Long term experimental analysis of thermal performance of extensive green roofs with different substrates in Mediterranean climate

Comentado [MP1]: Reviewer 3 Comment 1: The title does not appropriately indicate the actual scope and orientation of the study. It could be modified to read "Experimental analysis of thermal performance of extensive green roofs with different substrates in Mediterranean climate".

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ABSTRACT

Comentado [MP2]: Reviewer 3: Comment 2: The Abstract could be revised to present the following issues in a proposed sequence: Field of study, research questions, study area, research methods (including experimental design), pertinent results, main conclusion, key applications. Abbreviations and specific terms that readers may not understand can be avoided. If not, they should be explained.

Green roofs are passive construction systems that can contribute to reduce the energy demand of buildings and achieve the European goal of nearly zero energy buildings. The main objective of this work was to determine experimentally the thermal performance of extensive green roofs with different substrates, compared to a traditional gravel ballasted roof. Hence, a study on the annual reduction of energy demand throughout two years warmer than average years, 2016 and 2017, and a dynamic analysis based on decrement factor, DF, time lag, TL, cooling potential, CP, for these three green roofs were carried out.

The results showed that significant reductions of DF and increases of TL and CP were achieved, especially in the green roof with 100% of commercial growing medium substrate. Annual reductions of energy gains and losses were obtained in the three green roofs, with annual average reductions of 66% and 63%, respectively, compared to the traditional roof. These results were mainly related to the composition of the substrates, their capacity to retain water and the quantity of vegetation in each plot. This study indicates that the use of green roofs contributes significatively to reduce the energy demand of existing buildings under warm climatic conditions.

Keywords: green roofs; energy demand; time lag; decrement factor; cooling potential

Nomenclature	
C_{cover}	cloudiness factor of the sky
CP	cooling potential [ºC]
DF	decrement factor [dim]
E	East
F_{gnd}	view factor from surface to ground
F_{sky}	view factor from surface to sky
H	heat flux [W m^{-2}]
h_c	mean convective heat transfer coefficient [W m^{-2} K^{-1}]
$h_{c,f}$	foliage convective heat transfer coefficient
$h_{c,s}$	soil convective heat transfer coefficient
h_o	heat transfer coefficient by radiation and convection at the outer surface [W m^{-2} k^{-1}]
h_r	mean radiative heat transfer coefficient [W m^{-2} K^{-1}]
LAI	leaf area index [dim]
nZEB	nearly zero energy buildings
P	plot
RF	rain fall [mm/h]
RH	relative humidity [%]
SR	solar radiation [W m^{-2}]
t	time [h]
T	temperature [ºC]
T_{hs}	average temperature between the plot surface temperature and the sky temperature [K]
TL	time lag [h]
W	West
VWC	volumetric water content [m^3 m^{-3}]
WD	wind direction [º]
WS	wind speed [m s^{-1}]
Greek letters	
ΔR	infrared radiation difference between surface and sky and surroundings [W m^{-2}]
α	product of the solar absorptance of the exterior surface and the rate of total solar radiation incident per unit area upon surface [W m^{-2}]
α_o	solar absorptance of exterior surface
σ	Stefan-Boltzmann constant
σ_f	fractional vegetation coverage
ε	infrared emittance of surface
ε_0	emittance of the clear sky
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
Subscripts	
a	air
amb	ambient air
e	exterior

Comentado [MRdAS3]: Añadir CDW y RA

Comentado [FCM4]: Reviewer 1 Comment 8: How were the various thermal transfer coefficients selected (alpha, 0, hc, hr)? There is a citation, but the reader would like to see the values selected and the basis for this selection.

Comentado [MRdAS5]: Unidades W/m2 K

Comentado [MRdAS6]: Añadir unidades W/m2 K

Comentado [MRdAS7]: K

Comentado [MP8]: Reviewer 3 Comment 22: The term “nZEB” could be added to the Nomenclature list.

Comentado [MRdAS9]: Unidades W/m2 K4

E	East
g	ground surface
Glob,H	global on the horizontal axis
i	interior
min	minimum value
max	maximum value
n	probe number
sa	sol air
sky	sky
W	West

1 INTRODUCTION

EU Directives [1,2] reinforce the goal of reducing energy consumption and introduce the concept of nearly zero energy buildings (nZEB) for the retrofitting of existing buildings and the construction of new buildings. An nZEB is a building that has a very high performance, with constructive systems of low environmental impact combined with installations that promote the use of renewable energies [3,4].

One of the possible passive construction systems of low environmental impact are green roofs. Some of the advantages of a green roof are that it has a good thermal insulation capacity, retains meteoric water, absorbs CO_2 and local noise pollution and minimises the heat island effects in cities [5–7]. Green roofs ensure less energy losses in winter and the maintenance of the internal temperature in summer [8]. There are three types of green roof: intensive, semi-intensive and extensive. An intensive green roof usually has a higher thickness, between 150 and 400 mm, and the plant species used require a lot of maintenance and irrigation [9]. A semi-intensive green roof needs periodically maintenance and irrigation and has a thickness of 120-250 mm, while an extensive green roof is used mainly to cover large non-walkable roofs, has a thickness of 60-200 mm and the plant species require low maintenance [9]. The present work focused on extensive green roofs.

Previous research studies on extensive green roofs analysed experimentally and numerically their behaviour under different climatic conditions. An extensive green roof was studied in the cool

Comentado [MP10]: Reviewer 3. Comment 3: The Introduction section could include more literature review on green roof thermal performance in the tropical and subtropical regions, and the pertinent long-term studies regardless of the location of study areas.

wet climate of the Pacific Northwest [10], showing the necessity of plants that retain a great quantity of water to counter the environmental constraints imposed by regional climate. In tropical climate, green roofs showed good thermal benefits and urban heat island mitigation potential [11,12]. Other research focused on subtropical climate, showing the importance to choose droughts tolerant plants [13] and a high deep of the substrate [14], to obtain good thermal benefits. Some authors achieved a reduction of the surface temperature of a bare rooftop for subtropical climatic conditions [15], although the relative humidity affected negatively the reduction of surface temperature. Long term studies about thermal performances of green roofs in subtropical climates showed that the best cooling effects were obtained in summer. However, an improve of the thickness of substrate layer helped to reach better insulation, both in summer and winter [16]. Other works focused on weekly studies of green roofs in Mediterranean climate [17,18] achieving suitable reduction of the total transferred energy. A long term study in Mediterranean climate showed the hydrological efficiency of the green roofs as effective systems to control the volume of rainfall [19].

Different types of substrates in extensive green roofs were studied by other authors. Commercial substrates showed to be very suitable for these type of installations [20,21]. Other studies analysed the performance of extensive green roofs with substrates composed of low-cost and waste materials, such as materials from the construction sector, to reduce their economic costs, achieving acceptable performances [22–24]. In other studies, it was seen that the amount of water in the substrate helps to minimise the cooling demand in summer [25,26].

The overall performance of extensive green roofs has been studied from several dynamic parameters. Many authors studied the heat flux through the layers of the roof as a performance parameter [27,28], where they obtained significant reductions compared to traditional roofs. The cooling potential of the surface temperature of the green roof was another dynamic parameter analysed. This parameter was related to the mitigation of the effects of urban heat islands [29,30]. Two dynamic parameters used to study other passive construction systems, such as green façades, are time lag ,TL, and decrement factor, DF, [31,32]. Both parameters were used to study the heat storage capabilities of any materials and the reduction of energy demand [32]. Recently, these parameters were studied for a green roof with different plants during a summer week for the climatic conditions in the south of Italy [33], achieving an increase of TL and a reduction of DF in respect to a roof with only substrate.

Most of the previous studies carried out weekly analyses of green roofs. However, it would be interesting to evaluate the thermal performance of green roofs with different substrates over a long period of time.

The main objective of this work was to determine the thermal performance of three green roofs with different substrates for the retrofitting of existing buildings, compared to a traditional gravel ballasted roof. The substrates used were a combination of different percentages of commercial growing medium and recycled construction materials. Hence, several dynamic parameters were studied for each roof, such as decrement factor, DF, time lag, TL, sol-air temperature, T_{sa}, cooling potential, CP, and annual reduction of energy demand. The green roofs were installed in an office building at the University of Córdoba (Spain) and studied throughout two warmer than average years, 2016 and 2017, in Córdoba (Spain).

2 METHODOLOGY

2.1 Climatic conditions and degree days

The University of Córdoba is located in Southern Spain, where the climatic conditions are typically Mediterranean, defined as subtype Csa dry-summer subtropical, according to Köppen-Geiger climate classification [34]. Córdoba has relatively mild winters and very warm summers. The daily and yearly temperature fluctuations are very high. Summers tend to be dry with less than one-third of the precipitation of the wettest winter month. This study was developed in the period 2016-2017. The monthly average temperatures from 2011 to 2015 and from 2016 to 2017 in Córdoba are shown in Fig. 1. It can be observed that the average temperatures from 2016 to 2017 increased 0.72 ºC compared to the previous 15 years, 2001-2015. The greatest difference between the monthly average temperatures was obtained in June, 1.4ºC. The monthly average maximum and minimum values and other significant climatic parameters of 2016 and 2017 are reported in Table 1.

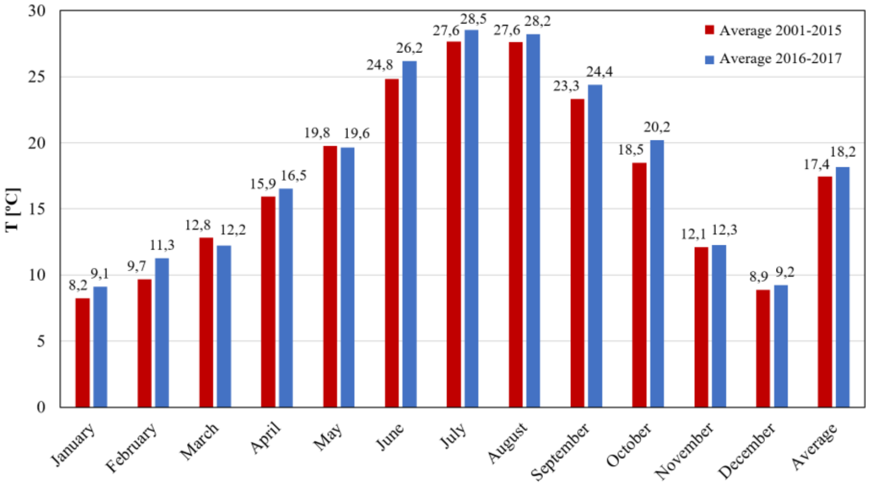


Fig. 1. Monthly average temperature values from 2011 to 2015 and from 2016 to 2017 in Córdoba, Spain.

