



# Enhancing biodiversity and functionality of extensive green roof: A comparative study of five native Mediterranean perennial species in Rome

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## ABSTRACT

Research widely demonstrates the usefulness of green roofs for energy saving and climate mitigation, such as their role in favoring biodiversity in urban ecosystems. However, challenging conditions for plant growth, particularly in Mediterranean regions with dry summers, require careful species selection. Through an in-situ experiment on a pre-existing extensive green roof in Rome, this research evaluated five native Mediterranean species (*Helichrysum italicum*, *Convolvulus cneorum*, *Anthemis maritima*, and *Thymus vulgaris*) in comparison with the commonly used *Sedum album* as a control. The 14-months experiment monitored plant health, reproductive stages, and coverage across nine experimental modules. Results revealed a superior performance of the Mediterranean species compared to *Sedum album*, with particularly good health and coverage rates of *Convolvulus cneorum* and *Helichrysum italicum*, that together *Anthemis maritima* displayed extended flowering periods, contributing to both aesthetic values. Thermal imaging analysis showed temperature reductions of 2.9–4.4 °C in green roof areas with respect to adjacent concrete surfaces and all planted areas contributed effectively to thermal regulation, with daily temperature fluctuations significantly reduced compared to conventional roofing. The poor performance of the *Sedum album* challenges its widespread use in Mediterranean climates and highlights the importance of selecting regionally adapted species. This research provides valuable insights for sustainable urban development, demonstrating that Mediterranean perennials can effectively enhance green roof performance while supporting biodiversity and improving thermal regulation in challenging climatic conditions.

## 1. Introduction

Considering the increasingly frequent dramatic events linked to climate change, growing emphasis emerges on the need to reintegrate green spaces into urban environments [1–4]. Urban expansion has led not only to a reduction in green areas [5] but also to greater environmental damage through increased heat production, waste generation, and air pollution, while negatively impacting biodiversity [6,7]. This urban development trajectory poses significant environmental, social, and economic challenges that require immediate attention and innovative solutions [8,9].

Urban vegetation extends far beyond merely decorative elements. Green infrastructure, including parks, street trees, green walls, and green roofs, plays a vital role in improving urban resilience and livability [10–12], offering multiple ecosystem services [13–17] that are crucial for addressing climate change impacts [18,19]. These services include

mitigating the urban heat island effect, reducing stormwater runoff [20, 21], sequestering CO<sub>2</sub>, improving air quality, and supporting urban biodiversity [18,19].

Notably, the effectiveness of green roof thermal regulation properties dates back to ancient times, with evidence of use from the Neolithic Era [22,23]. In modern contexts, green roofs demonstrate significant benefits for building energy efficiency through multiple mechanisms: the shading effect of vegetation, increased thermal mass, and evapotranspiration phenomena reduce heat flux entering buildings in summer, while providing additional insulation to reduce heat losses in winter [24–26]. Studies have shown that green roofs can reduce heat fluxes through roofing systems by 70–90 % in summer and 10–30 % in winter [27–29].

However, implementing traditional ground-level green spaces often faces significant constraints in dense urban environments where available space is increasingly scarce [30,31]. Among the nature-based

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solutions proposed for improving urban conditions, extensive green roofs (EGRs) represent a particularly promising approach [23,32–34]. These systems, consisting of vegetation growing above a series of protective roof layers, can transform otherwise unused roof space into functional green infrastructure [35]. EGRs require minimal maintenance and a relatively shallow growing medium compared to intensive green roofs, making them a more practical solution for widespread urban implementation [36].

However, green infrastructure implementation cannot follow a one-size-fits-all approach [37]. Just as natural ecosystems vary by region, urban greening solutions must be carefully adapted to local conditions [38]. This principle is particularly crucial in plant selection for EGRs, where species must not only survive but thrive in often extreme rooftop conditions [39]. While *Sedum* genus species are commonly used worldwide due to their drought tolerance [40,41], growing recognition suggests that native species adapted to local climate conditions may offer superior performance while supporting local biodiversity [42,43].

Despite the ecological benefits of plants and research suggesting expansion of the potential species pool [10,36,44], species selection often remains limited to *Sedum* species [23]. Recent studies across various Mediterranean regions have begun to challenge this conventional approach. In Spain, Azeñas et al. [45] evaluated five Mediterranean species under water-limited conditions, finding that several native species demonstrated excellent potential for ecosystem service provision. In Greece, Papafotiou et al. [42] found that native sages (*Salvia* spp.) showed promising adaptation to green roof conditions, even under reduced irrigation. Van Mechelen et al. [46] conducted extensive evaluations of vegetation development on different extensive green roof types in Mediterranean and temperate maritime climates, highlighting the importance of substrate properties and plant selection suited to local conditions.

This adaptation to local conditions becomes even more critical in Mediterranean climate regions, where long, hot summers pose particular challenges for plant survival on EGRs [47,42]. The Mediterranean flora includes numerous species that have evolved to cope with such conditions, offering a rich palette of potential alternatives to traditional EGR plantings [45,48,49]. These native species not only possess natural adaptations to local climate conditions but also contribute to preserving local ecological character and enhancing urban biodiversity [36,40]. Recent studies have demonstrated the successful establishment and high survival rates of native species in various climatic conditions, including humid subtropical climates [50]. However, considering that Mediterranean bioclimatic characteristics occur in five different regions (the Mediterranean Basin, coastal California, central Chile, the Cape region of South Africa, and the southwest and southern parts of Australia) [51–53], attention should also be given to geographical distribution. For nature conservation, it is important to sustain native species and distinguish among them those that belong to different regional flora.

Furthermore, recent research by Richards et al. [54] has raised concerns about the future resilience of *Sedum*-based systems under changing climate conditions, suggesting that species diversification may be essential for maintaining green roof functionality in the face of intensifying climate stressors. This aligns with findings from Vannucchi et al. [55], who demonstrated that low-productivity substrates can lead to functional diversification of green roof plant assemblages, potentially improving long-term resilience.

Plant species selection for Mediterranean green roofs must also consider thermal performance. Pumo et al. [56] analyzed the climate adaptive properties of an advanced multilayer green roof in Palermo, Italy, finding that properly designed green roofs can provide significant cooling effects during hot summers, contributing to building energy performance. Similarly, in Rome, Asdrubali et al. [24] reported substantial thermal resistance improvements in buildings with green roofs compared to conventional roofing systems, with differences of approximately 50 %.

## 1.1. Research objectives and contribution

Through comprehensive assessment, this research aims to expand the range of suitable plant species for Mediterranean green roofs while quantifying their contribution to building energy efficiency. This knowledge will be crucial for developing more effective and locally adapted green roof solutions that can better address urban climate challenges and contribute to sustainable urban development.

This study, based in the Roman area (which biogeographically and bioclimatically belongs to the Mediterranean context), aims to compare the performance of native perennial species suitable for extensive green roof conditions with that of commonly used *Sedum* species, and to evaluate their potential thermal insulation capacity. The specific objectives of this research are:

1. Evaluation and comparison of the health, reproductive stages, and coverage rates of four selected Mediterranean perennial species (*Helichrysum italicum*, *Convolvulus cneorum*, *Anthemis maritima*, and *Thymus vulgaris*) with the commonly used *Sedum album* over a 14-month period in a Mediterranean climate.
2. Preliminary assessment of the thermal insulation benefits of green roof areas planted with these different species compared to conventional concrete roofing.
3. Identification of which Mediterranean perennial species show the greatest potential for enhancing green roof performance in terms of both plant viability and thermal regulation.

