007; Nagase and Dunnett, 2012; Berardi et al., 2014; Gong et al., 2021). These benefits include amongst others energy efficiency of buildings, storm water control, enhancement of microclimate and amelioration of the urban heat island effect, cleaner air, filtering water, increased biodiversity in cities, psychological benefits and aesthetic enhancement of urban landscapes. Each of these themes has attracted different levels of interest, while overall, researchers' interest in green roofs has increased over time (Liu et al., 2021).

As roofs are harsh environments, the selection of appropriate plants for different climates (Monterusso et al., 2005; Benvenuti and Bacci, 2010; Dvorak and Volder, 2010; Takahiro et al., 2010; Williams et al., 2010; MacIvor et al., 2011; Provenzano, 2011) has occupied researchers. Studies have shown that a combination of different species on a green roof improves resilience to stresses (Gedge and Kadas, 2005; Nagase and Dunnett, 2010).

Parameters, like irrigation (Maclvor et al., 2013; Carbone et al., 2014; Rowe et al., 2014; Vestrella et al., 2015a; Palermo et al., 2019; Zhang et al., 2021) and substrate, that influence plant growth have been significant research concerns in the recent years. The depth of the substrate has repeatedly been suggested as a main parameter influencing plant growth (Dunnett and Nolan, 2004; Durhman et al., 2007; Getter and Rowe, 2009; Rowe et al., 2012; Papafotiou et al., 2013). Nagase and Dunnett (2013) in their study of geophytes on extensive green roofs in the United Kingdom found that plants did better in terms of growth, flowering and survival rate in the deeper substrate of 10 cm. They hypothesized that this was due to better moisture retention and steadier temperatures. However, they also found that some plants, like different species of Tulipa, performed well at 5 cm substrate depth too without irrigation. Vangergrift et al. (2019) study showed that deeper substrates supported a larger variety of species, while irrigation was identified as critical for the maintenance of species diversity in the long term. Generally, different substrate depths – between 4 and 25 cm – support different vegetation forms from mosses and sedum to herbaceous plants and grasses (FLL, 2008; Ntoulas et al., 2017). Other studies, like Hawke's (2015) evaluation of different plants for use on green roofs, demonstrated that some plants did equally well in all tested growing substrate depths, while others that displayed differences in their growth ratings scored better in deeper depths. Other studies have demonstrated that other characteristics of the growing medium, like its organic content, nutrients or pH, are important (Nagase and Dunnett, 2011; Bates et al., 2013; Kotsiris et al., 2013; Thuring and Dunnett, 2014; Tassoula et al., 2015; Papafotiou et al., 2016; McAlister and Rott, 2019). Further studies have investigated the influence of different types of substrates (A'saf et al., 2020; Paraskevopoulou et al., 2021), or other parameters relating with the substrate like the role of bacteria in the soil (Xie et al., 2020; Wang et al., 2021), on plant performance, or on the functions of green roofs (Naranjo et al., 2020). Bates et al. (2013) investigated vegetation development on low-fertility growth substrates emulating brownfields and their responses to drought conditions. They noted that plants living in more fertile substrates and doing better when water is available are more vulnerable to drought disturbance. Young et al. (2014) demonstrated that substrate depth had no significant effect on plant growth under controlled temperature conditions, while they argued that substrate composition is significant for plant performance on green roofs and it should be carefully considered in green roof design. Some have investigated more specifically the type/source of organic component of the substrate and its influence on plant growth (Papafotiou et al., 2013).

Local climatic conditions influence the design considerations for green roofs. As green roofs are harsh environments in any case, the Mediterranean climate poses additional challenges for them due to its dry and hot summers. For this reason, only relatively recently modern green roofs started being installed in Mediterranean cities. In the same period, scientific interest in designing and establishing Mediterranean green roofs has increased (Benvenuti and Bacci, 2010; Provenzano, 2011; Caneva et al., 2013; Kotsiris et al., 2013; Papafotiou et al., 2013; Raimondo et al., 2015; Vestrella et al., 2015b). Relevant scientific literature has investigated which plants are more suited for Mediterranean green roofs and studies have generally shown that certain plant taxa and xerophytes or succulent plants are the most appropriate for them (e.g., Provenzano, 2011; Papafotiou et al., 2013; Tassoula et al., 2015). Some studies have examined and identified specific plant species (such as *Sedum sediforme* and other *Sedum* species, *Lavandula angustifolia*, *Anthemis tinctoria*, etc.) as most appropriate for green roofs in the Mediterranean climate (Nektarios et al., 2011; Kotsiris et al., 2012; Ondoño et al., 2016; Azenas et al., 2018, 2019). Vasl et al. (2017) examined the contribution of *Sedum sediforme* to the creation of biodiverse Mediterranean green roofs and concluded that the combination of sedum with annuals improved the performance of green roof functions. However, Nektarios et al. (2021), who investigated the appropriateness of seeded sedum species on a Mediterranean roof as well as the influence of substrate depth and irrigation regime on them, suggested that their use in the Mediterranean climate is not appropriate. Others (like Papafotiou et al., 2013; Ondoño et al., 2016) investigated the significance of substrate depth for plant growth on Mediterranean green roofs and have generally reiterated that deeper growing medium better promotes the establishment, growth, and survival of vegetation. Nevertheless, Papafotiou et al. (2013) indicated that other characteristics beyond the depth of the substrate (i.e., compost-amended substrate with sparse irrigation) can result in similar plant growth with that of deeper growing mediums. Water availability has been another issue that has been investigated in Mediterranean green roofs (Carbone et al., 2014; Palermo et al., 2019). Azenas et al. (2018) identify water availability as the main limiting factor for urban greening in Mediterranean climates and suggest that this should be a main criterion for the selection of plants for green roofs in these areas.

This pilot study aims to investigate the influence of substrate depth, organic content in the substrate and the type of the green roof (i.e., modular or open extensive approaches to green roofs) on plant growth in a typical urban Green Roof (i.e., sometimes obstructed with structural elements) without any human interference (i.e., no pruning, replanting etc.) after the original set up, approximating real conditions as much as possible. For this reason, the green roof was left to evolve without any human interference for the whole duration (∼2 years) of the experiment. The aim was to examine a green roof situation that is akin to a real-life, non-experimental site.

