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# Real-time monitoring of green roofs in Barcelona

**Alva, Aleix[a], Lacasta, Ana M.[b], Bosch, Montserrat[b], Berigüete, Fanny[b] y Cantalapiedra, Inmaculada R.[b]**

[a]Universitat Politècnica de Catalunya, ETSAB-Avda Diagonal 649, Barcelona, alex.alva@upc.edu
[b]Universitat Politècnica de Catalunya, EPSEB- Avda Doctor Marañon 44, Barcelona,
ana.maria.lacasta@upc.edu, montserrat.bosch@upc.edu, fanny.esther.beriguete@upc.edu,
inmaculada.rodriguez@upc.edu

## Abstract

Green roofs are Nature-based solution (NbS) that have been gaining popularity in recent years due to the environmental, economic and social benefits attributed to them. In the framework of the "BCN - Verd de Proximitat" (Barcelona - Proximity Green) project, a continuous monitoring system has been implemented on 4 green roofs in that city. One of the goals of this monitoring is the evaluation of the influence of these solutions on aspects like the heat island effect, air quality, environmental noise or rainwater runoff.

Various types of sensors have been used. On the one hand, temperature and humidity probes have been installed in the substrate, while surface temperatures are recorded by infrared cameras. On the other hand, citizen-science kits have been used to determine environmental parameters such as noise or particulate matter (PM) concentrations. Weather stations have also been installed to record air temperature and humidity, wind speed and rainfall. Where possible, sensors have also been installed on neighbouring conventional roofs for comparison purposes.

One of the analysed cases has a water harvesting system to reduce irrigation-demand of supply. In order to assess the effect of vegetation on runoff control, sensors have been installed to monitor water levels in the tanks. The comparison between the time evolution of the rainwater recorded by the rain gauge and the corresponding curve of the water reaching the tanks shows a time lag that allows to quantify the water retention capacity of the vegetation.

***Keywords:*** Green roof, Environmental monitoring, Runoff control

## 1 Introduction

The presence of vegetation plays a twofold role in urban zones. On the one hand, it enhances the healthiness, sustainability and pleasantness of the environment. On the other hand, it improves air quality and temperature control (De Carvalho & Szlafsztein, 2019; Leung et al., 2011). Contrarily to conventional waterproofed surfaces, which hamper water absorption, green areas favour water infiltration into the soil, replenishing aquifers, restraining flood severity and, in general, improving water management (Ferrini et al., 2020). They not only provide an increase of the urban vegetation surface, but also a potential habitat to a wide spectrum of animal species, helping to sustain local biodiversity (Threlfall et al., 2017). Added to these environmental benefits, urban vegetation has a positive impact on human well-being, since it provides an opportunity to find relaxing spaces that also stimulate physical activity and community interaction (Parsons & Ulrich, 1990). For all these reasons, not only the conservation but also the creation of green spaces should be a priority for every city, despite the tight spatial constraints suffered by densely-built areas. The scarceness of non-constructed land makes building-based green, mostly on roofs and façades, especially relevant.

Green roofs and façades have multiple benefits from both thermal and energy-saving viewpoints (Raji et al., 2015; Coma et al., 2016;Susca et al., 2011). They shield constructed surfaces from extreme temperature values and fluctuations in hot weather by improving the overall thermal inertia of the whole solution (Guattari et al., 2020). During low and medium-latitude summers, the vegetation-induced reduction of surface temperature is substantial (Baryla et al., 2019), and provides an enhanced thermal comfort to both regular users and occasional visitors. Regarding water management, green roofs noticeably hamper the effects of rainfall runoff by providing a substrate with the capacity to absorb and retain substantial amounts of water (Sims et al., 2016, Xing and Jones, 2021;Liu et al., 2021). Acting as temporary reservoirs, they regulate the draining flow, thus alleviating the load on the sewage system. In addition, and when possible, the implementation of a rainwater-harvesting circuit for local irrigation greatly relieves freshwater supply demands in drought-stricken regions. Additionally, green-based architecture has a great potential to host a wide range of species by providing a habitat for them. If properly managed, such habitats can significantly contribute to urban biodiversity (Mayrand & Clergeau, 2018; Wooster et al., 2022). From a social standpoint, they also bring opportunities to enhance the well-being of their users by providing spaces where people can interact in a Nature-friendly context (Ode Sang et al., 2022; Williams et al., 2019). Also worth mentioning is their capacity to absorb pollution and release oxygen, thus contributing to a cleaner and healthier urban air (Liu et al., 2021).