This research makes several novel contributions to the field. First, it provides one of the first long-term (14-month) comparative studies of multiple native Mediterranean species on an extensive green roof in Rome, offering insights into their performance across different seasons. Second, it challenges conventional plant selection approaches by providing quantitative evidence of the adaptation capabilities of native Mediterranean species compared to the widely used *Sedum album*. Third, it develops a comprehensive evaluation methodology that combines plant health, reproductive, and coverage parameters with thermal performance assessment, providing a holistic understanding of green roof functionality. Finally, it identifies specific native species that show superior performance under Mediterranean conditions, offering practical recommendations for green roof design and implementation in similar climatic regions.

## 2. Material and methods

### 2.1. Site description and climate

The study took place on the green roof of the Giovanni Keplero State High School, located in the densely populated southern area of Rome near the Tiber River, Italy (N 41° 51' 47.133"E 12° 28' 20.719"). The site is characterized by a Mediterranean climate with mild, wet winters and hot, dry summers [57], defined as subtype Csa according to Köppen climate classification [58]. The meteorological data (average monthly temperature and rainfall) for the experimental period (July 2023 - August 2024) came from a weather station located near the experimental roof (Fig. 1). During the experimental period, the site experienced typical Mediterranean seasonal patterns, with hot, dry Summers and mild, wet Winters. Temperatures reached their peak in July and August 2024 (29 °C), while the lowest temperatures occurred in January 2024 (11 °C). Rainfall showed an irregular distribution throughout the year, with the highest precipitation recorded in November 2023 (96 mm) and March 2024 (104 mm), and minimal rainfall during summer months, particularly in July 2024 (2 mm). This climate pattern, characterized by summer drought stress and winter rainfall, is representative of the Mediterranean conditions under which the selected plant species grew.



Fig. 1. Climatic graph of the monthly average temperature ( °C) and total amount of rainfall (mm) during the experimental period from July 2023 to August 2024, in the green roof area in Rome (Italy).

2.2. Green roof characteristics and experimental setup

The green roof was built in 2016 according to the European standard UNI EN11235. The total area of approximately 200 square meters was divided into two zones: a 50-square-meter area dedicated to experimentation subdivided into 9 vats (2 × 2 m each), and a 150-square-meter non-experimental area free of confinements. The green roof was equipped with a system produced by Harpo Verde Pensile called "SEIC extensive hanging green type Sedum" with a thickness of 15 cm for the experimentation area and 12 cm in the remaining area. The substrate consisted of a mineral material mixture (lapillus, pumice, zeolite) and organic material (peat) with grain size ranging from 0.05 to 20 mm. The water retention capacity of the system is not less than 85 l/m<sup>2</sup>. The runoff coefficient of the system according to FLL tests and certified by independent institutes is  $C \leq 0.20$ . The total hydraulic conductivity of the drainage element at 20 kPa (according to EN ISO 12,958) is not less

than 15.00 l/sm at a hydraulic gradient of  $i = 1$ , and not less than 1.3 l/sm at a hydraulic gradient of  $i = 0.01$ . Currently, the floristic composition of the non-experimental area, originally composed of the genus Sedum, has been enriched through subsequent interventions with the introduction of species from the Mediterranean flora, resulting in a significant increase in biodiversity.

After the settlement, and the first experimentations in 2017–2019, the roof remained unmaintained for 4 years (overall due to the COVID-19 emergency) before this experiment, and we also monitored the wild species occurrence [59].

In this experiment, which ran from July 2023 to August 2024, all nine vats had the same substrate and irrigation conditions. Eight of the nine vats contained the 4 selected native perennial species (see below), where 5 individuals of each of the four species grew with a density of 5 plants/m<sup>2</sup> (for a total of 40 plants per container) (Fig. 2). The ninth vat served as a control vat using only *Sedum album* individuals, for a total of

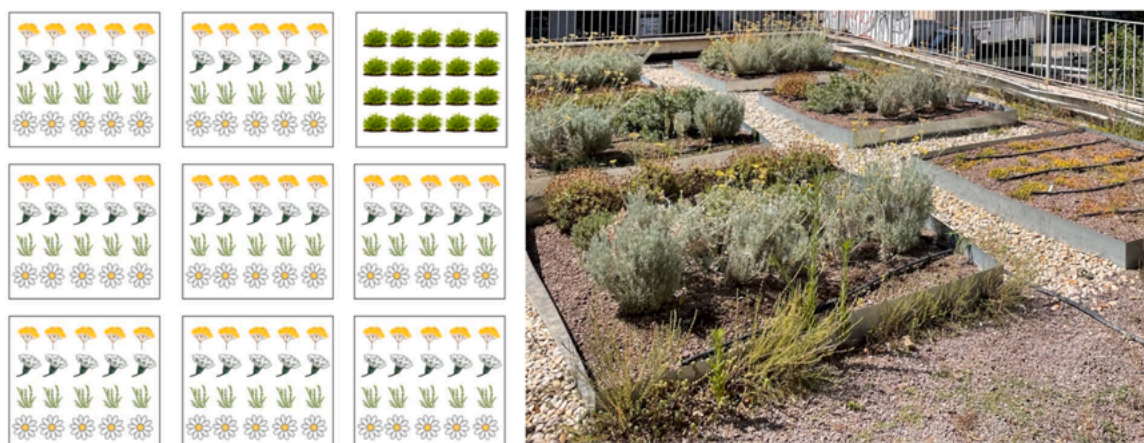


Fig. 2. – Plant Disposition scheme of Keplero green roof: *Helichrysum italicum*, *Convolvulus cneorum*, *Thymus vulgaris*, *Anthemis maritima*, and a control vat with *Sedum album*; and view of the real green roof.

20 plants. The plants came from 15-cm diameter nursery pots from the nursery company Bindi Secondo s.r.l.

Irrigation water, through different irrigation lines in each module, was settled only during summer months (from June to September 2023 and the same during 2024), when drought stress occurs. The irrigation was calibrated delivering water daily once at 5:00 am for a 5-minute duration [60], using drip tubes giving 4 liters per hour.

In parallel, the established weeds have been manually removed monthly.

### 2.3. Plant selection

The criterion for species selection was mainly based on ecological characteristics, following a previous study by Caneva et al. [36] and previous tests in the area by Bellini et al. [61]. The tested species were *Helichrysum italicum*, *Convolvulus cneorum*, *Anthemis maritima*, and *Thymus vulgaris* (Table 1) including also as control *Sedum album*, selected following the same ecological criteria.

In fact, prioritizing ecological aspects for the Mediterranean bioclimate, we considered at first the chorological type (Mediterranean to Euro-Mediterranean) (Index Plantarum Flora Italicae IPFI, [62]; <https://powo.science.kew.org/> [63]), and the phytosociological class of reference [64] (e.g. dunal and back dunal; meso-xerophilous grasslands, pioneer species of rocks, sandy, loose screes).

We also considered Ellenberg's indices applied to the Italian flora by Pignatti et al. [65]. While Caneva et al. [36] suggested species with moderate to high light tolerance ( $L > 6$ ), heat adaptation ( $T > 6$ ), and drought resistance ( $U < 5$ ), for this specific green roof we selected more extreme-adapted species with higher light ( $L > 8$ ) and temperature ( $T > 8$ ) values, and lower moisture ( $U < 4$ ) and nutrient ( $N < 4$ ) requirements.

The selection balanced theoretical ecological suitability with practical considerations. We prioritized perennial species with different growth forms (hemicryptophytes and chamaephytes) to evaluate diverse adaptation strategies. Additionally, we considered the potential for aesthetic value through extended flowering periods, which would enhance the multifunctionality of the green roof installation. *Sedum album* was selected as a control representing the conventional industry standard for extensive green roofs, particularly because it shares similar ecological requirements according to Ellenberg's indices ( $L = 11$ ,  $U = 2$ ,  $N = 1$ ), allowing for meaningful comparison with the tested Mediterranean species.