Five plants that are considered possible candidates for Mediterranean climates were selected. Our main research questions and the hypotheses we tested are:

1) What is the effect of substrate depth on plant growth in an open and closed (modular) green roof system?
   Hypothesis: Increasing substrate depth will positively impact the growth of plants.
2) What is the effect of different levels of organic content on plant growth in a closed (modular) green roof system?
   Hypothesis: Higher levels of organic content will positively impact the growth of plants.
3) Do selected plants grow better in an open or a closed (modular) green roof system?
   Hypothesis: No such study has been identified in the literature; thus, we had no pre-conceived hypothesis for this question. An open system allows for slightly more space but is also subject to more loss of substrate.

MATERIALS AND METHODS

The Experimental Site

The pilot green roof site was at Aghia Paraskevi, Greece (Lat 38° 00′ 16′′ N Long 23° 49′ 59′′ E) in the college campus of the American College of Greece, which is found at the Northeast side of the Hymettus Mountain at 270 m altitude, has a mild inclination and is exposed to north winds. As **Figure 1** illustrates, it was located at the Deree building complex, on the 6th level of a 7-level step-hill building with a Northwest-Southeast axis. Thus, this is a roof that is generally sheltered from winds. The choice of the roof was limited by campus-specific restrictions.

It was installed as a set of 3 plots (labeled A-C). Every plot had an area of 8 m^2 (2 m width by 4 m length) and included 8 quadrats (labeled a-h) of 1 m^2 each. **Figure 2** below provides a graphic representation of the research site. Each plot represented a different set of conditions, addressing the research questions. One plot (A) was an open extensive system with different substrate depths, including 20, 15, 10, and 6 cm. Another one (B) was a modular system with different substrate depths too, i.e. 12, 10, 8, and 6 cm. The largest depth of the modular system (12 cm) was smaller than the largest one in the open system (20 cm) as deeper modular pieces are too heavy to move; however, we ensured to have 2 common depths (i.e. 6 and 10 cm) in the A and B plots and 10 cm depth in all the quadrats of the C plot for comparison purposes. The third one (C) was a modular system with all quadrats having the same substrate depth (10 cm) but different organic content: 10, 7.5, 5, and 2% or less (reflecting existing literature and practice in the Mediterranean region). The two adjacent quadrats (i.e. a-b, c-d, e-f, g-h) in each plot were identical in their design, meaning that each group of conditions has two replicates. Each of the 11 groups (labeled i-xi) represent a specific combination of parameters (i.e., organic content, substrate depth and type of green roof). For example, quadrats denoted as a(i) and b(i) are replicates. Each plot aimed to address one of the 3 main research questions of this experiment.

The green roof plots were constructed by the research team in accordance with the official green roof installation guidelines (FLL, 2008). For the open extensive system (System A), a wooden box of 8 m^2 was constructed with 8 quadrats of 1 m^2 surface each and the following commercially available layers were installed: water-proofing and root-barrier membrane, geotextile, drainage layer, geotextile, irrigation system and substrate. The two layers of geotextile that were used were different: the lower one was thicker in order to increase water retention, while the second one was thinner allowing root and water penetration. The modular systems (Systems B and C) had the same initial layers: water-proofing and a root-barrier membrane, geotextile and drainage. Modular pieces (i.e., geotextiled pillowcases filled with substrate) were placed on top of them. The modular pieces were commercially available in the local market and adjusted to the needs of the Mediterranean region. The substrate (used in the open and modular systems) was a patented product produced and distributed by Oikosteges (a Small & Medium Enterprise with extensive experience on green roofs). The substrate is mainly composed of multiple granulometries of perlite and contains ∼2% organic matter, including mycorrhizae. The dry weight of each 1 m^2 module was ∼20 kg. An automatic irrigation system was also installed, common for all plots.

Weather, Soil Conditions, and Irrigation

At the location of the experiment, the typical Mediterranean climate (i.e., mild winters and hot dry summers) is experienced. Weather patterns were recorded for the whole period of the experiment, using data from the campus meteorological station.

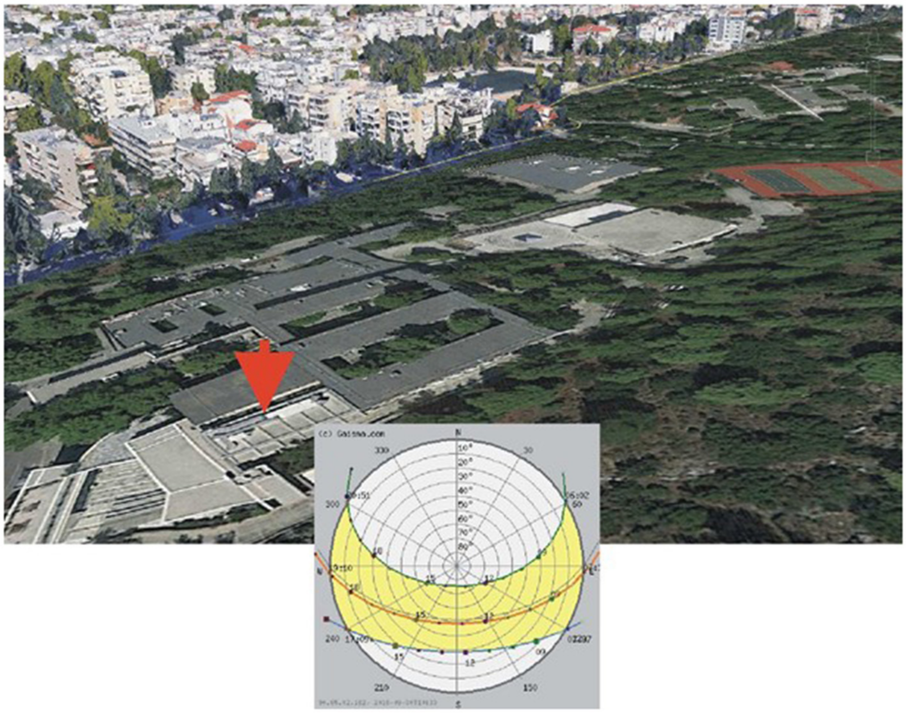


FIGURE 1 | The experimental site location and movement of the sun. Source: Google maps and www.gaisma.com.