Table 1. Climatic data of Córdoba, 2016 and 2017.

Comentado [MP11]: Reviewer 2 Comment 4: In the description of the climatic conditions of the study area, the potential evapotranspiration (PET) data could be included.

Year 2016	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Monthly average temperature	ºC	10.6	10.9	11.4	15.7	18.6	24.9	29.1	28.5	24.9	19.6	12.5	10.4	18.1
Maximum monthly average temperature	ºC	15.7	16.4	19.0	22.0	25.1	33.1	37.3	36.9	33.0	26.5	18.4	16.5	25.0
Minimum monthly average temperature	ºC	6.4	5.6	4.5	10.0	12.6	16.3	20.5	20.2	16.8	14.2	8.1	6.2	11.8
Monthly average rainfall	mm/month	59.6	42.6	30.2	115.4	92.4	0.2	0.4	0.2	3.0	84.0	142.2	469.0	86.6
Number of rainy days	days	19.0	12.0	13.0	12.0	11.0	1.0	1.0	1.0	1.0	10.0	15.0	24.0	10.0
Monthly average solar radiation on the horizontal surface	MJ/m^2	7.7	10.3	17.2	19.5	22.2	28.1	27.5	25.7	21.0	13.9	9.5	8.7	17.6
Reference evapotranspiration	mm	1.2	1.8	2.8	3.9	5.5	6.7	7.6	6.7	4.5	2.8	1.5	1.1	3.8
Year 2017	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
Monthly average temperature	ºC	7.6	11.7	13.1	17.4	20.7	27.4	28.0	27.9	23.9	20.8	12.1	8.1	18.2
Maximum monthly average temperature	ºC	15.4	17.3	20.8	25.9	28.4	35.9	37.0	36.4	32.6	30.0	20.8	15.0	26.3
Minimum monthly average temperature	ºC	2.0	7.1	6.7	9.7	13.3	18.4	18.6	18.9	15.1	13.8	6.0	3.2	11.1
Monthly average rainfall	mm/month	20.0	50.8	73.6	67.7	46.2	9.2	0.2	7.8	0.2	27.4	52.4	235.1	49.2
Number of rainy days	days	13.0	15.0	14.0	7.0	6.0	1.0	1.0	7.0	1.0	5.0	7.0	12.0	7.4

Monthly average solar radiation on the horizontal surface	MJ/m^2	10.6	9.9	16.8	22.4	25.8	29.3	27.9	24.4	20.9	15.7	11.0	8.5	18.6
Reference evapotranspiration	mm	1.2	1.7	2.9	3.9	5.1	7.3	7.7	6.6	5.0	3.1	1.7	1.1	3.9

2.2 Green roof experimental setup

An existing office building constructed in 1956 located Lat 37.9º N, Long 4.7º W was selected for this study. The office building had a rectangular footprint (27.7 m length, 9.5 m width, 7 m height) and a flat roof, as shown in Fig. 2. There was not a climate control program in the building, therefore, the indoor air conditions were in free evolution.

Comentado [FCM12]: **Reviewer 1 Comment 3: What was the climate control program for the building? What were the set points?**

Reviewer 2 Comment 13: In the indoor space below the green roofs, was indoor air temperature monitored in addition to ceiling temperature.

Fig. 2. Aerial view of the building (before the green roof was installed) [35].

The experimental extensive green roofs were installed in May 2015. Six plots were located on the building roof with a surface of 14.78 m^2 each. One additional plot was used as the reference roof, Pref. The green roof plots layout is shown in Fig. 3. The roof did not have shadows of trees or other buildings and the main façade of the building faces South.

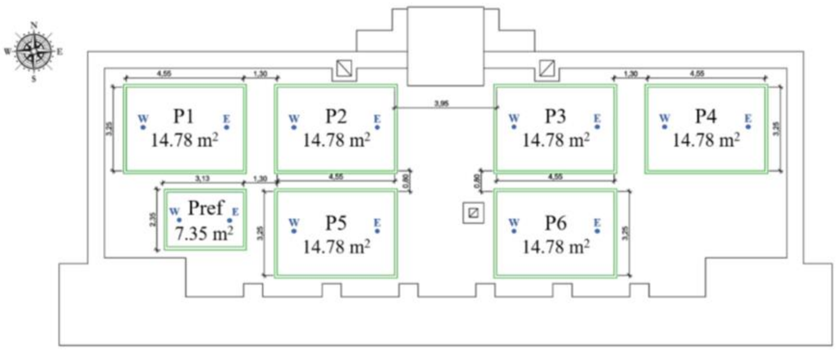


Fig. 3. Roof plan with green roof plots. *Note: E and W refer to East and West.

In this work, experimental results corresponding to P1, P2, P5 and Pref were analysed. The three green roofs consisted of the following layers, ordered from top to bottom: Mediterranean vegetation, growing medium (0.1 m), filter sheet, a drainage and water storage layer, a root-barrier waterproof layer, water proof membrane and a roof assembly (0.3 m concrete), see Fig. 4a and Fig. 5a. Pref consisted of the following layers, ordered from top to bottom: layer of gravel ballasted (0.03 m), waterproof membrane and roof assembly (0.3 m concrete), see Fig. 4b and Fig. 5b. The substrate composition in each plot was different, as indicated in Table 2, where different percentages (by volume) of commercial growing medium and recycled construction materials were used. Recycled aggregates construction material is defined as material derived from construction and demolition waste (CDW) of buildings. These new materials are then called Recycled Aggregates (RA). Their composition can be various in nature, depending on the origin of the waste. Generally, they are composed of different percentages of ceramic particles, concrete, gypsum, etc. Extensive green roofs with fine mixed recycled aggregate as growth substrate could revalue construction and demolition wastes, which currently present low added value.

The properties of both materials are summarised in Table 3. These properties were obtained by UNE-EN 1097–06:2014 Standard. The granulometry was obtained according to the UNE-EN 933-1: 2012 Standard. The maximum granulometry of the commercial growing medium was 8 mm and of the recycled aggregates construction materials was 9 mm. The RA material was

Comentado [MP13]: Reviewer 1 Comment 2: What is meant by "recycled aggregates construction material?" What is their source? What is their pH (do they contain mortar and cement)?

Comentado [FCM14]: Reviewer 2 Comment 3: P1, P2, and P5 were treated with different growing medium compositions. The reason for selecting these growing medium compositions should be stated first, as well as the detail information of those growing medium.

Comentado [FCM15]: Reviewer 1 Comment 1: A description, along with physical and chemical data on the various media mixtures is needed. I would refer the authors to standard tests promulgated by FLL.

Reviewer 2 Comment 3: P1, P2, and P5 were treated with different growing medium compositions. The reason for selecting these growing medium compositions should be stated first, as well as the detail information of those growing medium.

prepared with a sand-sized granulometry. The values of pH and electrical conductivity of each substrate were 7.8 and 2.0 mS/cm for P1, 8.6 and 1.9 mS/cm for P2 and 9.4 and 1.7 mS/cm for P5.

Comentado [FCM16]: Reviewer 1 Comment 2: What is meant by "recycled aggregates construction material?" What is their source? What is their pH (do they contain mortar and cement)?

Table 2. Growing media composition of experimental green roof plots.

Plot	P1	P2	P5
Commercial growing medium	100%	75%	50%
Recycled aggregates construction materials	0	25%	50%

Table 3. Properties of the used materials.

Comentado [FCM17]: Reviewer 1 Comment 1: A description, along with physical and chemical data on the various media mixtures is needed. I would refer the authors to standard tests promulgated by FLL.

Reviewer 2 Comment 3: P1, P2, and P5 were treated with different growing medium compositions. The reason for selecting these growing medium compositions should be stated first, as well as the detail information of those growing medium.

	Commercial growing medium	Recycled aggregates construction materials
Saturated-surface-dry density [g/cm^3]	1.5	2.6
Dry density [g/cm^3]	1.1	2.5
Dry bulk density [g/cm^3]	0.3	1.4
Water absorption [%]	41.3	3.6
pH	7.3-7.7	10.8
Electric conductivity [mS/cm]	2.0	1.7

Twelve autochthonous Mediterranean plant species were planted in P1, P2 and P5. These were selected by their adaptation to tolerate drought stress, intense lighting, extreme heat and shallow substrates, which are exactly the biological and ecological characteristics needed for green roofs in urban Mediterranean ecosystems. The species used were: Acinos alpinus, Bellis perennis, Brachypodium retusum, Cerastium tomentosum, Dianthus arenarius, Lobularia maritima, Lotus corniculatus, Paronychia argentea, Phagnalon saxatile, Sanguisorba minor, Sedum sediforme and Trifolium repens.

Comentado [FCM18]: Reviewer 2 Comment 4: Line, 128-131. The 12 species were planted in P1, P2, and P5. Were the three plots all be planted with the 12 species? at what percentage/density? The planting plan affects LAI and vegetation coverage

Reviewer 3 Comment 9: Please explain the choice of the 12 plant species used in the experiments. What are the justifications to use so many species within the rather small plots? How were the individual species mixed in the plots? Was each species planted systematically in rows or squares, or were the species planted in a random manner? What was the seedling size, and the planting density? How long did it take for them to establish? Was data collection started after full vegetation establishment?

The area of each plot was divided into 18 experimental micro-plots of 0.75 m^2. 12 plants were planted in each micro-plot, 1 unit of each selected species. The placement of the different species was not carried out randomly. It was based on the premise that all the species interacted with each other, in order to evaluate these interactions. The number of units planted in the available area of the plot resulted in a planting density of 15.34 plants/m^2, density very close to that recommended by the German Guideline FLL [36], 16 plants/m^2.

The experimental extensive green roofs were installed in May 2015. The experimental results were collected after obtaining all the vegetation coverage of each plot. The fractional vegetation coverage, σ_f, and the leaf area index, LAI, were estimated through direct measurements on each green roof plot, obtaining values of σ_f= 0.59 and LAI= 2 for P1, σ_f =0.56 and LAI= 1.7 for P2, and σ_f= 0.53 and LAI=1.5 for P5. These values were considered constant throughout the period studied. This method of direct measurement was based on obtaining the areas using the Image J software [37].