**Table 1**

– Taxonomical, structural, chorological and ecological characteristics of the selected plants.

SPECIES (FAMILY)	BIOLOGICAL FORM	CHOROTYPE	PHYTOSOCIOLOGICAL CLASS	ELLENBERG INDICATORS			
				L	T	U	N
<i>Anthemis maritima</i> L. (Asteraceae)	H SCAP	MEDIT	<b>EUPHORBIO PARALIAE-AMMOPHILETEA AUSTRALIS</b> Géhu & Rivas-Martínez in Rivas-Martínez, Asensi, Díaz-Garretas, Molero, Valle, Cano, Costa & Díaz 2011	11	9	1	1
<i>Convolvulus cneorum</i> L. (Convolvulaceae)	CH FRUT	STENOMEDIT	<b>ASPLENIETEA TRICHOMANIS</b> (Br.-Bl. in Meier & Br.-Bl. 1934) Oberdorfer 1977	11	10	2	1
<i>Helichrysum italicum</i> (Roth) Don (Asteraceae)	CH SUFFR	EURIMEDIT	<b>CISTO CRETICI-MICROMERIETEA JULIANAE</b> Oberdorfer ex Horvatić 1958 <b>HELICHRYSO—CRUCIANELLETEA MARITIMAE</b> (Sissingh 1974) Géhu, Rivas-Martínez & Tüxen in Géhu 1975 em. Biondi & Géhu in Géhu & Biondi 1994 <b>ROSMARINETEA OFFICINALIS</b> Rivas-Martínez, T.E. Díaz, F.Prieto, Loidi & Penas 2002 <b>THLASPIETEA ROTUNDIFOLII</b> Br.-Bl. 1948	8	8	4	2
<i>Thymus vulgaris</i> L. (Lamiaceae)	CH FRUT	STENOMEDIT	<b>CISTO CRETICI-MICROMERIETEA JULIANAE</b> Oberdorfer ex Horvatić 1958 <b>CISTO LADANIFERI-LAVANDULETEA STOECHADIS</b> Br.-Bl. in Br.-Bl., Molinier & Wagner 1940 <b>FESTUCO VALESIIACAE-BROMETEA ERECTI</b> Br.-Bl. & Tüxen ex Br.-Bl. 1949 <b>ROSMARINETEA OFFICINALIS</b> Rivas-Martínez, T.E. Díaz, F.Prieto, Loidi & Penas 2002	11	10	2	1
<i>Sedum album</i> L. (Crassulaceae) Control species	CH SUCC	EURIMEDIT	<b>ASPLENIETEA TRICHOMANIS</b> (Br.-Bl. in Meier & Br.-Bl. 1934) Oberdorfer 1977 <b>PARIETARIETEA JUDAICAE</b> Oberdorfer 1977 <b>SEDO ALBI-SCLERANTHETEA BIENNIS</b> Br.-Bl. 1955	11	X	2	1

All selected species were evaluated for their commercial availability in local nurseries to ensure that successful candidates could be readily implemented in future green roof projects in the region. This comprehensive selection approach aimed to identify species that are not only ecologically suited to Mediterranean extensive green roof conditions but also practical for implementation in urban greening projects.

### 2.4. Plants performance assessment

We evaluated plant performance through monthly systematic surveys from July 2023 to August 2024, monitoring three key parameters: health, reproductive stage, and soil coverage.

To assess individual health and reproductive stage, we relied on visual appearance scales with values from 0 to 5 as suggested by Dvorak et al., [50] and Rowe et al. [66]. In our experiment, we adapted Dvorak et al. [50] methodology by separately evaluating health and reproductive stages using individual scales. The specific parameters are shown in Table 2. We also compared the observed flowering periods with each species' natural flowering period according to Index Plantarum Flora Italicae (IPFI, 2007). We evaluated plant coverage according to the Braun-Blanquet scale [67], which is commonly used in the ecological assessment for vegetation analysis. We defined a unitary area as 30 × 30 cm plot around everyone, and we estimated by field observations the surface covered by each species.

**Table 2**

– Parameters used for plants visual assessment.

Values	* Plant health	* Reproductive stages	* Coverage rate (30 × 30 cm plot)
1	Few-to-no healthy leaves with no indication of new growth	Flower buds present	>5 % cover
2	Plants with browning leaves	Mix of buds and open flowers	5 - 25 % cover
3	Plants healthy but showing loss of vigorous growth	Full flowering	25 - 50 % cover
4	Plants with healthy green leaves	Senescent flowers	50 - 75 % cover
5	Plants with healthy green full foliage	Fruits present	75- 100 % cover

\* 0 was used for dead plants.

## 2.5. Data analysis and statistical analysis

Monthly mean scores were calculated to evaluate plant health for each species from July 2023 to August 2024. For reproductive stages, we assessed the monthly percentage distribution across different phases (buds, flowers, senescent flowers, and fruits) for each species, comparing these with their natural flowering periods. Vegetation coverage patterns were visualized through heatmaps over time for all species, based on monitoring of 40 specimens each of *Convolvulus cneorum*, *Helichrysum italicum*, *Anthemis maritima*, and *Thymus vulgaris*, and 20 specimens of *Sedum album* as control species. The color gradient in the heatmap represents coverage values from 0 to 5, where white areas indicate no coverage (0), light green represents low coverage values (1–2), medium green indicates moderate coverage (3), and dark green shows high coverage values (4–5).

Performance data were analyzed using R ([68], version 4.3.2). Month-to-month variations (delta values) and monthly means of health, reproductive status and coverage were calculated for each species. These variations were standardized using z-scores to enable comparison between different measurement scales. A composite performance index was created by averaging the z-scores of the three parameters. To account for uneven sampling, data were weighted by the inverse of the sample size. Finally, we conducted a comprehensive statistical analysis using linear mixed-effects models (LMMs) to account for the repeated measures design and individual plant variability. The analysis was performed in R using the packages lme4 for model fitting, lmerTest for significance testing with Satterthwaite's degrees of freedom approximation, and emmeans for post-hoc comparisons. Post-hoc pairwise comparisons between species were performed using estimated marginal means with Tukey's HSD adjustment for multiple comparisons.

All the results were visualized using ggplot2 [69].

## 2.6. Thermal assessment

To quantify differences in substrate microclimate conditions between different planting schemes and correlate them with observed plant performance and thermal regulation effects, we installed continuous monitoring sensors in the experimental vats. Xiaomi Plant Flower Care sensors measured substrate temperature (accuracy  $\pm 0.5$  °C), volumetric soil moisture (accuracy  $\pm 2$  %), and light intensity (accuracy  $\pm 5$  %) at 5 cm depth in both the Mediterranean species vats and the *Sedum album* control vat. Additionally, we deployed a weather station near the experimental roof to collect environmental meteorological data, including air temperature, humidity, wind speed, and precipitation. Data were recorded at hourly intervals throughout the experimental period, with particular focus on diurnal variations during peak summer conditions (July 2024).

To evaluate thermal performance, we measured ceiling temperatures during peak summer conditions (July 29th, 2024, at noon) using a FLIR E85 thermal camera, comparing areas beneath the green roof and the adjacent conventional concrete roof located at the same height. Within the green roof section, we conducted specific comparisons between three distinct areas: *Sedum*-only vat, vats with the four tested species, and unvegetated sections. For the conventional concrete roof, we collected measurements without distinguishing different sampling zones since the surface presents uniform characteristics throughout.