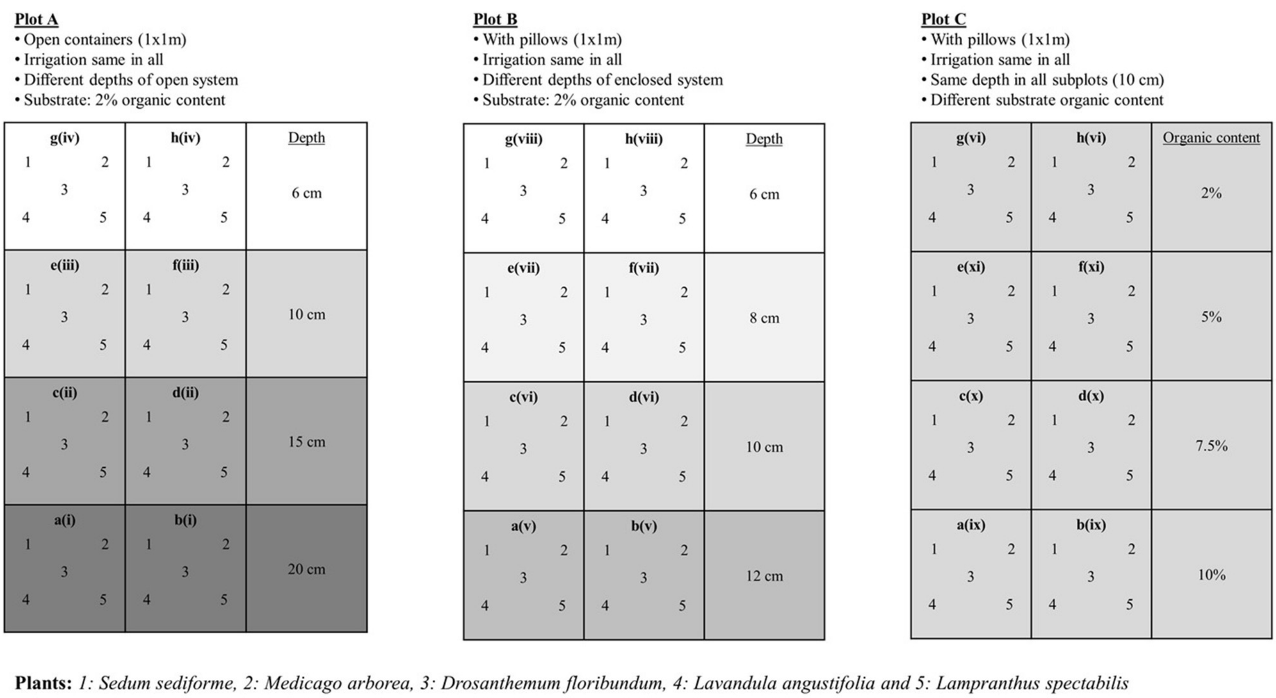


FIGURE 2 | Set-up of the experimental site. Source: Authors.

The climatic conditions in the area during the experimental period (September 2016 – July 2018) are shown in **Figure 3** below. The air temperature ranged from −2.9 to 42.1°C, and soil temperature from 13°C (in winter 2018) to 24.5°C (in summer 2018). The average humidity was 39.72% and the storm total ranged from 0 to 131.2 mm.

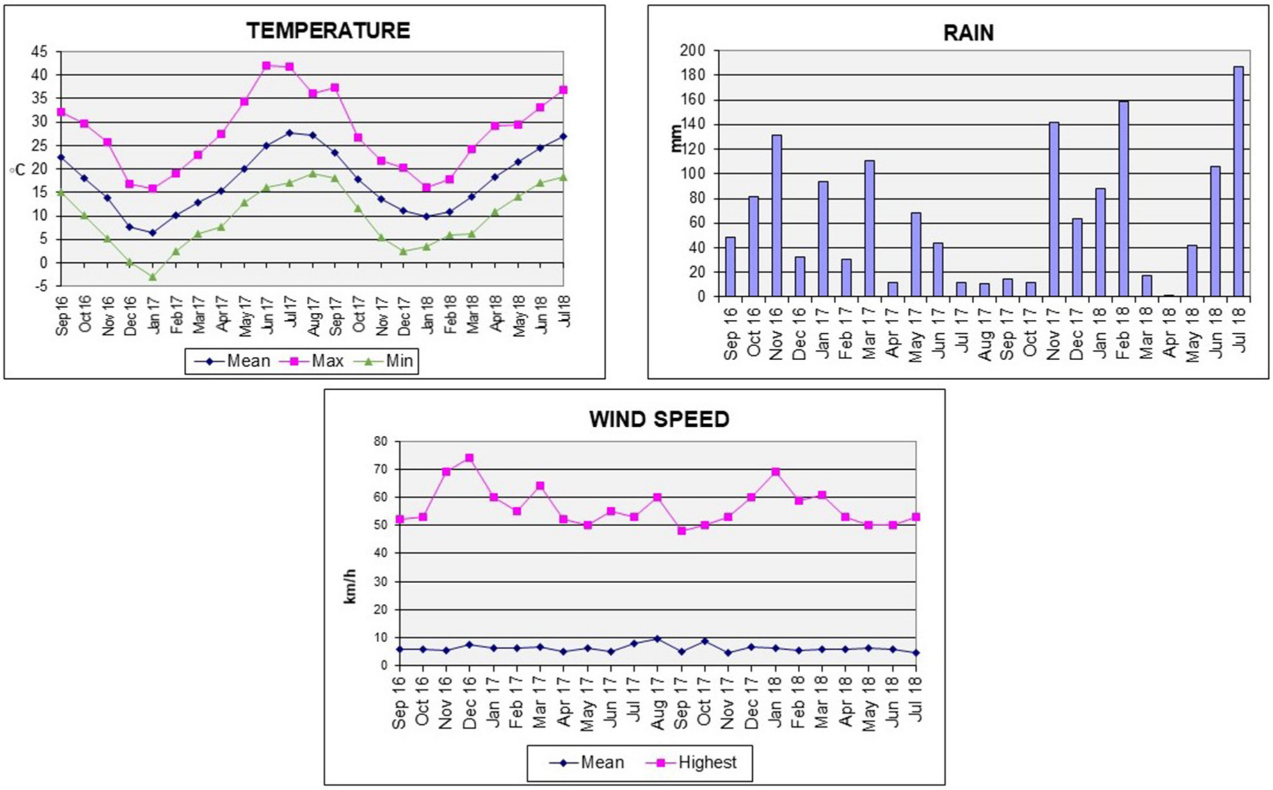


FIGURE 3 | Air temperature, precipitation and wind speed for the experimental period. Source: NOANET Database (Ag. Paraskevi meteo station); http://meteosearch.meteo.gr/.