Despite common fears of potential water infiltration from these green solutions, it is important to emphasise that these are professionally executed systems with well-known long-term reliability, so these fears are unfounded. Statistics on humidity-related problems from green roof implementations don’t show significant differences in the number of problematic cases with respect to other modern types of solutions (Carretero Ayuso, 2021). Additionally, the increase of thermal inertia provided by vegetation and its substrate reduces the ageing of the waterproofing layers, thus potentially increasing the lifespan of the overall system (Cascone, 2019; Korol et al., 2018; Vijayaraghavan, 2016).

In the last decade, Barcelona’s City Council has actively promoted the implementation of green roofs via contest-based funding. This bold policy has allowed the appearance of an interesting network of green roofs and façades with not only ecological but primarily educational and exemplary value to inspire and spread an urban-greening wave. These new roofs are also great opportunities for real-case research, which is where the scope of our project lies. Our main goal is the design and the subsequent implementation of a monitoring system that allows the quantification of several physical and social impacts of green roofs on the city. The monitoring system encompasses six different roofs distributed across Barcelona, where we measure different variable in different locations, according to the idiosyncrasies of each case. In four of them we have implemented real-time environmental monitoring.

This work presents the methodology used to quantify several physical magnitudes in four green roofs and shows preliminary results obtained in the initial data-collection run. Although this project involves the measurement of a wide span of variables, we show here data from a selected set of them and only from one of the roofs, named as GR1. Specifically, we focus on the analysis of surface temperatures and rainfall retention.

## 2 Methodology

### 2.1 Real-time monitoring

In order to allow a citizen-friendly quantification of green-roof-based data, this project places its emphasis on the use of low-cost sensors. This approach gives preference to scalability over high-precision measurements, but without sacrificing the science-focused perspective. In fact, the accuracy offered by currently available low-budget equipment significantly lies within the relevance range of measured quantities. A good compromise between amateur-level knowledge and scientifically valuable data is crucial if green solutions are to be widely implemented. Also essential is the development of an extensive (and freely-available) documentation of the studied cases.

In particular, this project has experimented with a wide variety of sensors targeting different sets of magnitudes. On the one hand we have implemented several weather-based setups that include temperature, relative humidity, barometric pressure, noise levels, particulate matter, volatile organic compounds (VOC), rainfall, wind speed and wind direction. On the other hand, sensors for more specific variables have been tested. Specifically, we have measured soil temperature and moisture to analyse irrigation, surface temperatures to study heat-island effects and water-tank levels to monitor the rainfall harvesting circuit, always trying different sensor models and assessing their reliability and performance.

Each of these sensors are connected to a user-friendly microcontroller, either a Arduino Uno R3 or a BBC micro:bit V3. These two models are extensively used in educational programs and have affordable price, approachable documentation and thriving supporting communities, three important criteria from a citizen-science point of view. Additionally, these microcontrollers can easily store the data in SD cards, to be periodically retrieved by local neighbours. However, in this project we have implemented a more sophisticated system for data centralisation. We have used A20-OLinuxXino-LIME2 microprocessors to capture the data from the aforementioned microcontrollers via serial port and, through a WireGuard VPN, send the data via MQTT protocol to a central server. Crucially for an affordable and therefore scalable setup that every motivated citizen can implement, all software and hardware involved in this project is open-source, except the central server, which is an old Dell Inc. OptiPlex 3020 machine (recycled from an electronic waste container) running under Debian Linux. All data is processed under Bash scripts and ingested by a VictoriaMetrics database, which is then integrated into a custom instance of Grafana for real-time visualisation. On average, the server draws 16 W of power and each A20 board draws less than 2 W.

### 2.2. Surface temperatures

Surface temperatures are measured with Panasonic AMG8833 thermal infrared (IR) sensors. Being 8x8 px arrays, they can show simple thermal images that we later interpolate and plot with Gnuplot (see Figure 1). For time series IR data we take the average value of the 64 pixels. In order to protect the sensors from rain and to shield them from the Sun’s radiation we have attached them into inexpensive dummy surveillance cameras. In Figure 2 we show three images of these implementations.