## 3. Results

### 3.1. Plant's health

Fig. 3 shows plant health analysis, based on foliage condition and growth parameters, revealing distinct performance patterns among species throughout the monitoring period. *Sedum album* (control species) maintained stable average values during the initial three months, followed by a sharp increase in November 2023. Subsequently, the

species exhibited a declining trend until February 2024, followed by rapid recovery in March that remained stable until May 2024, after which it declined steeply during the summer months.

*Convolvulus cneorum* demonstrated the highest values with remarkable stability throughout the monitoring period, exhibiting a slight increasing trend during spring months. *Thymus vulgaris* and *Helichrysum italicum* displayed similarly stable, elevated patterns throughout the year, with minor fluctuations but no significant decreases. *Anthemis maritima* maintained relatively stable values from July 2023 to May 2024, after which it showed progressive decline during the summer months.

Seasonal comparison revealed that while *Sedum album* and *Anthemis maritima* exhibited marked declining trends during the final summer period, *Convolvulus cneorum*, *Thymus vulgaris*, and *Helichrysum italicum* maintained stable patterns throughout all seasons.

### 3.2. Reproductive stages

The stacked bar graph visualization in Fig. 4 illustrates the monthly percentage distribution of different reproductive stages (buds, flowers, senescent flowers, and fruits) of the four selected Mediterranean species over the 14-month experimental period (July 2023 - August 2024). *Sedum album* exhibited no reproductive activity (flowers, buds, or fruits) during the study period and was therefore excluded from the analysis.

*Anthemis maritima* (Fig. 4a), which naturally flowers from April to November, displayed reproductive activity beginning in late spring (June 2023), with alternating flowering and fruiting stages. *Convolvulus cneorum* (Fig. 4b), with a natural flowering period from March to May, demonstrated reproductive activity both within and beyond its natural period, extending through August 2024, with an intermediate resting phase. *Helichrysum italicum* (Fig. 4c), which naturally flowers from April to September, produced fruits and flowers during its natural flowering period, with temporal variations in reproductive stage timing. *Thymus vulgaris* (Fig. 4d), despite its natural flowering period from February to October, remained largely in a vegetative state throughout most of the observation period, developing flower buds only in July 2024.

### 3.3. Coverage rate

The heatmap visualization in Fig. 5 shows the coverage patterns over time for each tested species. *C. cneorum* showed consistently high coverage, with most individuals maintaining strong performance throughout the observation period, as indicated by predominant dark green areas. *H. italicum* displayed variable coverage, with alternating areas of different green intensities across individuals. *A. maritima* presented a pattern characterized by areas of intense green and white spaces, indicating the presence of individuals with high coverage alongside no-coverage areas. *T. vulgaris* shows uniform light green coverage across the monitoring period. Finally, *S. album*, used as a control species, showed predominantly very light green shades and white areas throughout the study period, indicating low coverage values and absence of plants in several cases.

### 3.4. Plant performance

Performance z-scores (Fig. 6) showed temporal fluctuations across all species, with peak values observed in May 2024 for *S. album* and *T. vulgaris* (z-score  $\approx 2$ ), and minimum values recorded in December 2023 for *H. italicum* (z-score  $\approx -2$ ). The control species *S. album* exhibited frequent negative deviations from the mean performance, particularly in August 2023, December 2023, February 2024, and March 2024. *C. cneorum* displayed notable positive performance in August and October 2023, while showing negative peaks in December 2023 and March 2024. *A. maritima* exhibited its highest performance in September 2023 (z-score  $\approx 1.5$ ) followed by a sharp decline in the subsequent

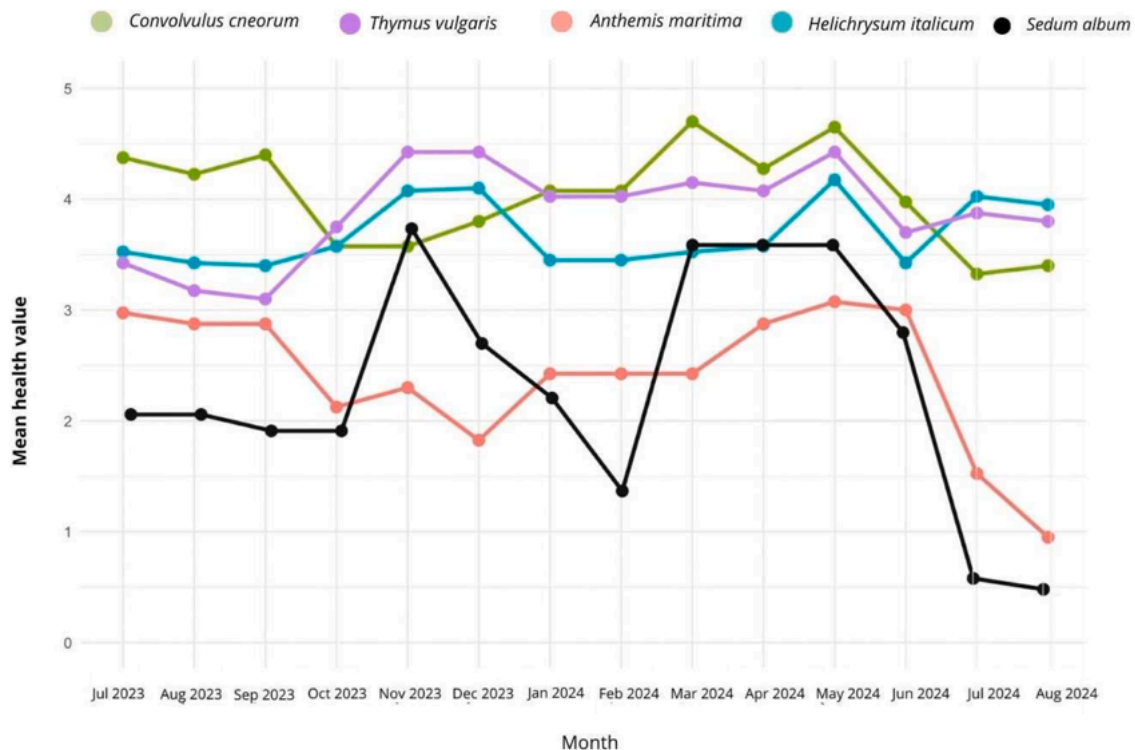


Fig. 3. - Health monitoring of the five tested species (*Convulvulus cneorum*, *Thymus vulgaris*, *Anthemis maritima*, *Helichrysum italicum*, and the control species in black *Sedum album*) from July 2023 to August 2024. The graph shows the trends in monthly mean health scores, with time (months) on the x-axis and mean health score (scale 0–5) on the y-axis, where 0 represents the poorest health condition and 5 represents optimal health.

month and showed consistent negative values in the summer months of 2024.

Analysis of individual parameters Reproductive stages showed the highest variability among the measured parameters, with notable peaks for *C. cneorum* and *H. italicum* in spring-summer 2024. Health measurements displayed sharp fluctuations in *S. album*, with pronounced peaks in September 2023 and May 2024. Coverage values generally showed more stable patterns across species, with moderate variations throughout the study period (Appendix 1).

All the mixed-effects models revealed highly significant main effects of species and significant Species  $\times$  Month interactions ( $p < 0.001$  for all models), confirming distinct temporal performance patterns among species. Post-hoc analyses comparing Mediterranean species to *S. album* revealed consistent patterns of superiority across performance metrics (Table 3). For plant health, three Mediterranean species (*C. cneorum*, *H. italicum*, and *T. vulgaris*) significantly outperformed *S. album*, while *A. maritima* showed no significant difference. Coverage rate performance demonstrated the most uniform superiority of Mediterranean species, with all four species significantly exceeding *S. album* performance. Reproductive stage performance revealed species-specific patterns, with *H. italicum* demonstrating exceptional reproductive success, followed by *A. maritima* and *C. cneorum*, while *T. vulgaris* showed no significant flowering advantage over *S. album* (Table 3).