All plots and quadrats were subjected to the same irrigation plan. Given that each plant has different irrigation needs, we selected an average irrigation scheme to cover the needs of the selected plants. In the period June 2016 to end of January 2018 and 17 April 2018 to the end of the experiment, the plots were irrigated 15 min per day at 5:00 A.M., while in the period February 2018 to 16 April 2018, they were watered for 5 min per day at the same time. Given our irrigation system (i.e., size of pipes, length etc.), in the periods with the longer irrigation schedule, 250 ml of water were provided per day from each hole, while in the period with the shorter irrigation time, 80 ml. Plants were not irrigated for almost 2 weeks, in the first 2 weeks of April 2018, as the battery of the automatic irrigation system ran out.

Plants

Five plant species were selected to be tested on this green roof experiment, based on green roof practicioners' knowledge regarding plants that are considered appropriate for the Mediterranean green roofs and relevant literature. Three of them are succulent plants (*Sedum sediforme, Drosanthemum floribundum* and *Lampranthus spectabilis*) and two shrubs (*Medicago arborea* and *Lavandula angustifolia*). The same five plants were planted in each quadrat in the exact same arrangement. **Table 1** below presents the taxonomy and main characteristics of the selected plant species.

Data Collection: Plant Growth

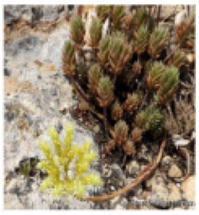
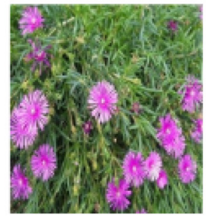
Data on plant height and two-dimensional width (longest called length) were collected approximately every 2 weeks for a period of 22 months, for the estimation of plant growth (like Monterusso et al., 2005). In total, data were collected in 34 different time points, leading to 816 data points. Height was measured starting from the bottom of the plants (soil top in the midst of the plant). Length was considered to be the longest distance between the two furthest ends of the plant's canopy. The width was the longest vertical line to the length. For the Open system - Plot A - (see **Figure 2**), width and length of plants were recorded even when they exceeded their wooden frames. Furthermore, observations regarding the plants' physical appearance (dry or dead), and flowering period, as well as other factors that affect plant growth such as presence of wild grass and flowers were also recorded.

Specifically, the physical appearance was recorded as Status (0: alive, 1: dry, and 2: dead) and as Absence (0: present, 1: absent). Flower denotes the presence (1) or absence (0) of flowers of the plants, while Grass denotes the presence (1) or absence (0) of wild flowers or grass.

Data Analysis

Based on the above-mentioned measurements, a Growth Index (GI) was calculated to assess plant growth, as the average of the three dimensions according to the following formula:

TABLE 1 | Selected plants and their characteristics.

Taxonomy and characteristics					
Order	Saxifragales	Fabales	Caryophyllales	Lamiales	Caryophyllales
Family/Genus	Crassulaceae/Sedum	Fabaceae/Medicago	Aizoaceae/Drosanthemum	Lamiaceae/Lavandula	Aizoaceae/Lampranthus
Species	*1.Sedum sediforme*	*2.Medicaco arborea*	*3.Drosanthemum floribundum*	*4.Lavandula angustifolia*	*5.Lampranthus spectabilis*
First Published in:	Actas Mem. Prim. Congr. Nat. Esp. Zaragoza 1908:246 1909.	*Medicago arborea* Linnaeus, Species Plantarus 2:778. 1753.	*Drosanthemum floribundum* (Haw.) Schwantes in Z. Sukkulentenk. 3:29. 1927 Basionym: *Mesembryanthemum floribundum* Haw.	*Lavandula angustifolia* Mill., Gard. Dict. Ed. 8: Lavandula no. 2. 1768.	*Lampranthus spectabilis* Published in Gard. Chron. Ser. 3, 87:212. 1930.
Image of plant					
Lifespan	Perennial plant Lives from 1 to 10 years	Perennial plant Lives more than 2 years	Perennial plant Lives 5–7 years	Perennial plant Lives up to 15 years	Perennial plant Lives 6 years in cultivation and up to 10 in natural habitat.
Water Conditions	Able to tolerate dry periods and can survive under minimal or no irrigation even at the shallow depth of 7.5 cm.	Succeeds in dry or well-drained moist soils.	Requires little to moderate water.	Loves rather dry than too moist soil; Even short-term drying of well-grown roots does not do any harm.	Requires low water. If soil is too wet, it will suffer and grow poorly.
Soil Conditions	Needs a very porous soil. Suitable for acid, alkaline and neutral pH. Needs enough root space for optimum growth. It is susceptible to rot due to too much moisture. Cannot tolerate competition.	Suitable for light (sandy), medium (loamy) and heavy (clay) soils; and acid, neutral, or alkaline soil. Soil can be either dry or moist. The plant can tolerate maritime exposure.	Drought & salt tolerant; stable on slopes and banks. Good drainage is needed.	Needs a sandy and chalky soil, possibly interspersed with many stones or gravel; low-nutrient soil. Needs a pH between 6.5 and 8.3. Good drainage is needed.	It prefers loam, sandy, gravelly soils, nutritionally poor soils, well-drained soils. Acidic, alkaline and neutral pH.
Climate Sun Exposure	Cannot grow in the shade; bright light prevents "stretching." It prefers light shade with ample airflow rather than full sun.	Requires a warm position in full sun. It cannot grow in the shade. Tolerant of wind and salt spray. It tolerates frost conditions and low temperatures as well as drought conditions and high temperatures.	Very hot and dry climatic conditions. Thrives in full sun in dry well-drained soils; easy to grow; most survive temperatures down to the freezing point.	Requires full to partial sunlight.	Requires very hot and dry climatic conditions. Full sunlight.
Maximum growth	Height: 20–25 cm Spread: 60 cm Flower stalks to 50 cm	Evergreen Shrub Height: 2 m Spread: 2 m Size may be a limiting factor of other plants next to it.	Height: up to 15 cm Spread: can cover areas up to 2 m^2. Spreading may be a limiting factor for other nearby plants.	Height: 20–100 cm Spread: 60–100 cm Spacing: 50–90 cm.	Height: up to 15–30 cm Spread: 45–65 cm Spacing: 60 cm
Blooming time	Summer (July-August)	May to October	Spring to early summer	June to August	Late winter to spring in warm winter areas. From early summer to early fall in cooler locations.