Comentado [FCM19]: Parte del Reviewer 1 Comment 6

Reviewer 2 Comment 5: What method was used to measure LAI?

Reviewer 1 Comment 6: It would be very helpful to see a plot of plant index for the three green roof systems over the experimental period. How does leaf index correlate with the performance. Only TL is referred to. Why aren't heat flux, CP and DF also affected?

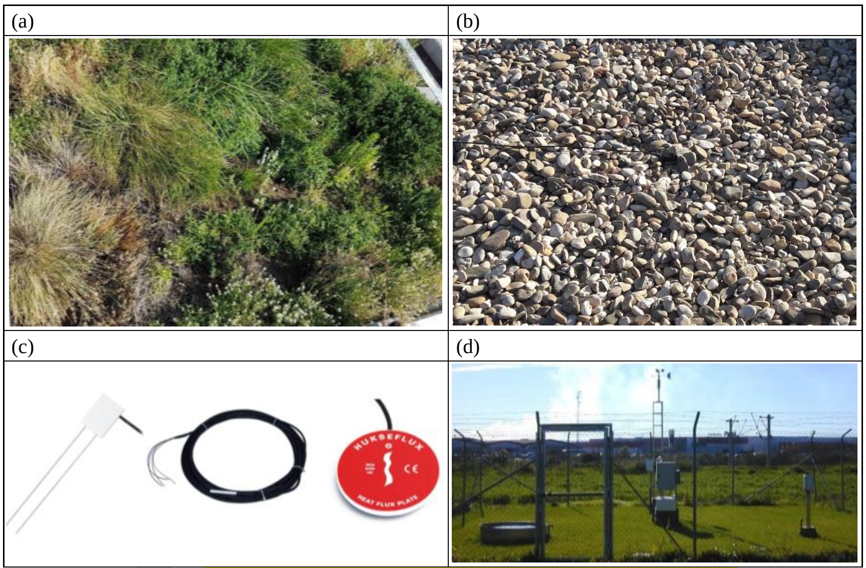


Fig. 4. Images of a) P1, b) Pref, c) probes used, d) weather station.

Comentado [FCM20]: Reviewer 3 Comment 7: Please add one or more photos showing the green roof plots with the vegetation and the instruments.

2.3 Description of monitoring system

Meteorological data were monitored by a weather station, placed near the experimental installation, see Fig. 4d. The data recorded were: ambient air temperature, relative humidity, rainfall, atmospheric pressure, speed and direction of the wind and solar radiation, see Fig. 4c. The specification of measuring devices, the type of sensor and its accuracy are shown in Table 4.

Comentado [FCM21]: Reviewer 3 Comment 12: As the specifications of the monitoring sensors have been summarized in Table 3, their descriptions in the text could be considerably shortened. It may not be necessary to repeat the factual information in the text

Two acquisition point (East and West) properly spaced from their edges to avoid boundary effects, were installed in P1, P2 and P5, for the monitoring of the main variables, see Fig. 3 and Fig. 5. In each acquisition point, along the vertical profile, five probes of temperature were installed. The temperature probes were located under the roof slab, $T_{W0,Pi}$ and $T_{E0,Pi}$, between the roof slab and the root barrier , $T_{W1,Pi}$ and $T_{E1,Pi}$, between the drainage layer and the bottom part of the growing media, $T_{W2,Pi}$ and $T_{E2,Pi}$, in the middle height of growing media, $T_{W3,Pi}$ and $T_{E3,Pi}$, and in the upper part of the growing media, $T_{W4,Pi}$ and $T_{E4,Pi}$, as shown in Fig. 5a.

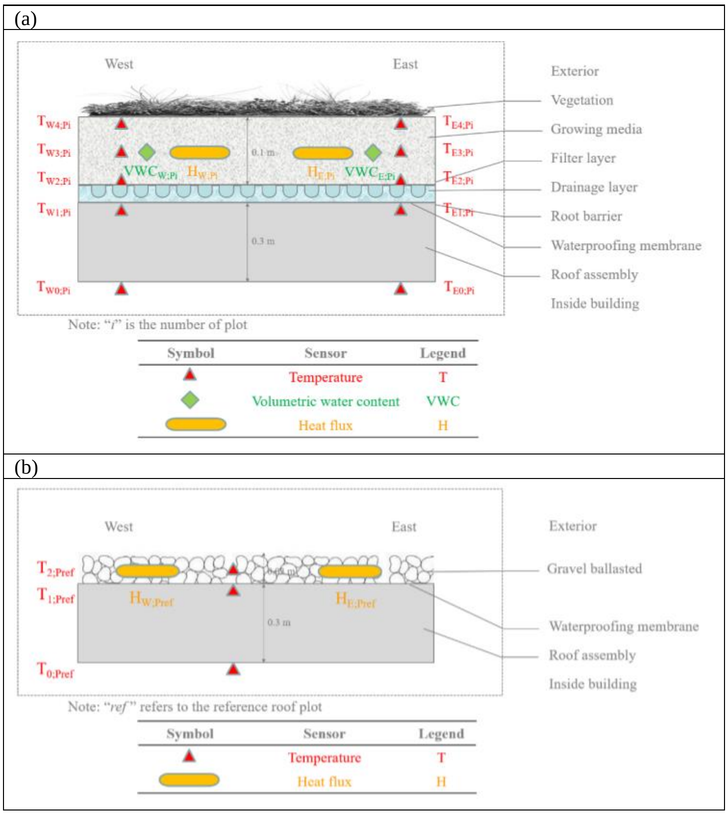


Fig. 5. Plots layers and sensors; a) P1, P2 and P5; where "i" is the number of the plot; b) Pref.

Volumetric water content, VWC, was measured using a water content reflectometer in each acquisition point, $VWC_{W,Pi}$ and $VWC_{E,Pi}$, as shown in Fig. 5a. Heat flux was measured using a heat flux plate in each acquisition point in the middle of the growing media, $H_{W,Pi}$ and $H_{E,Pi}$, as shown in Fig. 5a. Two acquisition points (East and West) were also installed in Pref to monitoring the main variables, Fig. 5b. In each acquisition point, along the vertical profile, three temperature probes were installed. The temperature probes were located under the roof slab, $T_{0,Pref}$, between the roof slab and the gravel ballasted layer , $T_{1,Pref}$, and in the upper part of the gravel ballasted, $T_{2,Pref}$, as shown in Fig. 5b. Heat flux was measured in Pref using a heat flux plate in each acquisition point in the middle of the gravel ballasted, $H_{W,Pref}$ and $H_{E,Pref}$, as shown in Fig. 5b. The characteristics of the equipment of the experimental installation are shown in Table 4.

Table 4. Equipment and variables measured in the experimental campaign.

Equipment	Models	Accuracy	Variable	Name	Unit	City
Thermistors	Campbell 109	±0,25ºC (-10 to 70 ^{0}C)	Temperature	T	[ºC]	Logan (USA)
Heat flux plate	Campbell HFP01	±5%	Heat Flux	H	[W/m^2 K]	Logan (USA)
Water content reflectometer	Campbell CS616	±2.5% (0 to 50%)	Volumetric Water content	VWC	[%]	Logan (USA)
Platinum resistance temperature	Vaisala HMP45C	0.2ºC (-40 to 70ºC)	Air temperature	Ta	[ºC]	Vantaa, (Finland)
Capacitive relative humidity	Vaisala HMP45C	2% (0 to 100%)	Air relative humidity	RH	[%]	Vantaa, (Finland)
Silicon photocell solar radiation	Campbell SP1110 pyranometer	5% (350 nm to 1100 nm)	Solar radiation	SR	[W/m^2]	Logan (USA)
Wind speed and direction sensor	RM Young 05103	1% (0 to 100 m/s) 3º (0 to 360º)	Wind speed and direction	WS WD	[m/s] [º]	Traverse (USA)
Rain gauge	Campbell ARG100	98% at 20 mm/h	Rainfall	RF	[m^3/m^3]	Logan (USA)

The green roof was equipped with a drip irrigation system managed by a time schedule module. The irrigation was provided during the warmest months in summer to prevent water stress in plants. The irrigation system operated twice a day in P1, P2 and P5, for 10 minutes and fed by 27 l each time.

A dedicated data acquisition system was used to sample the information of the sensors every 15 min. The experimental data was recorded for two years, from January 2016 to December 2017. The measured values were filtered and then, analysed in spreadsheets for time steps of 15 min. For the values measured at two points, East and West, $T_{n,Pi}$, VWC_{Pi} and H_{Pi}, a mean value was calculated, where n is the probe number with respect to Fig. 5 and Pi is P1, P2, P5 or Pref. These mean values were used to calculate the dynamic parameters, with the same time steps. Finally, daily average values were obtained for the dynamic parameters. Important hiatus was not produced during the period studied, less than 0.3% of the data collected, which were removed.

2.4 Dynamic variables used in the energy analysis

The experimental green roof analysis was evaluated according to several dynamic parameters used in previous studies [33,38]. The dynamic parameters evaluated were the following:

- Sol-air temperature, T_{sa}, which is defined as the outside air temperature which, in the absence of solar radiation, would give the same temperature distribution and rate of heat transfer

Comentado [FCM22]: Reviewer 2 Comment 6: Add irrigation plan. How much water was given?

Reviewer 3 Comment 16: The irrigation regime may have notable influence on the cooling performance of the green roofs. Please explain the time of the day when irrigation was applied, and how much water (estimated) was applied in each watering episode. The effect of irrigation could be added to the results and discussion sections.

Comentado [FCM23]: Reviewer 1 Comment 9: What was the time step for the recording and interpreting the measurements?

Reviewer 1 Comment 10: More discussion of the quality of the data. Was there a hiatus or excursion in the any of the data that would be relevant to interpreting the data?

Reviewer 2 Comment 8: Data treatment and analysis were not clear. Add a section to describe them.