### 3.5. First insight on thermal insulation

The thermal analysis in Fig. 7 presents two comparative scenarios labeled as [a] and [b], with precise temperature measurements recorded at multiple monitoring points.

Fig. 7a documents the green roof installation with five monitoring points (Sp1, Sp2, Sp3, Sp4, and Sp8) distributed across different vats. Points Sp1 and Sp2, monitoring the vat with the four tested Mediterranean species, recorded temperatures of 29.7 °C and 29.6 °C respectively. Points Sp3 and Sp4, positioned over the control vat with *Sedum album*,

both registered temperatures of 30.0 °C. Point Sp8, located on the walkway between vats, measured 30.3 °C.

Fig. 7b presents a reference concrete roof adjacent to the green roof installation. The regular photographic image shows the bare concrete surface labeled as *sp0*, while its corresponding thermal image displays the ceiling below. The thermal mapping of this section showed a temperature distribution with a minimum value of 33.2 °C, a maximum of 34.0 °C, and an average temperature of 33.2 °C. The temperature differential between the two roof sections ranged from 2.9 °C to 4.4 °C, with the green roof section consistently recording lower temperatures.

The continuous monitoring data provided additional insights into the microclimate conditions within the experimental vats (Fig. 8). Substrate temperature measurements revealed significant differences between the diurnal temperature profiles of the two planting schemes. The vats containing the four Mediterranean species (Points Sp1 and Sp2) consistently maintained lower substrate temperatures during peak daylight hours (10:00–17:00) compared to the *Sedum album* vat (Points Sp3 and Sp4), with the greatest difference (approximately 5 °C) observed at 15:00 reaching 37 °C (Fig. 8a).

Soil moisture readings showed that the Mediterranean species vats maintained slightly higher moisture levels throughout the day (average 20 % volumetric water content) compared to the *Sedum* vats (average 16 %), suggesting more efficient water retention or reduced evaporation rates under the denser Mediterranean plant canopy (Fig. 8b). Light intensity measurements indicated that the Mediterranean species provided more effective shading of the substrate, with peak light intensity values approximately 75 % lower than those recorded in the *Sedum* vats during midday hours (Fig. 8c).

## 4. Discussion

The experimental results demonstrate distinct adaptation and performance patterns among selected Mediterranean species on extensive green roofs, providing valuable insights into their applications. Our

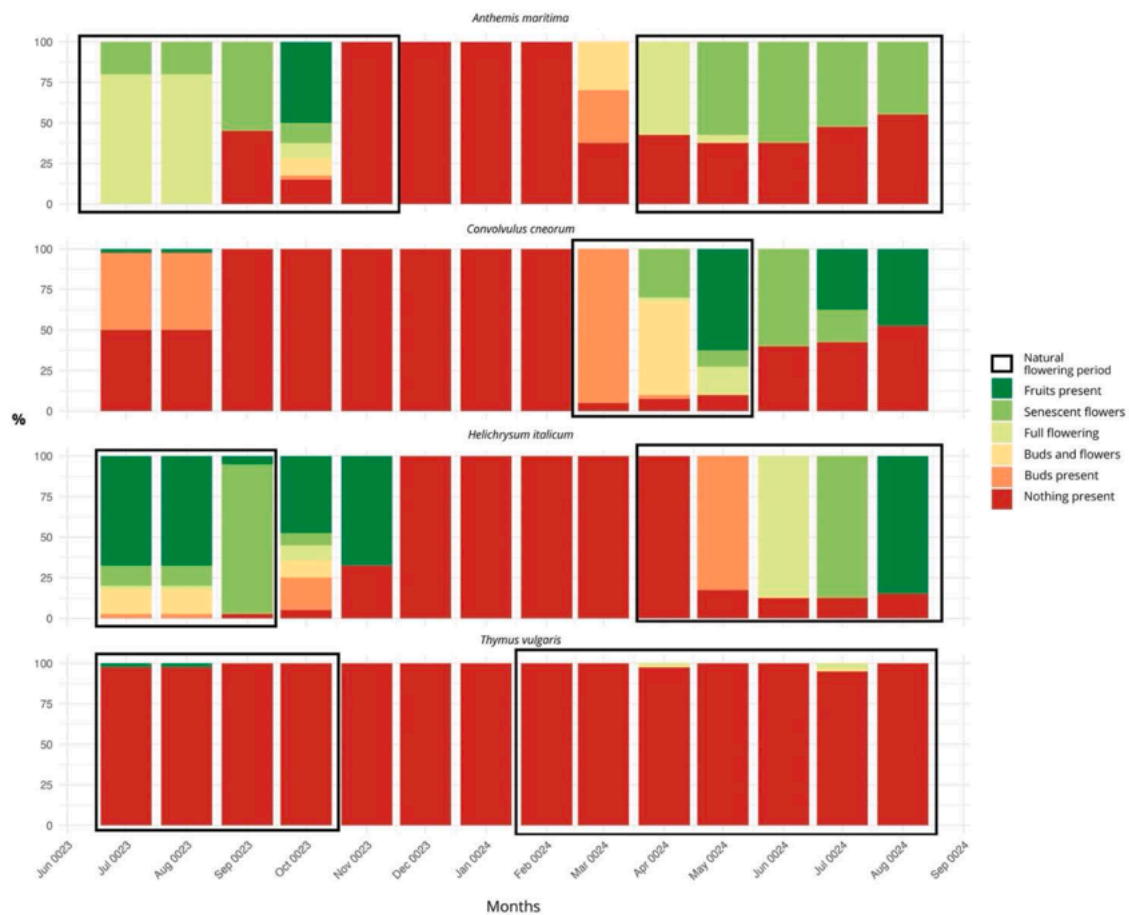


Fig. 4. - Phenological monitoring of *A. maritima* (a), *Convolvulus cneorum* (b), *Helichrysum italicum* (c), and *Thymus vulgaris* (d), from June 2023 to August 2024: monthly percentage distribution of reproductive stages with indication of natural flowering periods (black boxes).

findings contribute to the growing body of evidence supporting the use of regionally-adapted native species for green roof applications in Mediterranean climates. The significant differences in performance observed among the tested species highlight the importance of careful species selection beyond simple drought tolerance metrics [44,70].

Our findings reveal a clear performance hierarchy among the tested species, with *C. cneorum* and *H. italicum* demonstrating superior adaptability to Mediterranean green roof conditions compared to the conventional *Sedum album*. *Convolvulus cneorum* demonstrated the highest adaptation among the tested species to the roof conditions, with consistently high health scores throughout the monitoring period. Its non-glandular mechanical hairs and carbon cellular inclusions enhance water use efficiency and stress tolerance [43], functioning as protective barriers against insect herbivory and pathogens while reducing leaf temperature through ultraviolet radiation shielding [71–73]. Furthermore, the species showed extended reproductive activity beyond its natural flowering period, as well as high coverage throughout the 14-month observation period, demonstrating successful establishment. The superior performance of *C. cneorum* aligns with observations from similar Mediterranean species studies conducted in Greece, Spain, and Italy, suggesting that certain morphological and physiological traits typical of Mediterranean xerophytes may be particularly advantageous for extensive green roof conditions [45,49,61]. These include silvery pubescent leaves that reflect solar radiation, efficient water-use mechanisms, and extensive shallow root systems that effectively exploit limited soil moisture [43].