Sources: Huxley et al., 1992; Eggli, 2003; United States Department of Agriculture, 2020; National Center for Biotechnology Information NCBI, 2021. Adapted by authors.

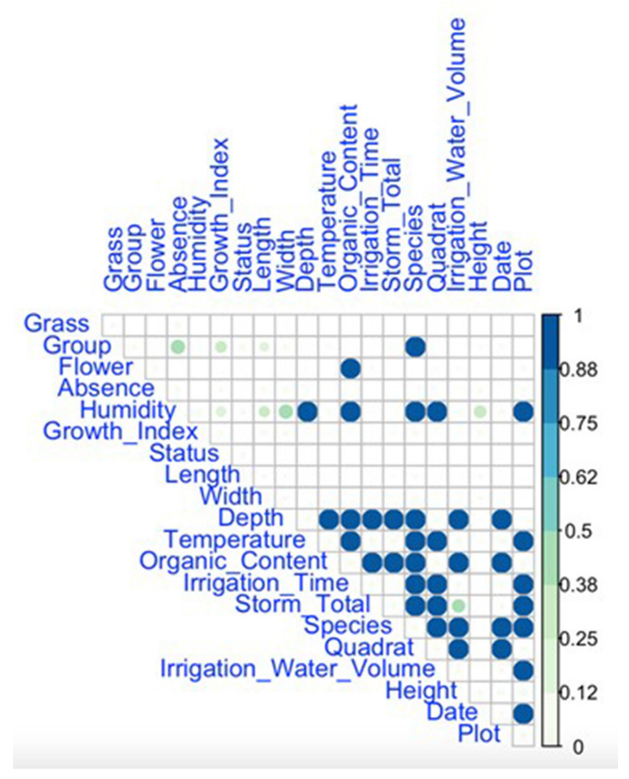


FIGURE 4 | A pairwise correlation plot for all parameters considered in the study. The color and size of the circle denotes the magnitude of the correlation value. Highly correlated parameters were considered to be those with absolute correlation values >0.7. Source: Authors.

GI = (H + W + L)/3, where H denotes the height parameter, W the width and L the length parameter. A qualitative assessment of the data was first performed, based on the graphical depictions of plant growth over time, followed by a basic statistical analysis aiming to assess the statistical significance of the parameters considered as well as any possible interactions between those. Data were analyzed using multiple linear regression with Analysis of Variance (ANOVA) to estimate the statistically significant parameters that affect the growth of plants as measured by GI. Pre-processing of the data was conducted. Correlation analysis was performed for pairwise comparisons of parameters to identify and exclude any correlated features from further analysis (**Figure 4**). The parameters Width, Length and Height were excluded for further analysis as highly correlated to GI (above than 0.8 by absolute value). Data were filtered to exclude correlated data and outlier data; particularly, three outliers were found based on the interquartile range values of the descriptors and they were all referring to one data point. A stepwise procedure was considered where independent descriptors were added to improve the fit of the model. The descriptors found to be statistically significant at a significance level of $\alpha = 0.05$ or less, specifically: Species, Flower, Grass, Status, Absence, Plot, Irrigation water volume, Humidity (all of them having $p < 0.0001$), as well as Temperature ($p = 0.00101$), and Group ($p = 0.0509$). Interaction terms were also considered (adjusted $R^2 = 0.7923$), depicting some statistically significant interactions between parameters, specifically between Species and Absence, Species and Status, Species and Temperature, Species and Group, Flower and Status ($\alpha = 0.05$). Some of the interactions found statistically significant such as Species and Absence, serve as a good validation for our results as they are evident; thus, these are not further discussed as an analysis outcome. Two triple interaction terms were found to be statistically significant at $\alpha = 0.05$: Species-Flower-Group ($p = 0.001025$), Species-Temperature-Status ($p = 0.0262884$). Detailed observational results are presented in the following section together with interaction plots for those parameters found to be statistically significant ($p < 0.0001, \alpha = 0.0001$).

RESULTS

Plant Growth and Substrate Depth

Plots A (open) and B (modular) were set up to investigate the impact of substrate depth on the selected plants. Overall, observations suggested that different plants might have different behaviors in relation to substrate depth. In **Supplementary Figure 1** of the supplement, growth curves for the plants in the highest and lowest depths of the open and modular systems are displayed, showing the Growth Index factor (y axis) against measurement (x axis). The statistical analysis demonstrated that substrate depth was not an important parameter affecting GI. The interaction plot of species, substrate depth and GI is depicted in **Figure 5A**. Observations from the analysis indicate that substrate depth did not impact the growth of *D. floribundum.* Due to the erratic growth and high mortality rate of *S. sediforme*, no clear association was identified with substrate depth and plant growth. It is important to mention that most of the individuals that managed to survive were in plot A at the deeper growing media. Whereas, the individuals that survived in plot B were in lower-depth substrates [Bc(vi), Bd(vi), Bh(viii)]. *L. angustifolia* showed high GI in intermediate depths (12 and 15 cm). *L. spectabilis* seemed to benefit from deeper growing media. Finally, there is not a clear connection between depth and GI for *M. arborea.*

Plant Growth and Organic Content of the Substrate

Plot C was set up to study the impact of the composition of the substrate, especially in relation to organic content, on plant growth. Qualitative observations (shown in **Supplementary Figure 2**) and the statistical analysis demonstrated that organic content did not significantly affect the GI (see **Figure 5B**). *M. arborea* did better in substrates with higher organic content. *S. sediforme* has higher GI mean value at 2 and 10% organic content, while *L. angustifolia* exhibited the highest end growth at the quadrats with the lowest organic content.