Comentado [MRdAS24]: Normalmente cuando hay datos erróneos se eliminan y se interpola con los valores próximos para rellenar huecos en la base de datos.
Decir solo que se eliminan puede sonar raro.
Propondría algo así:
appropriate interpolation methods were used in order to fill the gaps of the data

Comentado [MP25]: Reviewer 3 Comment 15: The meaning of "sol-air temperature" could be defined for the benefit of readers who are not familiar with this term.

through a roof as exists due to the combined effects of the actual outdoor temperature distribution plus the incident solar radiation [39]. T_{sa} was calculated with Eq. (1) for a traditional roof [40]. This equation was characterized to calculate T_{sa} for plots with green roofs, Eq. (2), taking into account evapotranspiration contribution, according to [33,38].

$$T_{sa} = T_{amb} + \frac{\Delta R}{h_o} + \frac{\alpha}{h_o} \quad (1)$$

$$T_{sa} = \frac{h_c}{h_c + h_r} T_{amb} + \frac{h_r}{h_c + h_r} T_{sky} + \frac{\alpha}{h_c + h_r} \quad (2)$$

Where T_{amb} is the external air temperature; ΔR is the infrared radiation difference between surface and sky and surroundings, expressed by Eq. (3); h_o is the heat transfer coefficient by radiation and convection at the outer surface, expressed by Eq. (4); h_c is the mean convective heat transfer coefficient, expressed by Eq. (5); h_r is the mean radiative heat transfer coefficient, expressed by Eq. (6); α is the product of the solar absorptance of the exterior surface and the rate of total solar radiation incident per unit area upon surface expressed by Eq. (7); T_{sky} is the sky temperature, which was calculated considering the sky as a black body [41], expressed by Eq. (8).

$$\Delta R = \varepsilon \cdot \sigma \cdot (F_{sky} \cdot (T_{sky}^4 - T_{amb}^4) + F_{gnd} \cdot (T_g^4 - T_{amb}^4) \quad (3)$$

$$h_o = 10.08 + 10.8 \cdot WS \quad (4)$$

$$h_c = \sigma_f \cdot h_{c_f} + (1 - \sigma_f) \cdot h_{c,s} \quad (5)$$

$$h_r = \frac{\varepsilon_f \cdot \varepsilon_g}{\varepsilon_g + \varepsilon_f - \varepsilon_g \cdot \varepsilon_f} \cdot (4 \cdot \sigma \cdot T_{hs}^3) \quad (6)$$

$$\alpha = \alpha_o \cdot SR_{Glob,H} \quad (7)$$

$$T_{sky} = T_{amb} \cdot (\varepsilon_0 + 0.8 \cdot (1 - \varepsilon_0) \cdot C_{cover})^{0.25} \quad (8)$$

- Decrement factor, DF, is defined as the ratio between the maximum daily excursions of the internal and external temperature fluctuations [31], expressed by Eq. (9).

$$DF = \frac{T_{i,max} - T_{i,min}}{T_{e,max} - T_{e,min}} \quad (9)$$

Comentado [FCM26]: **Reviewer 1 Comment 8: How were the various thermal transfer coefficients selected (alpha, 0, hc, hr)? There is a citation, but the reader would like to see the values selected and the basis for this selection.**

Reviewer 2 Comment 9: Eq.1 and 2. Is ambient temperature measured by the weather station (line 137-)? Where was the weather station placed? What were the meteorological data used for? What were the values that be used in Eq. 1 and 2? Delta R? ho? hc? hr? 𝛼? Tsky?

- Time lag, TL, is defined as the time difference between the maximum peak of the internal temperature and the maximum peak of the external temperature for summer climatic conditions, expressed by Eq. (10), and the time difference between the minimum peak of the internal temperature and the minimum peak of the external temperature for winter climatic conditions, expressed by Eq. (11), [31].

$$TL_{summer} = t_{Ti,max} - t_{Te,max} \tag{10}$$

$$TL_{winter} = t_{Ti,min} - t_{Te,min} \tag{11}$$

DF and TL were evaluated considering $T_{sa,Pi}$ as the external boundary temperature for all the plots and $T_{1,Pi}$ as the internal boundary temperature for P1, P2 and P5, see Fig. 5a. $T_{1,Pref}$ was considered the internal boundary temperature for the reference plot, see Fig. 5b.

- Cooling potential, CP, is defined as the difference between the maximum internal boundary temperature of the reference plot and the maximum internal boundary temperature of the green roofs, according to Eq. (12).

$$CP = T_{1,Pref,max} - T_{1,Pi,max} \tag{12}$$

Where $T_{1,Pref,max}$ is the maximum slab temperature value for Pref and $T_{1,Pi,max}$ is the maximum slab temperature value for P1, P2 and P5. CP was only calculated for the considered summer period.

- Heat flux, measured in the growing medium in the plots with green roofs and in the gravel ballasted layer in the reference plot, see Fig. 5. The heat flux sensors were placed such that a positive and negative reading signifies heat entering and leaving the building, respectively.

3 RESULTS AND ANALYSIS

Three different green roof plots were studied throughout the years 2016 and 2017. The analysis of the experimental results for 2016 is presented in weekly, monthly and annual analysis to correctly understand the behaviour of the extensive green roof plots for the climatic conditions of Córdoba. Nevertheless, the analysis of the experimental results for 2017 is presented in annual analysis, because the monthly average temperature values were similar for both years.

3.1 Summer behaviour of the extensive green roof

A typical summer week was selected for the study of the summer behaviour of the green roof plots, analysing in depth the climatic conditions, the substrate temperature profile and the TL, DF and CP parameters.

The climatic conditions for the selected summer period, from 23/07/2016 to 29/07/2016, are shown in Fig. 6. The values of total horizontal solar radiation and external air temperature were similar for each day of the week, reaching peaks of 994 W/m^2 and 39.4 ºC, respectively, see Fig. 6a. It can also be observed a weekly oscillation of relative humidity between 14.5% and 73.7%, a weekly variation of wind speed between 0 m/s and 4.8 m/s and absence of rainfall, see Fig. 6b.

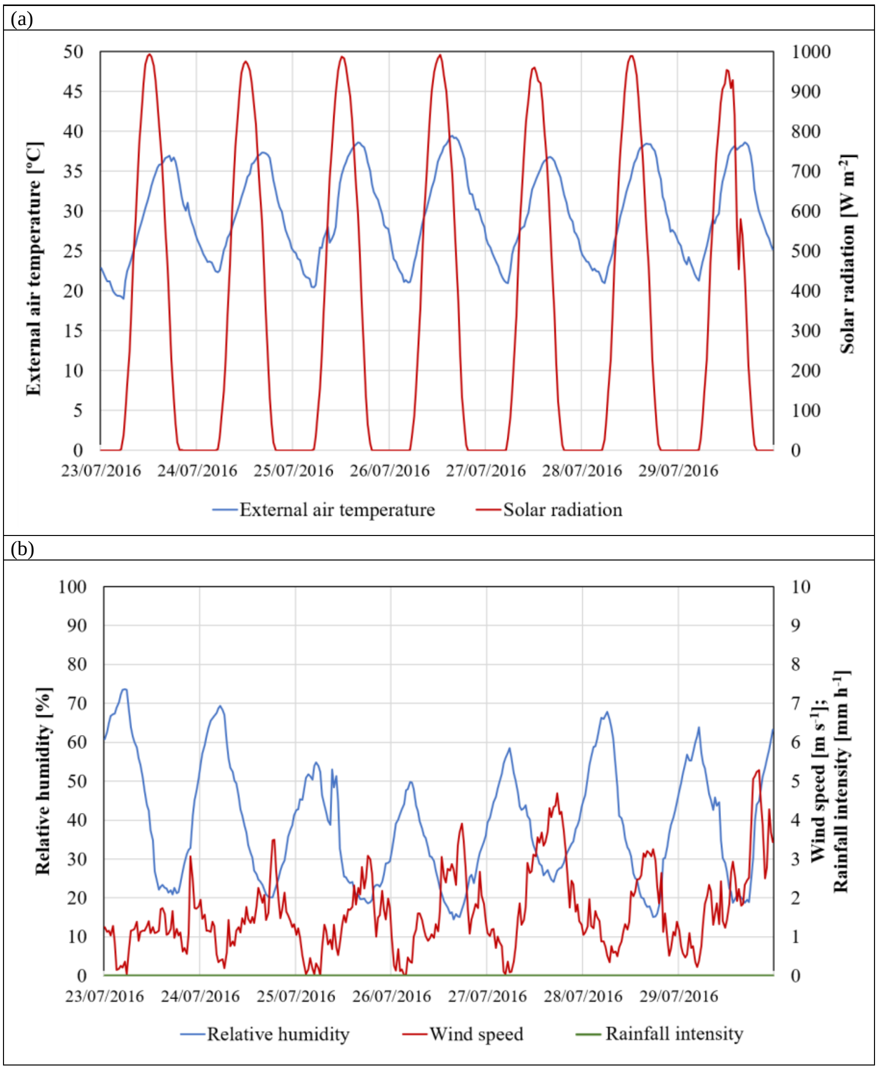


Fig. 6. Climatic conditions of the selected summer period. (a) Solar radiation and external air temperature. (b) Rainfall, windspeed and relative humidity.

Comentado [FCM27]: Reviewer 3 Comment 21: In Figure 5, the y-axis label "Rainfall" can be changed to "Rainfall intensity".

3.1.1 Analysis of the temperature profile and water content in the plots

The temperature values measured and sol-air temperature calculated, T_{sa}, for the four plots, and VWC in the substrates of P1, P2 and P5, for the selected summer period are shown in Fig. 7. The

T_{sa} and VWC values were obtained from the average value measured by the two probes located in the same horizontal profile. Regarding the water content in the substrate, it can be observed an increase in its value in the three green roofs when the irrigation was operating. For P1, VWC values oscillated between 18.3% and 26.4% during the week, with a weekly average value of 22.8%, see Fig. 7a. For P2, the variation was less than for P1, between 9.7% and 12.8%, with a weekly average value of 11.1%, see Fig. 7b, and finally, for P5, the oscillation obtained was between 14.1% and 17.9%, with a weekly average value of 15.9%, see Fig. 7c.