*Helichrysum italicum* showed variable but sustained health throughout the study period, aligning its reproductive stages with natural patterns. The observed mosaic pattern in coverage reflects its

natural adaptation to diverse Mediterranean habitats [74,75]. Despite this variability, *H. italicum* maintained moderate coverage, supporting Papafotiou et al. [49] findings regarding its viability for extensive green roof systems, albeit with careful consideration of substrate conditions. Its success can be attributed to several adaptive traits characteristic of Mediterranean shrubs, including small, aromatic leaves with reduced transpiration surfaces, high essential oil content providing thermal protection, and phenological plasticity allowing responsiveness to favorable growth conditions [76].

Mixed-effects statistical analyses robustly support this qualitative assessment, revealing highly significant main effects of Species and Species  $\times$  Month interactions across all performance metrics. Post-hoc analyses confirm that Mediterranean species significantly outperformed *Sedum*, challenging its widespread default use in Mediterranean climate regions and suggesting that biogeographical considerations should play a more central role in green roof plant selection strategies [36,44,77].

Both *Anthemis maritima* and *Thymus serpyllum* showed more varied but consistent performance than *Sedum*. *A. maritima* showed the widest range of performance scores, with the lowest values recorded during winter months but a heterogenic health score; only some individuals demonstrated remarkably successful adaptation with exceptional ground coverage. The extended flowering period observed in *A. maritima* has particular significance for urban biodiversity, potentially supporting urban pollinators during critical periods, as documented in several Mediterranean urban ecology studies [78]. Given that researchers have relatively understudied *A. maritima* in green roof applications compared to other Mediterranean species [40], these findings highlight a significant research opportunity.

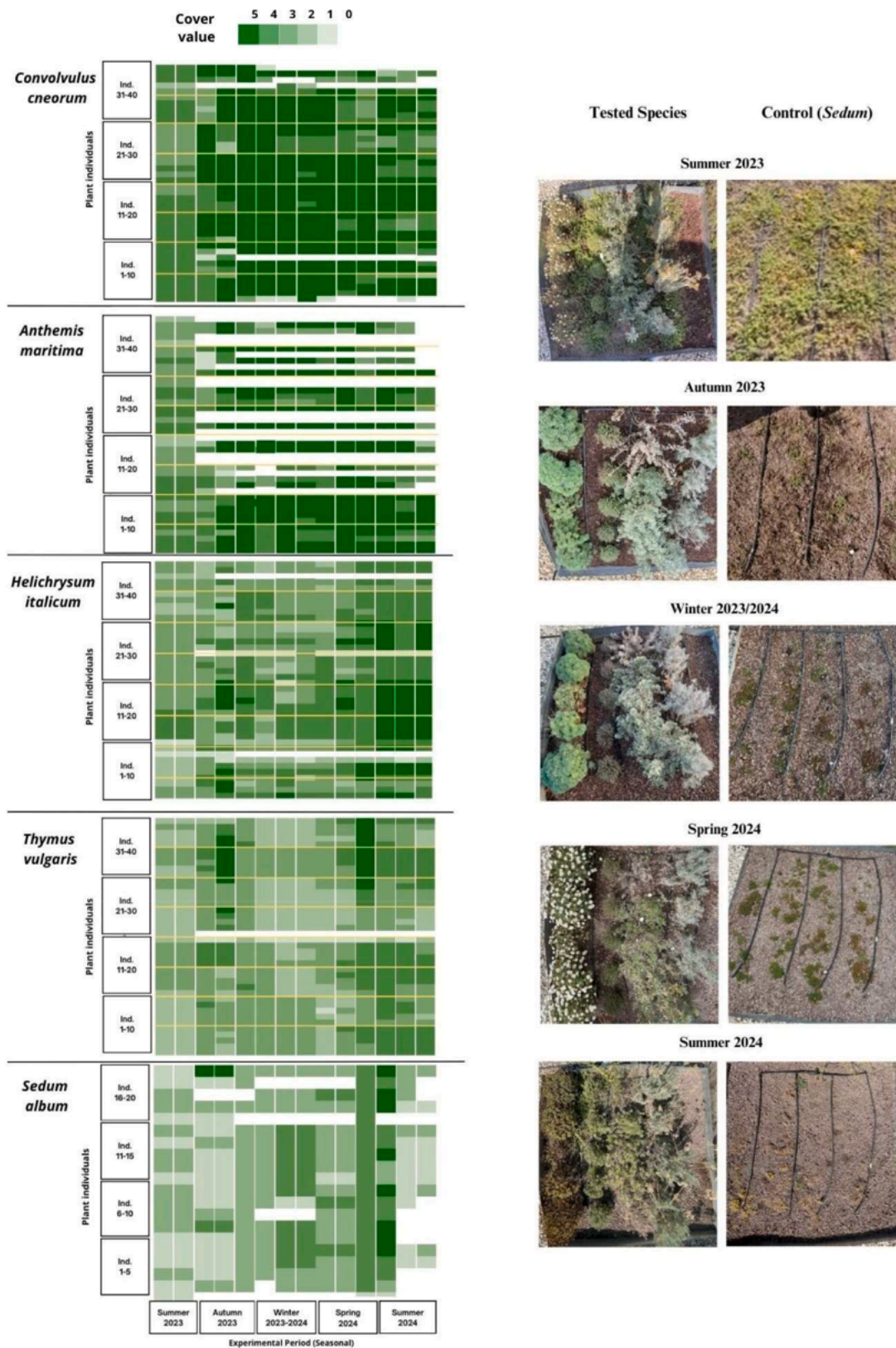
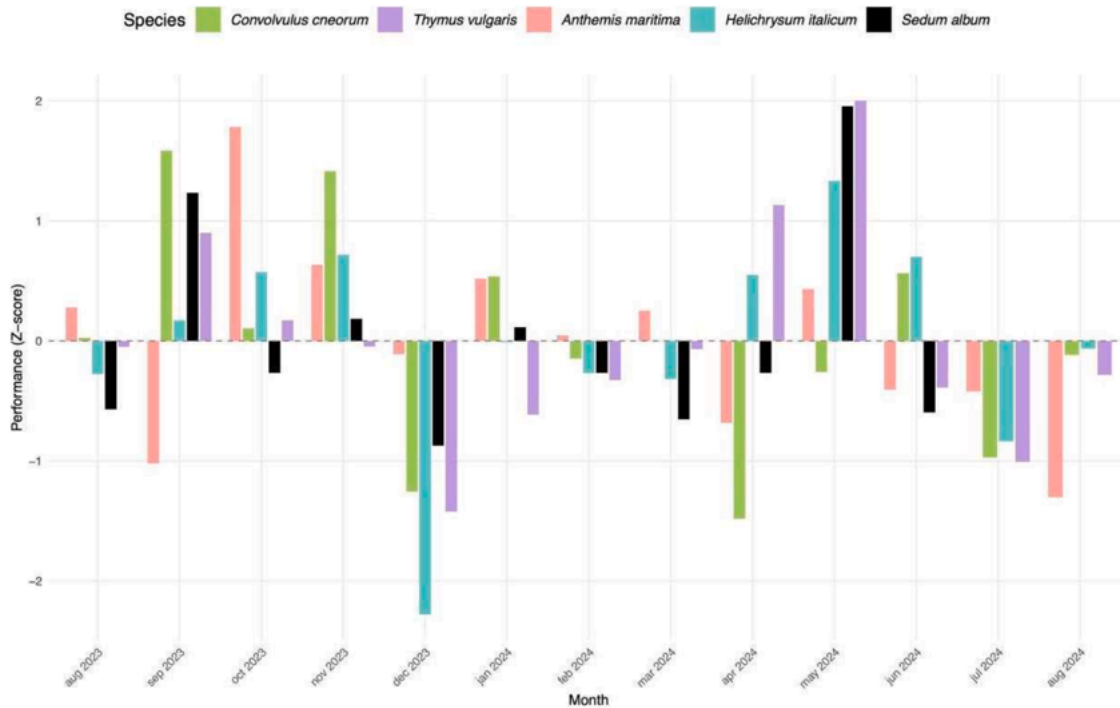


Fig. 5. - Vegetation coverage over time for five Mediterranean species (July 2023 - August 2024). The heatmap visualization shows the temporal evolution of coverage for 40 individuals of each main species (*C. cneorum*, *H. italicum*, *A. maritima*, and *T. vulgaris*) and 20 individuals of the control species (*S. album*). The intensity of green indicates the degree of coverage, where white represents no cover (0) and darker green represents greater coverage (V, five).