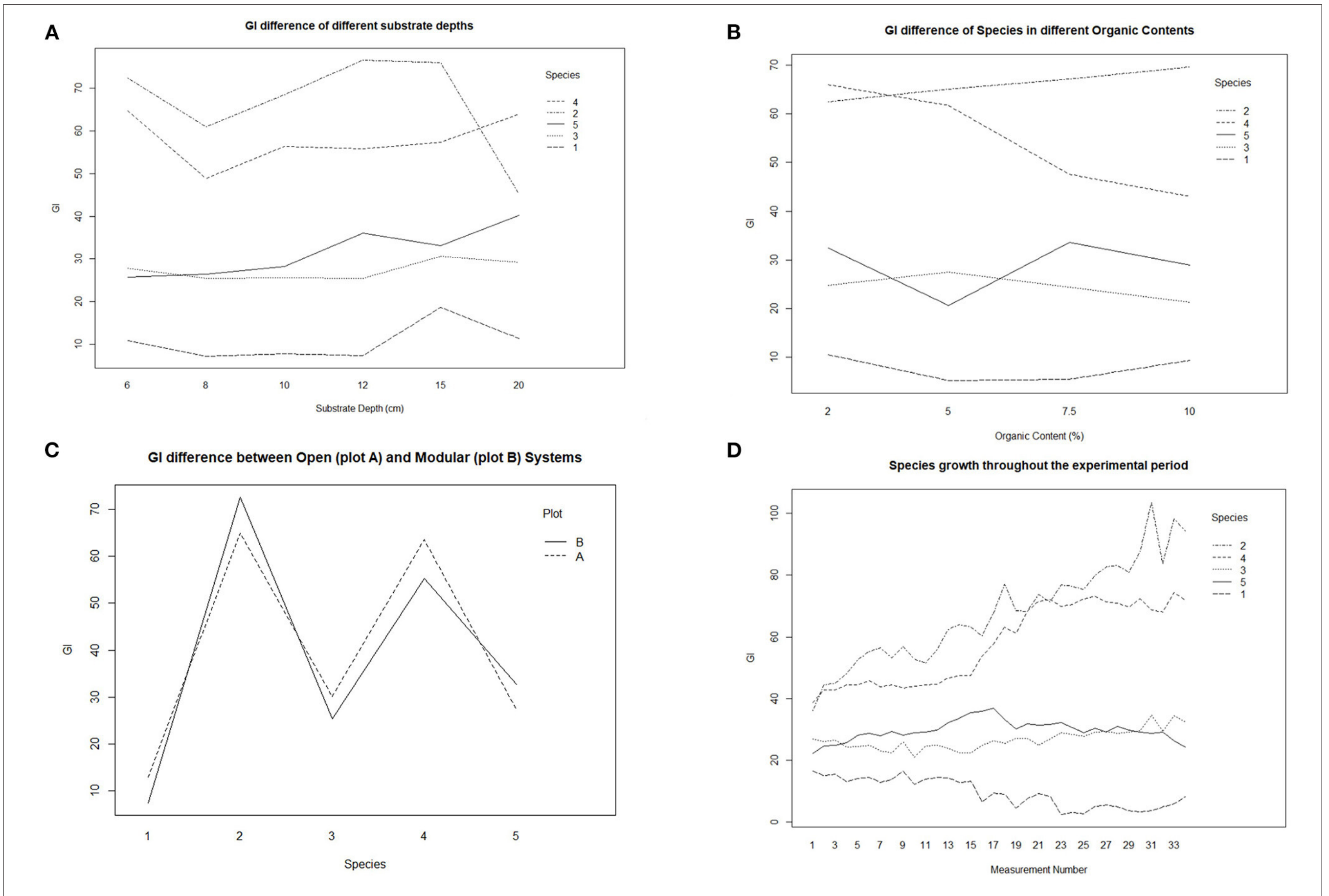


FIGURE 5 | Interaction plots of species in relation to substrate depth, organic content, type of green roof system, and measurement number. **(A)** GI difference of different substrate depths, **(B)** GI difference of species in different organic contents, **(C)** Mean GI difference between Open (plot A) and Modular (plot B) Systems and **(D)** Species growth throughout the experimental period (Measurement numbers: 1-34); where plant species: 1: Sedum sediforme, 2: Medicago arborea, 3: Drosanthemum floribundum, 4: Lavandula angustifolia and 5: Lampranthus spectabilis. Source: Authors.

Plant Growth and Type of Green Roof System

To compare the possible different patterns of growth in the two different systems (open and closed), the quadrats of plots A (open) and B (modular) were analyzed. Both the qualitative observations (shown in **Supplementary Figure 3**) and the statistical analysis found that the type of green roof system did not affect the GI. Based on **Figure 5C** some observations can be made for the specific species. Overall, *M. arborea* and *L. spectabilis* performed better in the modular system, whereas *S. sediforme*, D. *floribundum*, and *L. angustifolia* benefit more in the open system. Specifically, S*edum sediforme* did better in the open system, especially at the deeper growing media, while the three plants that disappeared in the open system [Ae(iii), Af(iii), Ag(iv)] reappeared. *S. sediforme* struggled and more than half (5) died in the modular system. Additionally, *L. spectabilis* did much better in the modular system, where all except one plant survived and several doubled their size. In the open system, more than half of the *L. spectabilis* (5) plants died. This may be an indication of how this species reacts differently in different types of green roof systems (open and modular).

Plant Species

The growth of the different plant species throughout the experimental period is depicted in the interaction plot "Species growth throughout the experimental period" (see **Figure 5D**). Similarly, the GI of species among the different groups is depicted in **Figure 6C**.

For the purposes of this experiment, it was considered that a plant did not survive (plant mortality) and was recorded as non-existent or "dead" when it had only dry stems and no leaves for three consecutive measurements (∼1.5 months). We faced a challenge with *S. sediforme*, which on some occasions re-sprouted after several weeks. Specifically, *S. sediforme* had an unpredictable pattern of growth, mortality and disappearance. A significant number of *S. sediforme* plants died (50%). *D. floribundum* and *L. angustifolia* did well and no individual died or was removed throughout the sampling period. For the latter, one plant died after an attack to all lavender plants by a certain invasive insect