These results showed that the substrate of P1, with 100% commercial growing medium, managed to retain more water in summer than the rest of the plots, using the same amount of watering. The substrate of P2, with 75% commercial growing medium and 25% recycled construction materials, was the one that retained the least water, with values lower than the substrate of P5, with 50% commercial growing medium and 50% recycled construction materials, see Fig. 7b and 6c. It can also be seen that the maximum temperatures in the green roofs were achieved for T_4, measured in the upper part of the substrate, with values of 48.5 ºC, 55.7 ºC and 48.2 ºC for P1, P2 and P5, respectively. For the last days of the week, the highest T_4 values of the green roofs decreased as the water content in the substrate increased, especially in P1, see Fig. 7a, 6b and 6c. However, the highest $T_{2,Pref}$ values were stable throughout the week, because there was no irrigation and the highest external temperatures was also constant, see Fig. 6a. Therefore, these results show the relation between the substrate used and VWC.

The temperature values measured decreased according to the depth of the four plots. The minimum temperature values for the three plots with green roofs were obtained for T_1, measured below the drainage layer, oscillating between 27.6 ºC and 34.8 ºC for P1, see Fig. 7a, between 27.2 ºC and 35.9 ºC for P2, see Fig. 7b, and between 27.3 ºC and 33.6 ºC for P5, see Fig. 7c. For Pref, $T_{1,Pref}$ values variated between 30.1 ºC and 50.1 ºC.

Regarding T_{sa}, similar values were obtained for the three plots with green roofs, with maximum and minimum values of 60.0 ºC and 18.5 ºC, respectively. However, T_{sa} values for Pref increased significantly during the morning, up to 80.5 ºC, and decreased during the night, up to 16.0 ºC.

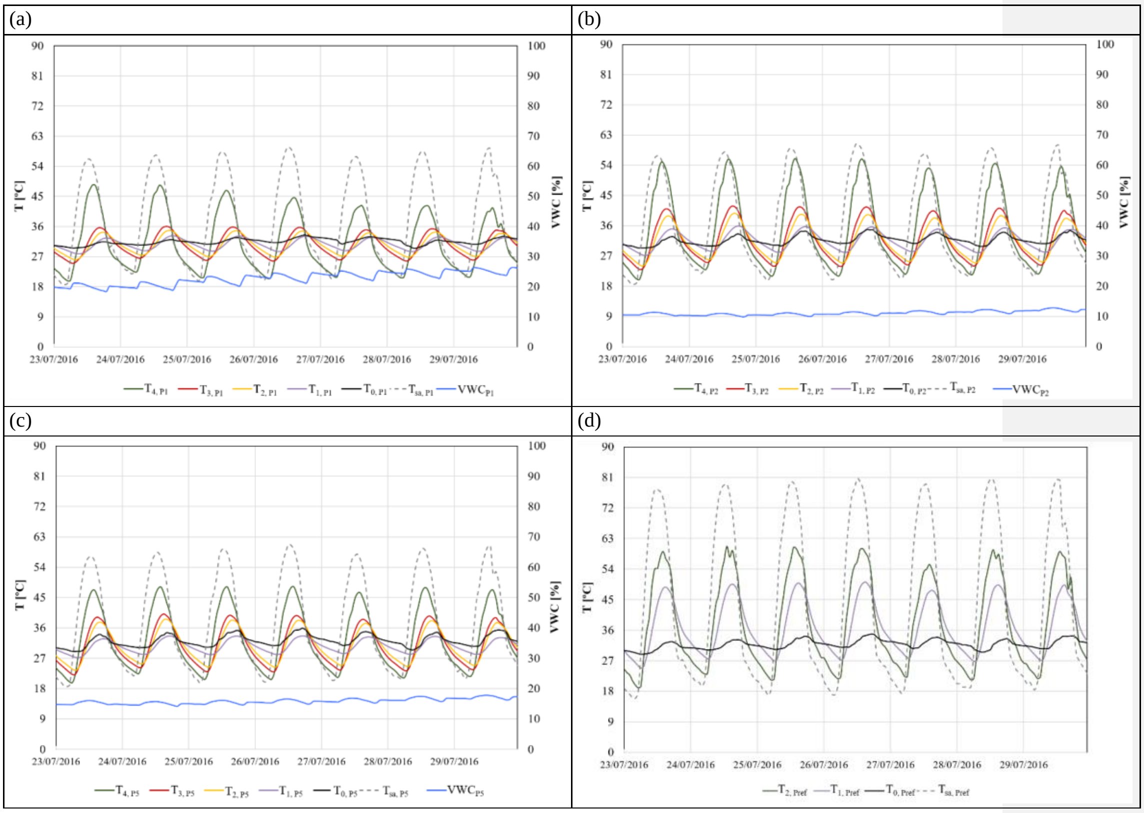


Fig. 7. Temperature profile measured, sol-air temperature and water content measured in the substrate for (a) P1; (b) P2; (c) P5; (d) Pref, in the summer period.

3.1.2 Time lag and decrement factor analysis

The values of decrement factor, DF, and time lag, TL, for the four plots were calculated using Eqs. (3) and (4), respectively. The daily results of DF and TL for the summer week are shown in Fig. 8.

The parameter DF showed the oscillations of $T_{1,Pi}$ (ΔT_i), temperature values between the roof slab and the root barrier, respect to the oscillations of $T_{sa,Pi}$ (ΔT_e), see Eq. (9). The higher ΔT_e or the lower ΔT_i, the lower DF is. In Fig. 7, it can be observed that ΔT_e values were similar for the three green roofs, because the T_{sa} values were similar. The ΔT_i values varied in each plot with green roofs, mainly due to the capacity of the substrate to retain water, VWC, during daily irrigation.

Comentado [FCM28]: Reviewer 1 Comment 4: How does the climate control program influence the determination of DF?

Reviewer 3 Comment 13: In the indoor space below the green roofs, was indoor air temperature monitored in addition to ceiling temperature.

Comentado [FCM29]: Reviewer 1 Comment 5: Regarding DF, wouldn't a low DF (low inside T fluctuation and high outside T fluctuation) indicate a higher potential for energy fluxes into and out of the building? The key factor for reducing heat fluxes would seem to be reduction in the temperature fluctuations at the surface of the media. It would be helpful to the reader if the implications of DF, TL and CP were explained in greater detail.

Reviewer 1 Comment 6: It would be very helpful to see a plot of plant index for the three green roof systems over the experimental period. How does leaf index correlate with the performance. Only TL is referred to. Why aren't heat flux, CP and DF also affected?

Reviewer 3 Comment 16: The irrigation regime may have notable influence on the cooling performance of the green roofs. Please explain the time of the day when irrigation was applied, and how much water (estimated) was applied in each watering episode. The effect of irrigation could be added to the results and discussion sections.

Therefore, the higher capacity to retain water, lower values of ΔT_i and DF were obtained, see Fig. 7. The lowest DF values were always achieved in P1, with an average weekly value of 0.12, see Fig. 8a, in agreement with the lowest values of $T_{1,P1}$, as shown in Fig. 7a, mainly due to the high capacity of the substrate to retain water. Comparing the three plots with green roofs, the highest DF values were obtained in P2, with an average weekly value of 0.19, , see Fig. 8a, mainly due to the low capacity of retaining water in its substrate, so the oscillations of $T_{1,\,P2}$ were higher, see Fig. 7b. The DF values increased significantly in Pref. It can be observed that Pref presented the highest DF values throughout the selected period, with an average weekly value of 0.36, see Fig. 8a, mainly due to the fluctuation of the slab temperature, $T_{1;Pref}$, see Fig. 7d. These results indicated that, for very warm and dry climatic conditions, the higher the capacity to retain water in the substrate, the higher the reduction in the oscillation of the slab temperature, $T_{1,Pi}$, and DF is.

The TL parameter measured the difference in time between the maximum daily $T_{sa,Pi}$ values and the maximum daily $T_{1,Pi}$ values for the summer climatic conditions, see Eq. (10). The TL results were related to the fractional vegetation coverage, the leaf area index, the composition of the substrates and their capacity to retain water and the water accumulated in the drainage layer.

The TL values shown in Fig. 8b could be divided into several part of TL according to the layers of the plots. There was a TL from the maximum daily $T_{sa,Pi}$ value to the maximum daily $T_{4,Pi}$ value (vegetation layer), see Fig. 7, another TL of maximum daily temperatures from $T_{4,Pi}$ to $T_{2,Pi}$ (substrate layer), see Fig. 7, and finally, another TL of maximum daily temperatures from $T_{2,Pi}$ to $T_{1,Pi}$ (water accumulation layer), see Fig. 7. The TL values due to the vegetation layer were similar for the three plots, between 1 h and 2 h. The TL values due to the substrate layer were higher for P1 than P2 and P5, due to volumetric water content of the substrates. Finally, the highest TL values due to the water accumulation layer were for P2, see Fig. 7, because its substrate drained more water than the other substrates and consequently there was more water accumulated in this layer. As a result, the order of the plots that presented from the highest to the lowest values of TL were P1, P2, P5 and Pref, with average weekly values of 6:08 h, 5:17 h, 4:17h and 2:42h, respectively, , see Fig. 8b, mainly due the cross-effects of the different layer of the plots. Previous

Comentado [MRdAS30]: Sobra una coma

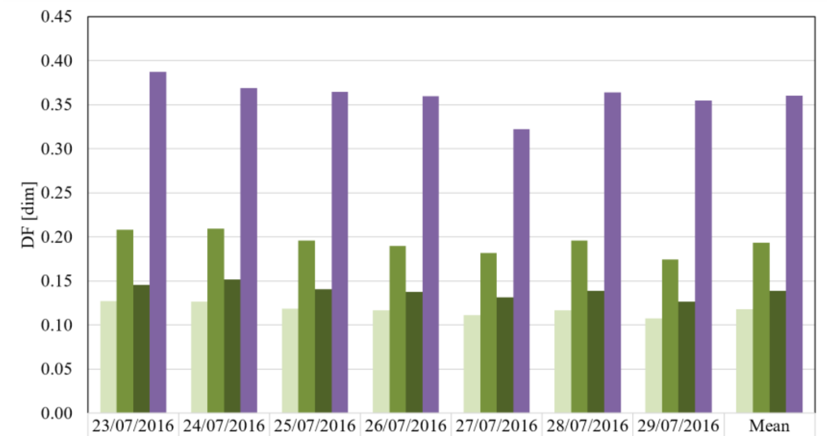
Comentado [MRdAS31]: were mainly related

Comentado [MRdAS32]: see Fig. 7. In this case, the substrate drained…

Comentado [MRdAS33]: sobra una coma

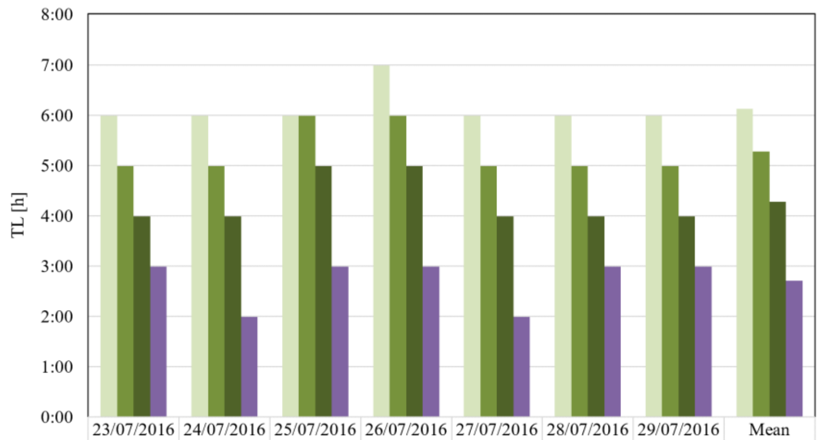
studies also showed the importance of vegetation and composition of the substrate in the dynamic characterization of a green roof [33], with maximum weekly average TL values of 4:20 h. Nevertheless, in the present work higher TL values were found, up to 6.08 h, as shown in Fig. 8b. The TL values confirm the green roof benefits for the retrofit of buildings without insulation by delaying the peak in the maximum surface temperature.