**Figure 1. Snapshot of a Grafana dashboard from one of the studied green roofs. From top to bottom, the first row shows real-time gauges for weather data, including daily, monthly and yearly rainfall. The second row shows, on the top-left side, a 72 h time series for surface temperature of three different systems, conventional ceramic roof tiles (green), dry substrate without vegetation (yellow) and a vegetation-covered parterre (blue); and on the bottom-left side the ambient temperature. The right side of the second row shows real-time (8x8 px) thermographic images of the three aforementioned surfaces, in the same order from left to right. The third row shows real-time gauges for soil temperature (left) and moisture (right) at four different locations, all of them buried in periodically irrigated substrate. The fourth row shows time series for all these eight gauges. The fifth row shows time series for the ambient humidity (left) and for the water tank levels where rainfall is harvested (right). This is only a part of the dashboard, where other gauges and time series have been omitted for the sake of simplicity.**

**Figure 2. Location of IR sensors in two of the studied green roofs. The two left images are from GR1 roof and the right image is from GR2 (another green roof for which we don't show results here). The top-left image shows the visual field of the IR sensor measuring the temperature of a parterre with vegetation. The bottom-left image shows two IR sensors, one pointing at a vegetation surface and the other at a neighbouring roof with ceramic roof tiles, the same system that GR1 had before the green solution was implemented. In GR2 we have set up 3 IR cameras, one pointing at high vegetation (right), another at low vegetation (left) and another at a bare-substrate zone (centre).**

### 2.3. Rainwater and runoff collection

Roof GR1 features a rainfall harvesting circuit for irrigation purposes. The system is composed of six mutually-connected (and therefore levelled) water tanks, each with a capacity of approximately 240 L. In order to monitor their levels, we have placed a Gravity industrial stainless steel submersible pressure level sensor at the bottom of one of the tanks. Additionally, we have placed a Sparkfun weather meter kit, which includes a self-emptying bucket-type rain gauge that allows us to read rainfall volume and rate with a reasonable accuracy. We have extensively calibrated this gauge to read accurate readings of both light and intense rain, and shared the whole calibration data and the final micro:bit code in a public Codeberg repository (Codeberg repository, s.f.) so that every interested citizen can directly use the whole weather kit with maximum performance. At the end of this project, all code and schematics will be publicly available in similar repositories.

## 3 Results

### 3.1. Surface temperature

Here we analyse some preliminary results from thermographic readings in GR1. Figure 3 shows a week-spanning time series for the average temperature given by sensors pointing at a parterre with vegetation (green) and at a conventional ceramic tile solution (orange). We observe how daily temperature variations are less pronounced on the green-roof case, being significantly (~ 10 ºC) lower at noon and appreciably higher (~ 2 ºC) at dawn. During morning, if sunny, ceramic roof tiles easily reach high temperatures, while during night they progressively cool down. The vegetation surface, however, shows less extreme variations, not only improving the comfort of the users living under the roof, but also alleviating the expansion-contraction stresses on the waterproofing materials. We further illustrate the contrasting behaviour between these two solutions in Figure 4, where we show two sets of thermal maps at the most relevant hours (08:00 and 15:00 CEST) for a given day.