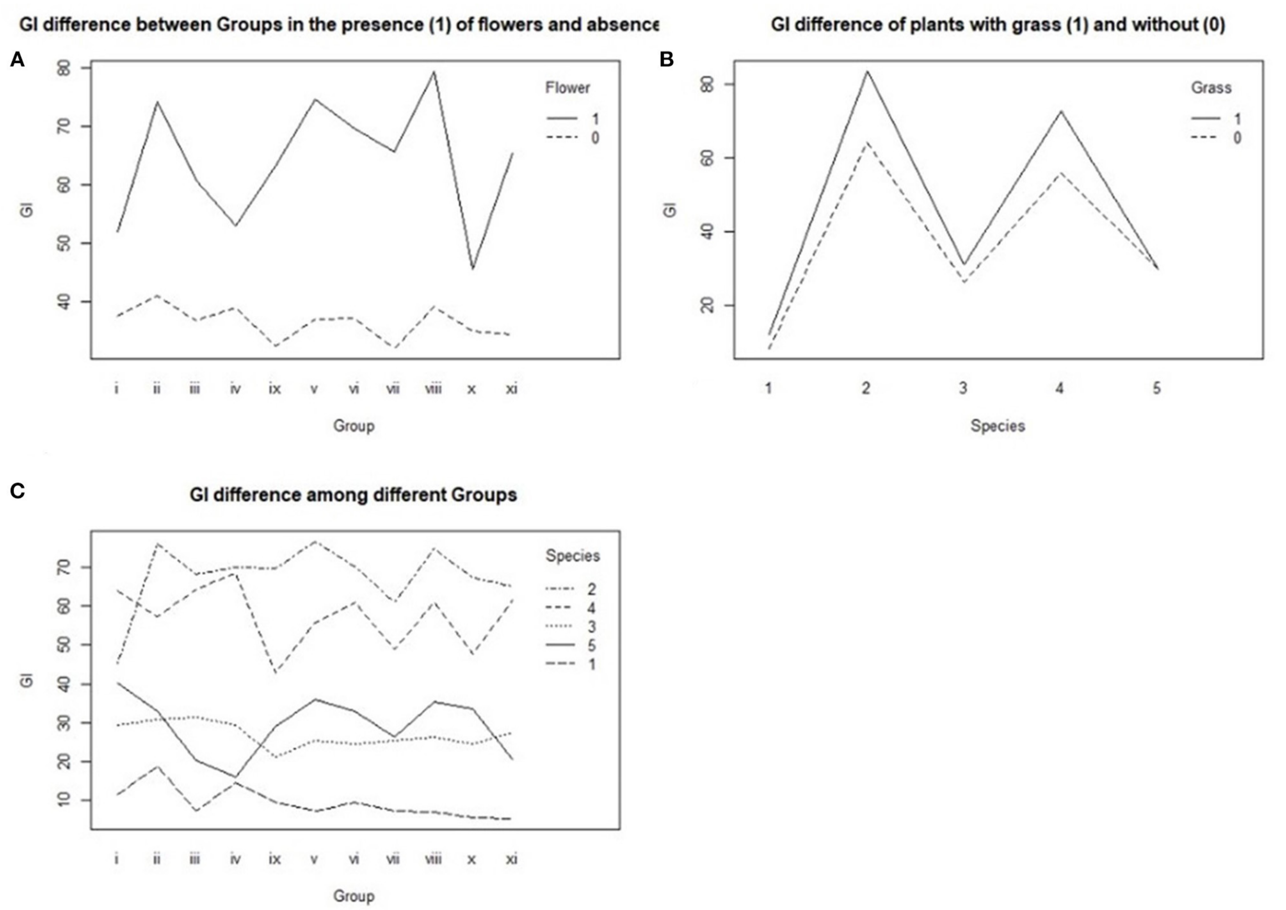


FIGURE 6 | Interaction plots of Species in relation to Flower, Grass and Group. **(A)** GI difference between Groups (i-xi) in the presence (1) and absence (0) of Flowers, **(B)** GI difference of plants with Grass (1) and without (0) and **(C)** GI difference of Species among different Groups (i-xi); where plant species: 1: Sedum sediforme, 2: Medicago arborea, 3: Drosanthemum floribundum, 4: Lavandula angustifolia and 5: Lampranthus spectabilis. Source: Authors.

in April 2018, while one plant disappeared probably by a human intervention. *M. arborea* proved very well-suited for this setting. All plants survived with the exception of Ab(i)2 which was removed probably by a human intervention before the first summer in 2017. Finally, high mortality (33%) was also observed among the *L. spectabilis* plants.

Throughout the sampling period and for all species dried (Status = 1), individuals that managed to survive were recorded. The statistical model constructed for this study showed, as expected, that the status of the plant ($p < 2e\text{-}16$) and mortality or absence ($p < 2e\text{-}16$) affected the GI, but also identified flowering ($p < 2e\text{-}16$) and grass presence ($p = 1.18e\text{-}06$) as statistically significant parameters affecting GI. **Figures 6A,B** show the interactions between Flower, Group, and GI as well as the interactions between Grass, Species, and GI, respectively.

It should be noted that *S. sediforme* never flowered during those 2 years and therefore there is no record for its flowering pattern. That sounds reasonable as these individuals were generally struggling for survival. Overall, the two main flowering periods of the green roof were from 11/2016 to 06/2017 and 02/2018 to 06/2018. More specifically, both *M. arborea* and *D. floribundum* did very well in our system. They displayed similar growth patterns irrespective of substrate depth or organic content. During the experiment, both plants flowered in the period from February or March to June. *L. angustifolia* flowered in the 1st year, from December 2016 to June 2017, and in the 2nd year, from October 2017 to March 2018. Finally, *L. spectabilis* plants flowered in April 2017, while in the 2nd year, only some individuals flowered. Overall, as it was expected the GI increased during the flowering periods as it is shown in **Figure 6A**. The presence of wildflowers or grass, denoted as Grass in **Figure 6B**, was found to be a statistically significant parameter ($p = 1.18e\text{-}06$) with higher GI and the flowering periods for all species. This may be related to seasonal climatic variations.

DISCUSSION

It is worth starting our discussion by emphasizing that this irrigated green roof was intended to approximate a "natural" green roof as closely as possible. Thus, aside of the daily

– same in all quadrats – irrigation, the only other human intervention was the hand-removal of the insects that attacked *L. angustifolia* plants in the spring periods of the experimental period. No pruning, mowing or replanting of disappeared individuals was performed.