(a)



	23/07/2016	24/07/2016	25/07/2016	26/07/2016	27/07/2016	28/07/2016	29/07/2016	Mean
P1	0.13	0.13	0.12	0.12	0.11	0.12	0.11	0.12
P2	0.21	0.21	0.20	0.19	0.18	0.20	0.17	0.19
P5	0.15	0.15	0.14	0.14	0.13	0.14	0.13	0.14
Pref	0.39	0.37	0.36	0.36	0.32	0.36	0.35	0.36

(b)



	23/07/2016	24/07/2016	25/07/2016	26/07/2016	27/07/2016	28/07/2016	29/07/2016	Mean
P1	6:00	6:00	6:00	7:00	6:00	6:00	6:00	6:08
P2	5:00	5:00	6:00	6:00	5:00	5:00	5:00	5:17
P5	4:00	4:00	5:00	5:00	4:00	4:00	4:00	4:17
Pref	3:00	2:00	3:00	3:00	2:00	3:00	3:00	2:42

Fig. 8. Values of (a) decrement factor and (b) time lag for P1, P2, P5 and Pref in the selected summer period.

3.1.3 Cooling potential

The cooling potential, CP, of the three plots with green roofs was evaluated for the selected summer period, according to Eq. (12). The results of daily CP and a weekly average value for each plot are shown in Fig. 9. It can be seen that the highest CP values were obtained in P1, with a weekly average value of 16.3 ºC. The second plot with the highest CP was P5, with a weekly average of 15.8 ºC, 3% less than P1. Finally, P2 had the lowest CP values compared to the rest of the plots with green roofs, a 15% less than P1. This study showed that the plots with green roofs always allowed the slab temperature to reduce by more than 12.7 ºC, compared to Pref. These results were inversely proportional to the DF values, Fig. 8a, where the green roof that had the greatest capacity to retain water in the substrate, P1, achieved the best results. Therefore, the higher the capacity to retain water in substrate, the higher CP is.

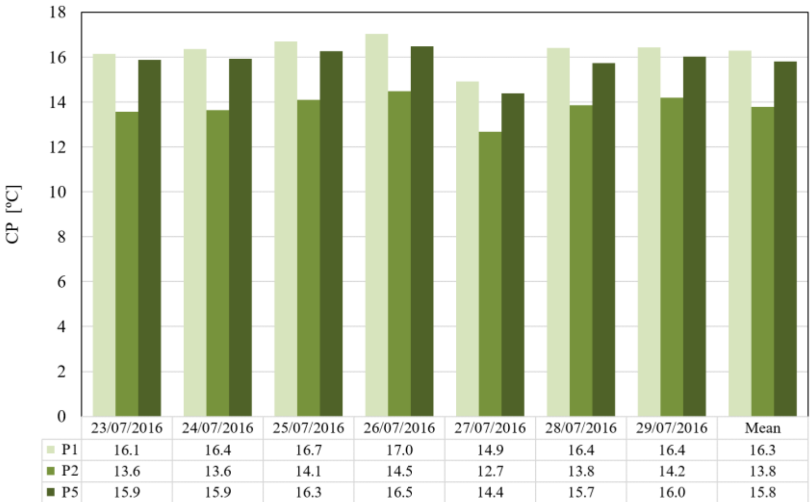


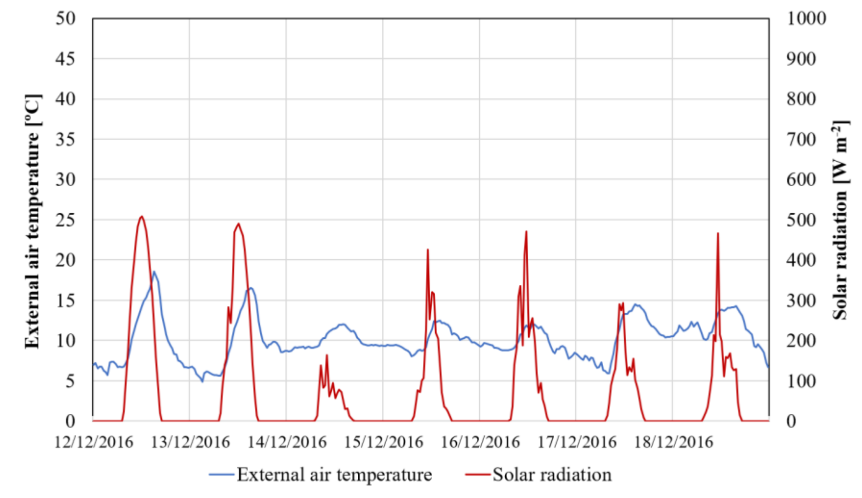
Fig. 9. Cooling potential values for P1, P2 and P5 in the selected summer period.

3.2 Winter behaviour of the extensive green roof

A weekly analysis for a typical winter week, similar to that performed in section 3.1, was carried out. The winter week selected was from 12/12/2016 to 18/12/2016. The climatic conditions, the substrate temperature profile and the TL and DF parameters were also analysed for this week.

The climatic conditions for the selected winter period are shown in Fig. 10. The peak values of total horizontal solar radiation and external air temperature varied each day, with maximum values of 507.7 W/m^2 and 18.6 ºC during the first day, respectively, see Fig. 10a. The selected week also had some rainy days, with a total weekly rainfall of 26.8 mm/h, see Fig. 10b. The minimum values of total horizontal solar radiation and external air temperature were obtained for day 14/12/2016, see Fig. 10a, coinciding with the day with the highest rainfall, see Fig. 10b. It can also be observed an oscillation of relative humidity between 50.7% and 96.1% and wind speed between 0 m/s and 4.7 m/s.

(a)



(b)

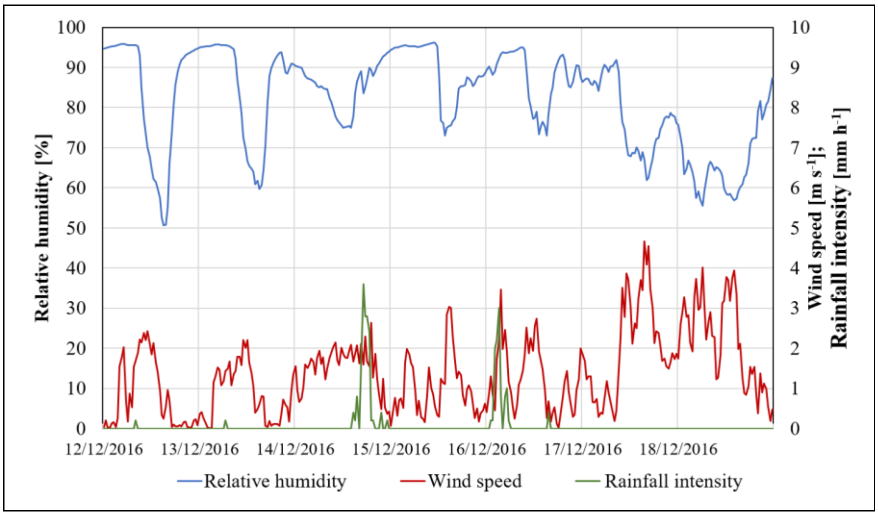


Fig. 10. Climatic conditions of the selected winter period. (a) Solar radiation and external air temperature. (b) Rainfall, windspeed and relative humidity.

Comentado [FCM34]: Reviewer 3 Comment 21: In Figure 5, the y-axis label "Rainfall" can be changed to "Rainfall intensity".

3.2.1 Analysis of the temperature profile and water content in the plots

Temperature profile, sol-air temperature and volumetric water content in the substrate of the four plots for the selected winter week are shown in Fig. 11. The irrigation during this week wasn't planned, so the percentage of water present in the substrate depended on the air humidity and the amount of rainfall, see Fig. 10b. It can be observed that the weekly average VWC values for the three plots with green roofs were similar, 47.6%, 48.2% and 47.7% for P1, P2 and P5, respectively. For the first two days, that had low rainfall, the VWC values oscillated between 39.5 % and 43.6%. However, these values increased in the following days, that had high rainfall, up to 56.8%, 56.7% and 51.2% for P1, P2 and P5, respectively. Regarding the temperatures measured, the T_4 values for green roofs and the T_2 values for Pref oscillated each day, more than the rest of the temperature values measured, due to the fact that the climatic conditions had more influence on their reading. The maximum T_4 values obtained were 17.8 ºC, 19.8 ºC and 17.1 ºC for P1, P2 and P5, respectively, and the maximum T_2 values obtained for Pref was 27.2ºC. These temperature peaks decreased as a function of the depth measured for the four plots, as well as for the summer period studied, obtaining the lowest oscillations for T_1 for all plots. The maximum values of T_1 for P1, P2, P5 and Pref were 11.6 ºC, 12.6 ºC, 12.2 ºC and 16.5 ºC, respectively. In Fig. 11, it can also be seen that the T_{sa} values for the plots with green roofs were similar, with maximum and minimum values of 28.2 ºC and 4.8 ºC, respectively. However, T_{sa} values for Pref increased significantly during the morning, up to 41.2 ºC, and decreased during the night, up to 3.2 ºC.