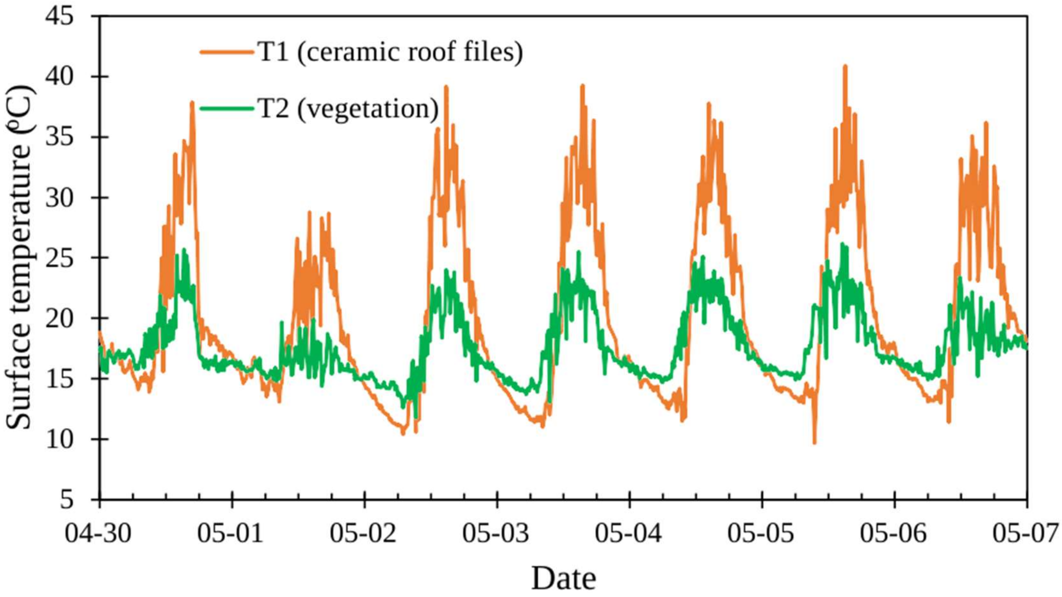

**Figure 3. Surface temperature time series, taken from 2023-04-30 to 2023-05-07 in GR1 for two different solutions. In orange we show the readings from a ceramic roof tile solution. In green we can see the readings from a vegetation parterre. Each data point is an average from the 64 pixels of an AMG8833 sensor. The reading frequency for almost all sensors in this project is 1 data point per minute. Notice how on 2023-05-01 the sky was partially clouded.**

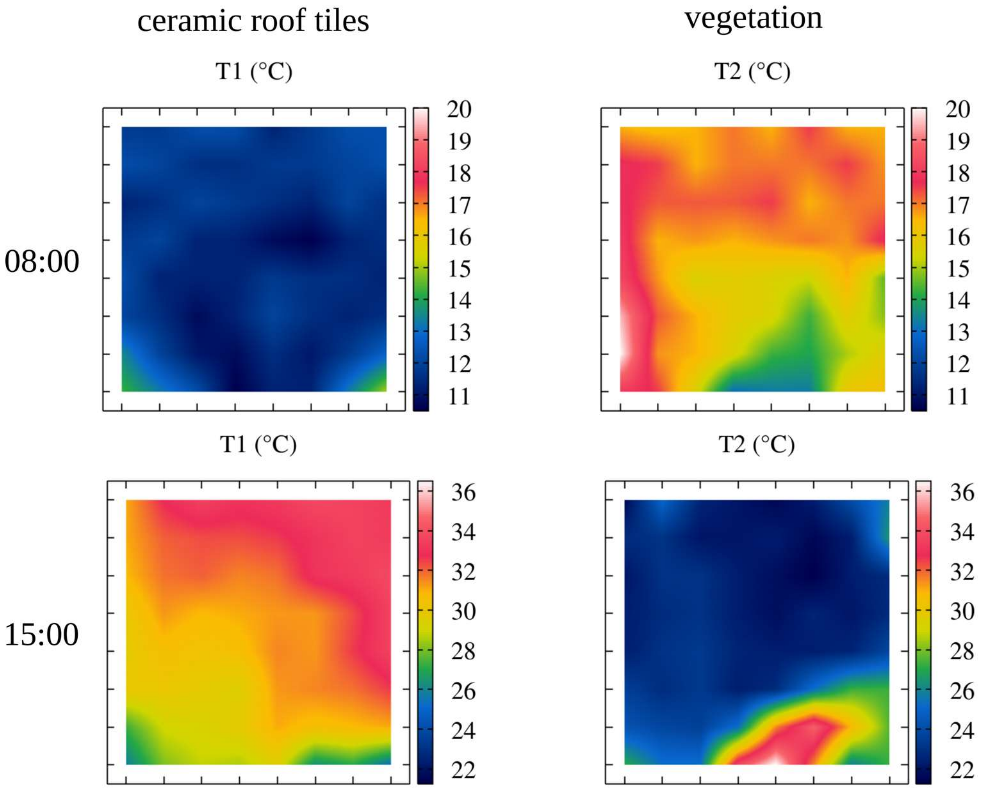

**Figure 4. Thermographic images from the IR sensors at GR1 at 08:00 (top row) and 15:00 (bottom row) on 2023-05-03, taken from a ceramic roof tile surface (T1, left column) and from a green roof surface (T2, right column). The right-bottom image shows a small region where the parterre has a metallic edge at ground level, which is partially covered by vegetation. The average values are, from left to right, (T1, T2) = (11.8, 16.4) ºC at 08:00 (top row), and (31.0, 24.3) ºC at 15:00 (bottom row). All times are CEST.**

This week-spanning data can be plotted in histogram form for a deeper analysis. In Figure 5 we show the results as normalised spectra, green for vegetation, orange for conventional ceramic roof tiles. The left graph, containing all the aggregated data from that week, shows two distinct curves for the two different solutions. The ceramic distribution is fat tailed on its right side, reaching temperatures around 10 ºC higher than the green distribution. Such tail comes from the presence of two opposed phenomena that gives the curve a bimodal character. In order to separate the two contributions, we show two additional graphs, first for only daylight hours (centre) and then for the rest of the day (left). The ceramic solution shows, during daylight, a wider distribution, according to its smaller thermal inertia, and is shifted towards higher temperatures. Specifically, both peaks have an 8 ºC gap. For the rest of the day this shift is inverted, with a less pronounced shift of 2 ºC.