**Fig. 6.-.** Performance trends of the five species during the experimental period (August 2023 - August 2024). Overall monthly performance expressed in Z-scores based on health, reproductive stages and coverage, with values above 0 indicating above-average performance and values below 0 indicating below-average performance.

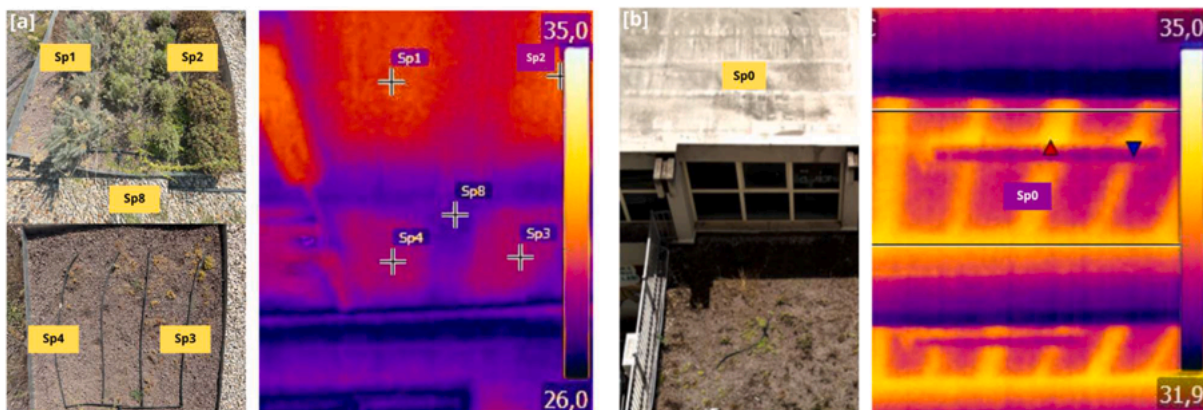
**Table 3**  
Summary of Mediterranean species performance relative to *Sedum album*.

Species	Plant health	Reproductive stage	Coverage rate	Overall Performance
<i>Convolvulus cneorum</i>	+1.61 ± 0.32***	+1.13 ± 0.14***	+2.45 ± 0.31 %***	Excellent
<i>Helichrysum italicum</i>	+1.27 ± 0.32***	+2.18 ± 0.14***	+1.57 ± 0.31 %***	Excellent
<i>Thymus vulgaris</i>	+1.46 ± 0.32***	-0.03 ± 0.14 <sup>ns</sup>	+1.15 ± 0.31 %**	Good
<i>Anthemis maritima</i>	-0.02 ± 0.32 <sup>ns</sup>	+1.66 ± 0.14***	+1.11 ± 0.31 %**	Moderate

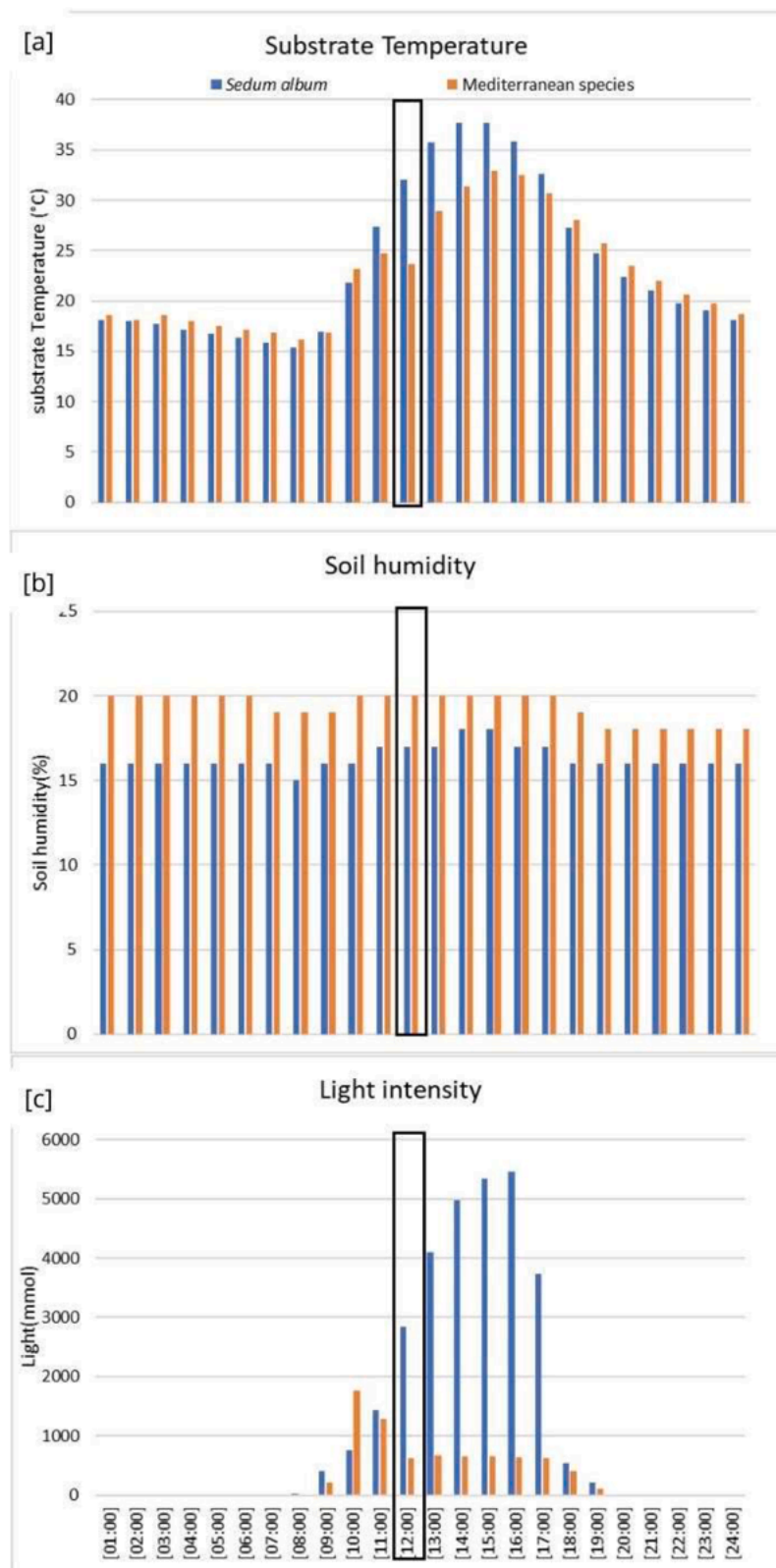
Significance levels: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , <sup>ns</sup> not significant. Values represent mean differences ± SE relative to *Sedum album*.

*T. vulgaris* demonstrated stable health patterns throughout the monitoring period, maintaining moderate but consistent coverage, aligning with findings by Walters et al. [79] who reported high survival rates (87.5–91.7 %) across different watering regimes. Despite its natural extended flowering period, it showed minimal reproductive activity. The modest but stable performance of *T. vulgaris* exemplifies an alternative adaptation strategy among Mediterranean species that may be particularly valuable in extensive green roof systems where minimal maintenance is desired [44].