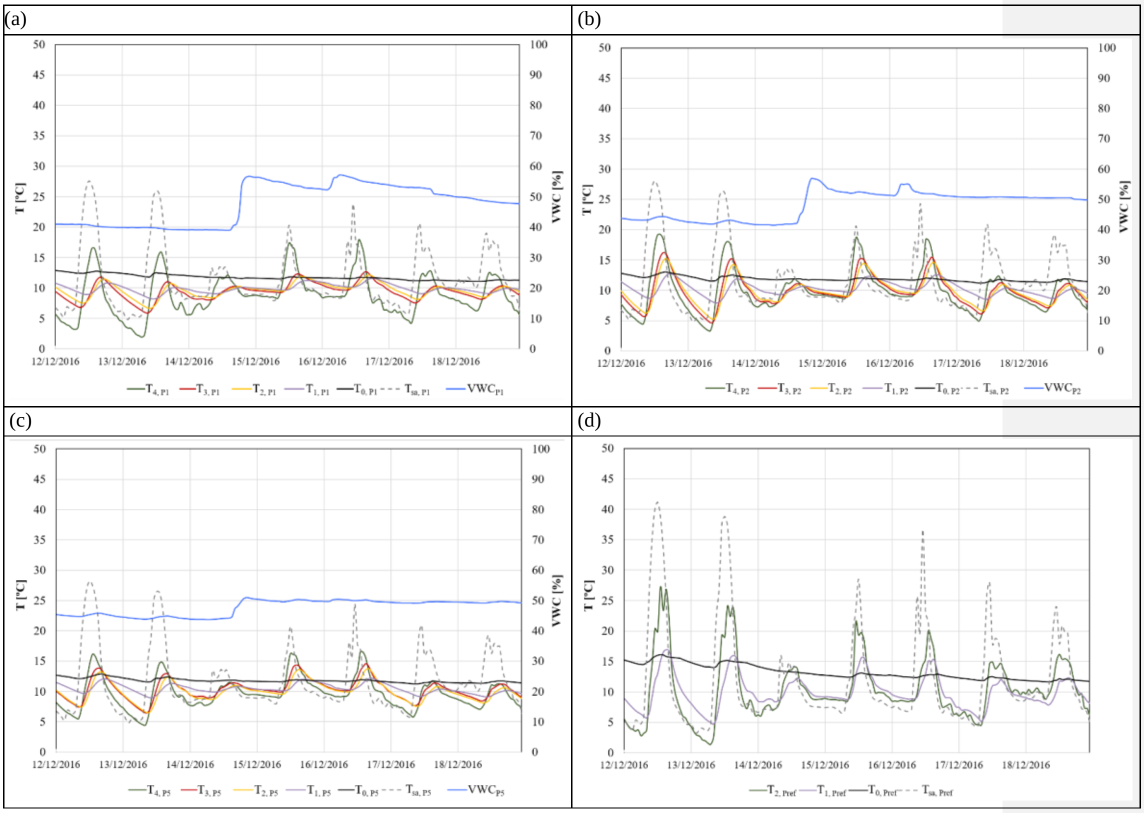


Fig. 11. Temperature and water content values in the substrate of (a) P1; (b) P2; (c) P5; (d) Pref, in the winter period.

Comentado [FCM35]: **Reviewer 1 Comment 4: How does the climate control program influence the determination of DF?**

Reviewer 3 Comment 13: In the indoor space below the green roofs, was indoor air temperature monitored in addition to ceiling temperature.

3.2.2 Time lag and decrement factor analysis

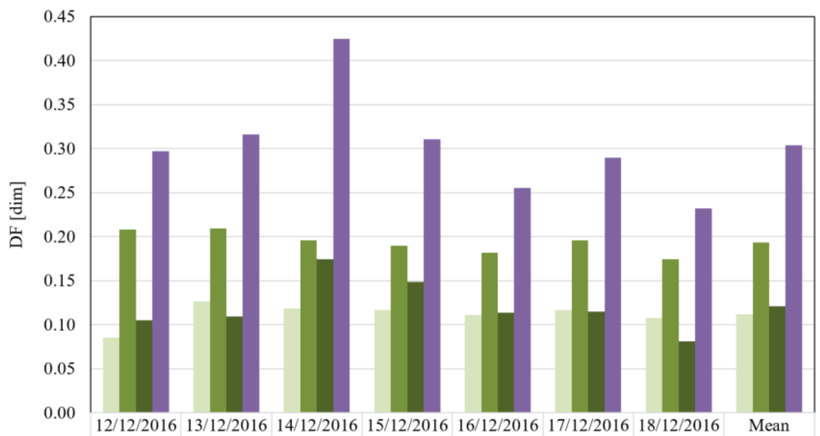
The values of DF and TL for the four plots were calculated using Eqs. (9) and (11), respectively. The results of both parameters throughout the selected winter period are shown in Fig. 12. It can be observed that Pref always presented the highest DF values, with an average weekly value of 0.30. These values were significantly reduced in the plots with green roofs, as was already observed in the summer week. The lowest DF values were obtained for P1 and P5, with weekly average values of 0.11 and 0.12, respectively. The highest DF values for the plots with green roof were achieved for P2, with a weekly average value of 0.19, due to the oscillations of $T_{1,P2}$, see Fig. 11b, since the T_{sa} values were similar for the three plots with green roof.

Regarding TL, this parameter measured the difference in time between the minimum daily $T_{sa,Pi}$ values and the minimum daily $T_{1,Pi}$ values for the winter climatic conditions, see Eq. (11). The results showed that the lowest values were achieved in Pref, with an average weekly value of 3:17 h, as shown in Fig. 12b, and the highest values were almost always obtained for P1, with an average weekly value of 6:34 h, mainly due to the higher amount of plants in P1. These TL values, usually reduced for P2 and P5, with average weekly value of 5:42 h and 5:25 h, respectively.

The green roofs allowed a significant reduction in the DF values and an increase in the TL values, compared to the Pref results, despite the high amount of water in the substrates, around 48%, see Fig. 11a, Fig. 11b and Fig. 11c. In fact, for rainy and cold climatic conditions in the winter period considered, the trends of DF and TL were mainly due to the vegetation coverage and the composition of the substrates each plot, achieving a reduction in the oscillation of the slab temperature and delaying the minimum peaks of temperature in winter.

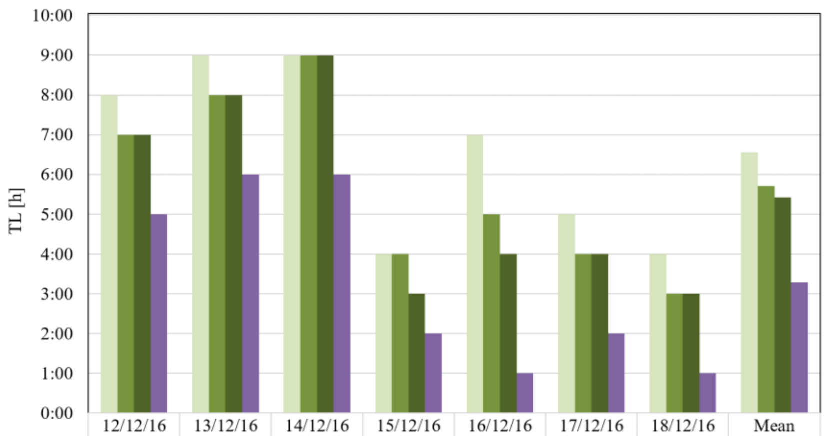
Comentado [MP36]: **Reviewer 1 Comment 13: In one instance the plant foliage is described as influencing insulation values. It is not correct to use the term insulation except in the context of true material thermal conductivity. Leaf surfaces are important in latent heat transfers (transpiration), shading, and thermal emissivity.**

(a)



	12/12/2016	13/12/2016	14/12/2016	15/12/2016	16/12/2016	17/12/2016	18/12/2016	Mean
P1	0.09	0.13	0.12	0.12	0.11	0.12	0.11	0.11
P2	0.21	0.21	0.20	0.19	0.18	0.20	0.17	0.19
P5	0.10	0.11	0.17	0.15	0.11	0.11	0.08	0.12
Pref	0.30	0.32	0.42	0.31	0.26	0.29	0.23	0.30

(b)



	12/12/16	13/12/16	14/12/16	15/12/16	16/12/16	17/12/16	18/12/16	Mean
P1	8:00	9:00	9:00	4:00	7:00	5:00	4:00	6:34
P2	7:00	8:00	9:00	4:00	5:00	4:00	3:00	5:42
P5	7:00	8:00	9:00	3:00	4:00	4:00	3:00	5:25
Pref	5:00	6:00	6:00	2:00	1:00	2:00	1:00	3:17

Fig. 12. Values of (a) decrement factor and (b) time lag for P1, P2, P5 and Pref in the selected winter period.

3.3 Energy flux analysis

A monthly and annual energy analysis for the plots with green roofs and the reference plot was performed. For this analysis, the transfer of heat flux between the roofs and the interior of the building was measured.

3.3.1 Monthly energy flux analysis

Monthly cumulative energy flux gains and losses for P1, P2, P5 and Pref for 2016 are shown in Fig. 13. The net energy is also shown in Fig. 13, which indicates the difference between the gains and losses of heat through the plot. First, the results obtained in July were analysed, in order to relate them to the parameters previously studied in the summer week. It can be observed that for this month the highest decrease of energy gains was achieved in P1, with a value equal to 11.9 kW h m^{-2}, 83% less than Pref, 69.6 kW h m^{-2}, see Fig. 13a and Fig. 13d. For P5, it was also possible to significantly reduce the energy gains in respect to Pref in July, with a value of 24.7 kW h m^{-2}, 64.5% less than Pref, see Fig. 13c. For the same month, P2 achieved the lowest reduction of energy gains, with a value equal to 26.6 kW h m^{-2}, 61.8% less than Pref, see Fig. 13b. This trend, for the month of July, agreed with the dynamic parameters previously studied, DF and CP, due to the capacity to retain water in the substrate, attenuating the maximum roof temperature peaks during a very warm month. Therefore, the lower DF and the higher CP, the lower heat flux gain is. This trend was similar to that obtained in August, because both months had similar climatic conditions, see Table 1. For June and September, P1 also achieved the highest reduction of energy gains, up to 84% less than Pref, however, P5 achieved lower reduction of energy gains than P2, mainly due to the reduction of the ambient temperature, 4.2 ºC less than in July.