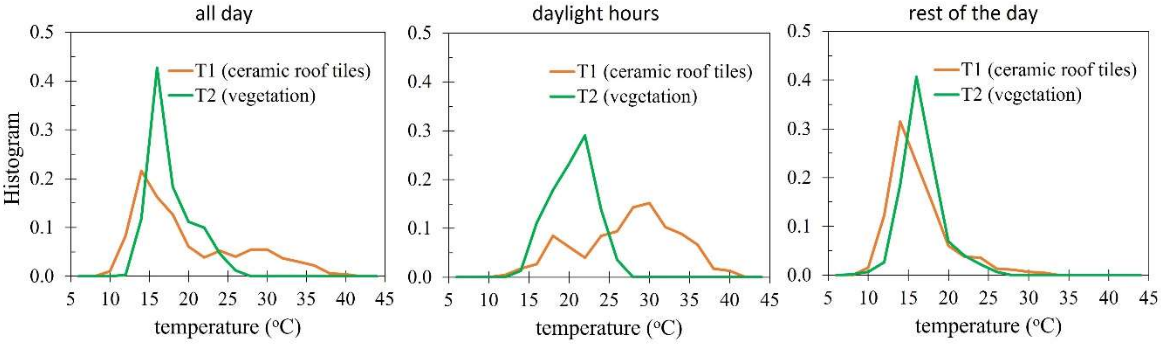

**Figure 5. Normalised histograms of accumulated surface temperature data from the week shown in Figure 3. The left graph shows the normalised spectra of measured surface temperatures where all data has been taken into account. By contrast, the central graph only registers daylight hours (10:00-18:00), and the right graph shows the histogram for the remaining parts of the day. Vegetation and ceramic tile surfaces are plotted in green and orange, respectively.**

## 3.2. Rainwater and runoff control

During a rain episode, the substrate of the green roof has the potential to store significant amounts of water. If the substrate has been recently irrigated or if a recent rain episode has occurred, this potential is then lowered. When the soil reaches a certain level of moisture, it begins to allow water into the harvesting circuit that leads to the storage tanks, although for light episodes, with less than 1 mm of rainfall, the filtration threshold is not reached and no water is harvested in the tanks. Both the rainfall and the tank-level time series are relevant to evaluate the runoff effect, so the time evolution of both need to be compared. It is expected for a rain episode to feature a time-delayed behaviour between the rain gauge readings and the distribution for the water volume rate in the tanks.

This is exactly what we observe. Figure 6 shows readings from two almost consecutive rain episodes, the first one on 2023-04-29T22:00 being light but with a mostly dry soil, and the second one (21 hours later on 2023-04-30T18:00) with more volume but starting with a moister substrate. The total rainfall of these events are 3.39 and 17.31 L per m², respectively. Since the roof has 79 m² of water harvesting area, these episodes approximately collected 265 and 1370 L, respectively.

The water tanks don't have a perfectly well-defined geometry, but their horizontal sections are approximately rectangular, so applying Cavalieri's principle we can integrate the total water volume at any time. In Figure 6, data from the rain gauge are already multiplied by the collecting area and data from the tanks are integrated so that both time series give either total volume (top graph) or its time rate (bottom graph). The bottom graph only shows a short time span corresponding to the second episode's rainfall duration, bounded in the top graph by two green dashed vertical lines.

It can be seen how the response curve from the tank shows a substantial hampering of the water flow. The long tail shown by the rate (bottom) graph indicates how the green roof slowly evacuates the rainfall, strongly regulating the runoff effect. In addition to that, the absolute volumes of water reaching the tanks do not correspond to the rainfall volumes, indicating that the substrate has a notable retention capacity. Readings of soil moisture for these episodes (not shown) reveal that even after the second episode, such retention is not yet at full capacity.