*Sedum album*'s health showed significant fluctuations, with sharp declines during summer periods and no reproductive stages throughout the monitoring period. Our observations indicate that beyond substrate characteristics [46,55], additional critical factors influence its growth. Shortly after the start of the experiment, the *Sedum album* vat experienced significant coverage reduction, further complicated by invasion of *Euphorbia maculata*. Despite its documented ability to switch from C3 to CAM metabolism under water stress [80], the species showed sensitivity



**Fig. 7. -** Thermal analysis comparison: [a] green roof vats with monitoring points (Sp1, Sp2, Sp3, Sp4, Sp8) and corresponding ceiling thermal image; [b] reference concrete roof (Sp0) with associated ceiling thermal image. Thermal scale: 26.0 °C - 35.0 °C.



**Fig. 8.** - Diurnal patterns of (a) substrate temperature ( °C), (b) substrate moisture content ( %), and (c) light intensity ( μmol) in the Mediterranean species vats (Points Sp1 and Sp2, orange bars) and *Sedum album* vat (Points Sp3 and Sp4, blue bars) on July 29th, 2024.

to high temperatures, aligning with recent findings by Richards et al. [54] who projected increasing vulnerability of *S. album*-based installations under future climate scenarios. Our findings suggest that while *Sedum* species may provide adequate performance in temperate

regions with moderate summer temperatures, they may face significant challenges in Mediterranean and other hot climate regions, particularly as global temperatures continue to rise. The vulnerability to high temperature stress observed in our study suggests that even

drought-adapted succulent species have thermal tolerance thresholds that may be exceeded in Mediterranean summer conditions.

These findings significantly inform green roof design in Mediterranean regions, demonstrating that success requires both careful species selection and understanding of species-specific growth patterns and stress responses. The superior performance of *C. cneorum* suggests that native xerophytes might offer more sustainable and effective alternatives to traditional green roof species, particularly in regions with similar climatic conditions. This aligns with the growing trend toward using locally adapted species that can provide multiple ecosystem services while requiring minimal resources for maintenance.

Green roofs provide particularly pronounced thermal benefits in Mediterranean climates, delivering significant cooling effects during hot summers and consequently improving building energy performance [56]. In Rome, Asdrubali et al. [24] documented a 50 % thermal resistance difference between green and conventional roofs, while Battista et al. [27] highlight that during summer, the peak power energy could be reduced up to 10.8 % and the cooling demand up to 16.1 % with the adoption of green roof. Although the initial thermal performance assessment was conducted as a single midday measurement during maximum solar radiation and ambient temperatures, the continuous substrate monitoring provides supporting evidence of the sustained cooling effect throughout the day.

Our findings revealed significant thermal benefits of the green roof with temperature reductions of 2.9–4.4 °C under peak summer conditions (average ambient temperature 31 °C, maximum 38 °C) compared to the adjacent concrete roof section. However, temperature patterns varied only modestly across the roof installation.

The areas planted with the four Mediterranean species showed slightly lower temperatures compared to the *S. album* control vat, correlating with variations in plant coverage and canopy characteristics, as evidenced by the continuous monitoring data of substrate conditions (Fig. 8a). The slightly higher soil moisture levels maintained (Fig. 8b) and the significant reduction in light penetration to the substrate (Fig. 8c) in the Mediterranean species vats demonstrate more efficient water retention and the shading effect provided by these species. This effective shading, particularly by *C. cneorum* and *H. italicum* with their broader leaf surfaces and denser growth habits, directly contributes to lower substrate temperatures, which in turn influences the thermal performance of the entire green roof system. This improved moisture retention not only supports plant health during drought conditions but also enhances evaporative cooling effects, contributing to the thermal regulation capacity of the system.

These findings align with previous research demonstrating that green roofs can reduce internal building temperatures, as shown by Lei et al. [81] reporting that green roofs have little insulation effect in winter but a significant cooling effect in summer, decreasing indoor temperature by up to 4 °C compared to bare roofs. Based on our observed ceiling temperature reductions, we can provide a preliminary estimation of potential energy savings for buildings utilizing such green roof systems according to Jim and Tsang's [82] and Olivieri et al. [83]. Our findings align with research demonstrating that certain plant species provide up to 20 % greater energy savings through superior evapotranspiration and shading, and that well-designed green roofs in Mediterranean coastal climates reduce summer cooling needs by up to 60 % compared to conventional roofs. Specifically, our findings align closely with Battista et al. [27], suggesting that green roof areas with Mediterranean species could potentially provide cooling energy savings at the upper end of the 14–16 % range compared to conventional roofing, while areas with *Sedum album* might deliver more modest savings of 8–10 %.

While these are preliminary estimates based on empirical correlations rather than building-specific simulations, they indicate the significant potential energy benefits of appropriate species selection for green roofs in Mediterranean climates. Actual energy savings in real-world applications would depend on multiple factors including

building construction, insulation levels, HVAC system efficiency, occupancy patterns, and climate variables beyond the parameters measured in our study.

Finally, the long-term thermal performance of the green roof system after a decade demonstrates the durability and effectiveness of extensive green roof installations in Mediterranean climates. While plant species needed periodic replacement over the years, the successful establishment of these Mediterranean species suggests that appropriate species selection can help maintain the thermal benefits of green roofs while potentially reducing maintenance requirements and associated costs [56]. This finding underscores the importance of species selection in creating sustainable and cost-effective green roof solutions for Mediterranean regions, contributing to both building energy efficiency and urban heat island mitigation [84].

## 5. Future research direction

Based on the promising performance of the tested Mediterranean species, several important research directions emerge for expanding our understanding of their potential contributions to building energy efficiency:

1. Exploration of optimal plant species combinations that maximize both biodiversity benefits and energy-saving potential through year-round thermal regulation.
2. Investigation of the interactions between plant species characteristics (leaf morphology, evapotranspiration rates, coverage patterns) and their impact on building energy performance through controlled experimental studies combined with dynamic energy modeling.
3. Assessment of the long-term thermal regulation performance of Mediterranean species under projected climate change scenarios, including increased drought frequency and heat stress conditions.
4. Evaluation of the cost-effectiveness of different Mediterranean species selections by balancing installation and maintenance costs against projected energy savings over the roof lifespan.

## 6. Conclusion

Our comprehensive evaluation reveals that Mediterranean species significantly outperform conventional green roof vegetation in challenging Mediterranean climates, with *Convolvulus cneorum* and *Helichrysum italicum* demonstrating superior adaptation, sustained coverage, and extended reproductive activity compared to traditional *Sedum album*. These native species maintained consistently higher health scores and greater coverage throughout the 14-month monitoring period while contributing to substantial temperature reductions during peak summer conditions.

Thermal analysis demonstrated ceiling temperature reductions of up to 4.4 °C compared to conventional roofing during peak summer conditions, indicating significant potential for building energy savings. Future research should implement comprehensive thermal monitoring to fully characterize diurnal and seasonal performance patterns.

These findings fundamentally challenge the widespread default use of *Sedum album* in Mediterranean regions and establish the critical importance of biogeographically-informed species selection for green roof installations. The successful establishment and superior performance of these Mediterranean perennials provide evidence-based solutions for developing climate-adapted urban green infrastructure that simultaneously enhances biodiversity, improves thermal regulation, and reduces maintenance requirements in water-limited environments.

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### Ethical standards

Not applicable.

### CRediT authorship contribution statement

**Amii Bellini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Flavia Bartoli:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Luca D’Amato:** Formal analysis, Data curation. **Roberto Casalini:** Methodology, Data curation. **Giulia Caneva:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2025.113285](https://doi.org/10.1016/j.buildenv.2025.113285).

### Data availability

Data will be made available on request.

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