For the cold months, the results obtained in December were first analysed, in order to relate them to the parameters previously studied in the winter week. The highest decrease of energy losses was obtained in P1, with a value of -9.1 kW h m^{-2}, 65.3% less than Pref in the same month, see Fig. 13a and Fig. 13d. For P2, the value of energy losses was -14.1 kW h m^{-2}, 46.0% less than Pref in the same month, see Fig. 13b and 12d. For the same month, P5 achieved the lowest

Comentado [FCM37]: Reviewer 1 Comment 5: Regarding DF, wouldn't a low DF (low inside T fluctuation and high outside T fluctuation) indicate a higher potential for energy fluxes into and out of the building? The key factor for reducing heat fluxes would seem to be reduction in the temperature fluctuations at the surface of the media. It would be helpful to the reader if the implications of DF, TL and CP were explained in greater detail.

reduction of energy losses, -17.5 kW h m^{-2}, 33.7% less than Pref, see Fig. 13c and 12d. This trend was in accordance with the previous TL results, see Fig. 12b, which were related to σ_f and LAI in each plot. For the other cold months, such as January and February, the trend was similar for all plots. The maximum reduction of energy losses was obtained in P1 during the month of February, with a value equal to -6.7 kW h m^{-2}, 77.4% less than Pref, see Fig. 13a and 12d.

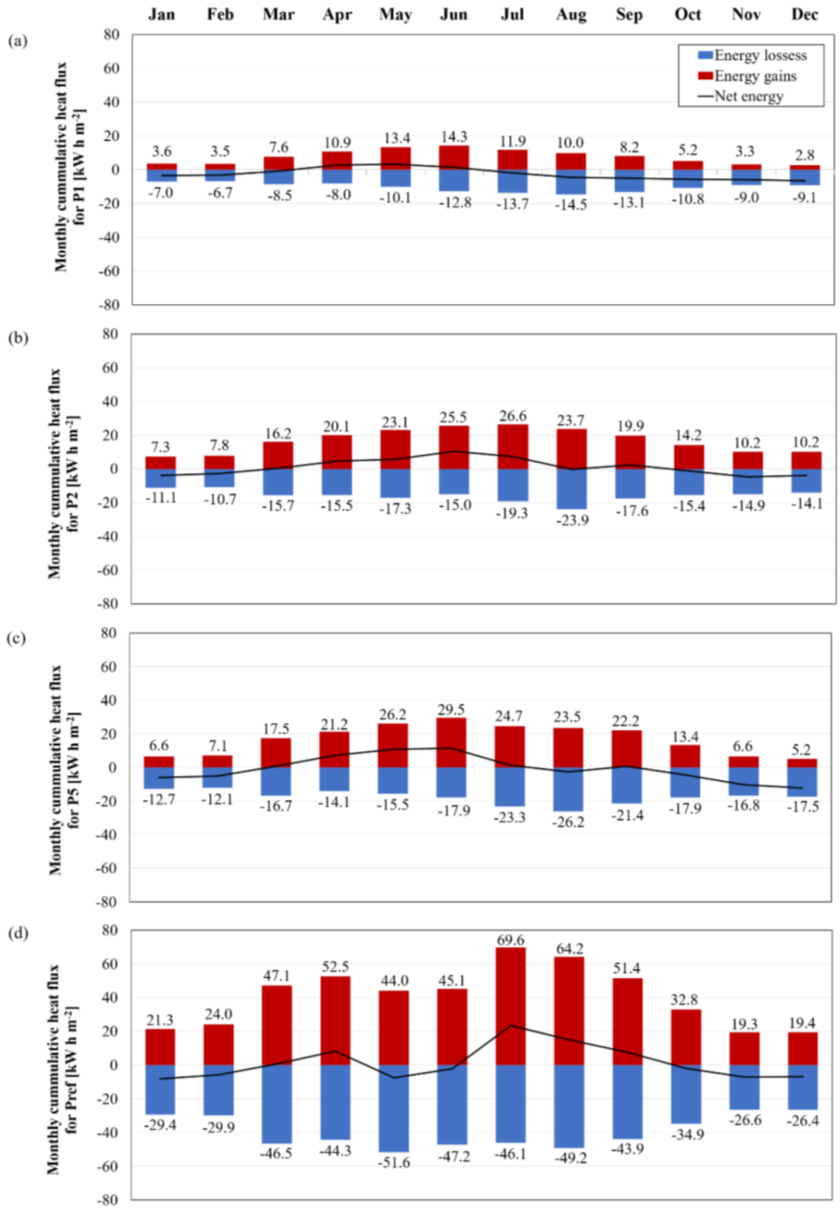


Fig. 13. Monthly cumulative energy flux for (a) P1, (b) P2, (c) P5, (d) Pref.

3.3.2 Annual energy flux analysis

In this section, the annual cumulative energy flux for P1, P2, P5 and Pref for years 2016 and 2017 are shown. The energy gains and losses values for 2017 were slightly higher than the results of the 2016 in all plots, see Fig. 14. This increase was mainly due to the slight rise in annual average ambient temperature and annual average solar radiation and, to the reduction in annual average rainfall during the 2017, see Table 1. The values of energy gains and losses in Pref for 2016 were of 490.7 kWh/m^2 and -476.0 kW h m^{-2}, respectively, and for 2017 of 549 kWh/m^2 and -507.6 kW h m^{-2}, respectively. Comparing these results with those obtained in the plots with green roofs, it can be observed that significant reductions in both energy gains and energy losses were achieved. As shown in Fig. 14, P1 presented the maximum reduction of energy gains and losses, with 81% and 74%, respectively, for year 2016, and with 80% and 70%, respectively, for year 2017. P5 was the plot with the lowest reduction in energy gains and losses, with a 58% and 55%, respectively, for 2016, and a 56% and 57%, respectively, for 2017.

These result show that the extensive green roofs under warm climatic conditions achieved high energy savings, between 55% and 81%, depending on the type of substrate and the fractional vegetation coverage of the plot. Green roofs with commercial substrate, as P1, obtained the best thermal performance, due to the capacity to retain water in the substrate.

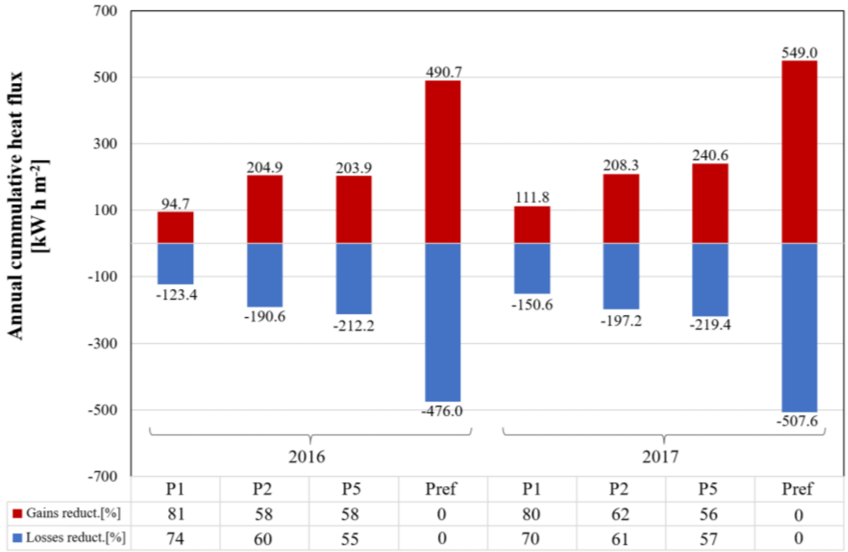


Fig. 14. Annual cumulative energy flux in P1, P2, P5 and Pref for 2016 and 2017.

4 CONCLUSIONS

In this work, the thermal performance of three plots with green roofs, P1, P2 and P5, with different types of substrates were studied and compared with a traditional gravel ballasted roof, Pref. The substrate of P1 was composed of 100% of commercial growing medium, P2 of 75% of commercial growing medium and 25% of recycled construction materials, and finally, P5 of 50% of commercial growing medium and 50% of recycled construction materials. The thermal performance of these three green roofs under warm climatic conditions were studied in Córdoba (Spain), during two years, 2016 and 2017. The potential of green roofs for retrofitting of existing buildings was studied. A dynamic analysis based on decrement factor, DF, time lag, TL, cooling potential, CP, and annual reduction of energy demand for these green roofs was performed.

The experimental results showed that the three plots with green roofs achieved high reduction of DF and high increases of CP, compared to Pref for warm and dry climate, especially in P1 with a weekly average reduction of DF equal to 0.24 and a weekly average increase of CP equal to 16.3 °C. This behaviour was mainly due to the capacity to retain water in the substrate. The results indicated that, for warm and dry climatic conditions, the higher the capacity to retain water in the substrate, the higher the reduction of DF and the higher the increase of CP is.

Significant increases of TL for the green roofs were obtained, up to 6:08 h and 6:34 h for P1 during the hot and cold periods considered, respectively, compared to Pref. The TL results were related to the fractional vegetation coverage, the leaf area index, the composition of the substrates and their capacity to retain water and the water accumulated in the drainage layer, that gave a delayed the maximum slab temperature peak.

Comentado [MP38]: Reviewer 1 Comment 13: In one instance the plant foliage is described as influencing insulation values. It is not correct to use the term insulation except in the context of true material thermal conductivity. Leaf surfaces are important in latent heat transfers (transpiration), shading, and thermal emissivity.

Finally, significant reductions of energy gains during the hot period and energy losses during the cold period were obtained in the three green roofs, compared to Pref, due to the capacity to retain water in the substrates and the fractional vegetation coverage of these plots. The annual average reductions in energy gains and losses of the three green roofs were 66% and 63%, respectively. These important energy savings were obtained during two particularly warm years in Córdoba (Spain).

It can be concluded that the use of green roofs could be considered for the retrofit of existing buildings under warm climatic conditions, as a measurement to achieve nZEB requirements.

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