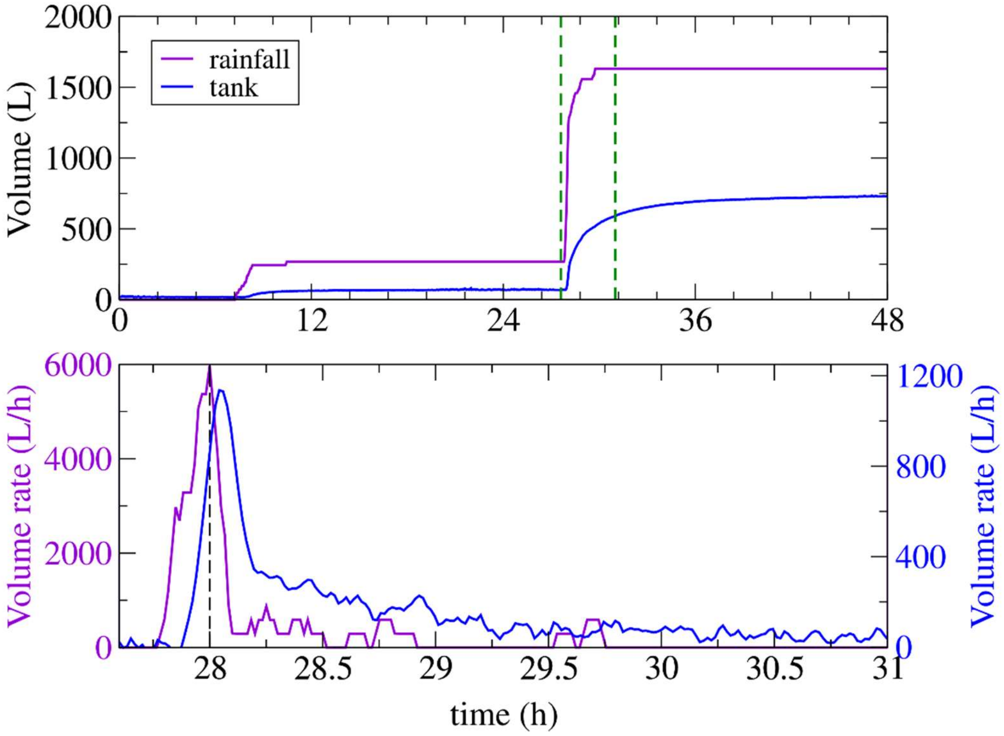

**Figure 6. Readings from two rain episodes (2023-04-29T22:00 and 2023-04-30T18:00). The top graph shows the time series for rainfall (blue) and tank (violet) volume. The bottom graph shows the time derivative of the top graph but restricted to the time span bounded by the two green dashed vertical lines. It also features two different vertical states, to emphasise the relevant long tail measured at the tank. This tail is the most important aspect of the runoff management's quantification.**

## 4 Conclusions

Green roofs are key players in urban areas in order to address the increasingly hard conditions associated with the climate emergency and the loss of biodiversity. Extreme temperatures, droughts and weather events are a call for urban architecture to be more resilient against these challenges and also to be kinder to Nature and all its inhabitants, human or not. However, all these claims need to be scientifically supported by data, without which policies favouring them would be hard to achieve. The green character of a solution does not only come from its colour but mainly from its ecological value, and this demands a thorough quantification of a wide variety of variables.

Consequently, quantitative data is needed from a large set of real-life cases, which makes the citizen-science approach indispensable. Expensive and difficult scientific equipment is not scalable neither economically nor practically. Our project aims to help closing this gap by developing simple monitoring approaches that provide fairly accurate data with only high-school-grade equipment. For this approach to work, extensive and user-friendly documentation is vital, and so is a set of social skills to motivate citizens to do science. In our experience, the latter is far more challenging than the former.

In this work we have presented preliminary results of two key aspects: surface temperatures and water management. Buildings in Mediterranean cities like Barcelona are exposed to increasingly high temperatures that reduce their thermal comfort and stress some of their constructive materials like the waterproofing layers on their roofs. Our results confirm that the presence of vegetation strongly reduces the daily temperature fluctuations of these materials, especially during daylight hours.

Also concerning is the increasing hydric stress due to severe drought episodes. We have studied a case of rainfall harvesting that alleviates the demand on the running water supply. In addition to this, the presence of a large volume of vegetation substrate strongly regulates the runoff effect that also alleviates the stress on the city's sewage system during torrential events.

There are many remaining challenges when monitoring green solutions, especially when assessing their true ecological value. For example, biodiversity indicators are not easily quantified, let alone automated. Furthermore, social and ethical questions, like whether green solutions are only accessible to the wealthy or whether the benefits and the comfort are just for humans at the expense of the ecosystem, are indispensable as well, and they can and should be quantified.

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