A number of studies have identified substrate depth as an important parameter influencing plant growth on green roofs, with deeper growing media supporting higher plant growth (Kazemi and Monorko, 2017). This has also been supported by studies in Mediterranean climates as well (see Benvenuti and Bacci, 2010; Panayiotis et al., 2011; Papafotiou et al., 2013). However, our study suggests that substrate depth does not seem to have a clear impact on plant growth. Different plants may react differently to depth of growing media. The statistical analysis verified this observation as it did not identify depth as a significant parameter influencing plant growth. This observation agrees with a few other published studies (Nagase and Dunnett, 2013; Hawke's, 2015). There are indications that *L. spectabilis* benefits from deeper growing media. These findings are in accordance with other relevant scientific findings that show that some species can grow well on less deep growing media too. Durhman et al. (2007) state that although deeper substrates support greater plant growth in general, "in the shallowest depth of 2.5 cm, several species were observed to form stable communities." Also, Nagase and Dunnett (2013) found that some dwarf geophytes could perform well on a substrate depth of 5 cm on an extensive roof without irrigation. Thus, based on the findings of this study, which are also supported by some previous literature, we propose that substrate depth as a parameter influencing plant growth on Green Roofs should be considered in relation with the plant species characteristics and physical parameters of the roof, like light (Getter et al., 2009) and water availability (see **Table 1** above).

Specifically, for *Lavandula angustifolia*, our study demonstrated that substrate depth does not impact plant growth. This finding contradicts the results of the study of Kotsiris et al. (2012), which showed that lavender grows better in deeper depths and with more compost; however, they examined deeper growing media (30 cm and 20 cm) than we did. This issue requires further research, focusing on specific plants' (e.g., *L. angustifolia*) behavior at shallower depths, for a more conclusive comment.

Young et al. (2014) identified substrate composition as a significant parameter influencing plant growth, with growing media richer in organic matter supporting more plant growth. This is not supported by our study which suggests that the substrate's organic content is not an important parameter influencing plant growth. Our observations for the different species (i.e., *S. sediforme* and *L. angustifolia* did better in the substrates with less organic content, while *M. arborea* in the substrates with higher organic matter) may suggest that plant species and their needs, in connection with the plant community (e.g., interspecies competition; aboveground and below ground interactions) as indicated by Elhakeem et al. (2018), may mitigate the impact of the organic content of the substrate. This allegation agrees with Lundholm et al. (2014) findings that plant traits can be used to predict plant growth, and Elhakeem et al. (2018) suggestion that plant interactions influence plant performance. Similarly, Bates et al. (2015) showed that in their study of a brown field or biodiverse green roof, low organic content was "ideal," and claimed that the most appropriate substrate organic content may vary with the green roof's water holding capacity.

The type of the Green Roof did not seem to significantly impact the growth of *M. arborea*, *D. floribundum,* and *L. angustifolia* as demonstrated by the statistical analysis and also indicated by qualitative observations. Based on the qualitative observations, the modular system seemed to better support plant growth for *L. spectabilis* (i.e., considerably better survival rate) and *M. arborea* (i.e., higher end growth). *D. floribundum* and *L. angustifolia* performed slightly better in the open system. Also, *S. sediforme* did better in the open system, especially in deeper growing media. These may be indications of how some species react differently in different types of green roof systems (open and modular), but they cannot be ascertained on the basis of this study. Further research is needed to examine to what extent the type of the Green Roof may affect plant growth and community development, and why.

This part of the study is quite original as we could not locate studies that compared modular and open Green Roof systems. The open system may allow the development of a more diverse bio-community potentially with both supportive and competitive relations, but it is also subject to more loss of particles through wind and easier evaporation of water.

Our experiment included three succulent plants – *S. sediforme, D. floribundum* and *L. spectabilis* – and two shrubs – *M. arborea*, which is a nitrogen fixer, and *L. angustifolia*. Low survival rate was observed for *S. sediforme* (50%) and *L. spectabilis* (33%). *M. arborea* and *L. angustifolia* proved more resilient. From these observations, we cannot conclude that *S. sediforme* and *L. spectabilis* species are inappropriate for Mediterranean green roofs; rather, we may need to consider the significance of other parameters like the community for *S. sediforme. S. sediforme* disappeared in large numbers in plots B and C (modular), while it did better in plot A (open system). In plot A, sedum plants reappeared after a period when they were considered as disappeared. This could be associated with inter-species competition, especially as it seems that sedum plants did better where other plants struggled. Furthermore, we had the opportunity to observe the impact of drought on our plants due to an accident with the automatic irrigation system, which left the plants without water for ∼2 weeks in spring 2018, but they all recovered to their previous stage after reinstating the irrigation program and sustained their optimum growth.

Thus, we agree with Kazemi and Monorko (2017) who indicate that: "While it is obvious that growing media components, depth, and attributes affect plant performances in green roofs, the extent to which these components and their ratios affect vegetation in different climates is still unknown." Further multi-criteria investigation is needed. Such an approach may also enhance our understanding regarding the influence of the type of green roof on plant performance. Furthermore, the influence of the plant community on different species' establishment and growth should be further examined (see Durhman et al., 2007; Lundholm et al., 2014).

CONCLUSION

This study aimed to contribute to the scientific basis of the practice and implementation of green roofs in the Mediterranean. It was conducted in the context of an educational setting; thus, there were both spatial constraints (in the selection of the roofs that could be used), and time constraints (in the data collection). A positive aspect of this study is that it provides a realistic green roof setting that can be found in Mediterranean urban environments and so enables useful lessons to be drawn for such contexts.

Based on our findings, it appears that substrate depth by itself can neither explain differences in plant growth nor predict plant performance on green roofs. Substrate depth may be an important factor in combination with other parameters (also indicated by Raimondo et al., 2015; Elhakeem et al., 2018; Vangergrift et al., 2019). Similarly, organic content is not appearing to affect the plant growth. However, plant species and their needs, as well as interspecies relations (Elhakeem et al., 2018) may mitigate the impact of the substrate organic content on their growth.

In addition, the type of green roof – open or modular – could not be associated with plant performance; some species in our experiment performed better in the open system (i.e., *S. sediforme*) and others grew better in the modular one (i.e., *L. spectabilis*). As this is an issue that has not been much explored in the scientific literature, an extensive study will be needed to investigate why and how the type of the green roof may be associated with plant performance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The research was designed by CM, AM, PP, and DG. Statistical analysis was performed by PS and GT. MK and PS were instrumental in data collection, processing, and presentation. The writing of the article was primarily done by PS and CM, with input from MK, PP, AM, GT, and DG. All authors significantly contributed to all aspects of the research process according to their expertise.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2021.796441/full#supplementary-material

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