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Infraestructura Urbana Verde: Techos Verdes y Sistemas Verdes Verticales que Brindan Múltiples Ecosistemas en el Entorno.

Urban Green Infrastructure: Green Roofs and Vertical Greening Systems Providing Multiple Eco-System Services in the Built Environment.

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Resumen— **El desarrollo sostenible requiere la consideración de toda una serie de elementos interconectados, como la reducción de la demanda de energía y el consumo de agua, la minimización de los residuos y la contaminación y la provisión de un transporte público eficiente. Bajo ese enfoque de "construcción sostenible", el cierre de los ciclos de materiales y agua, así como la reducción del consumo energético son los principales objetivos en el sector de la edificación. En este contexto, el concepto de Infraestructura Verde Urbana (UGI) se ha definido como un conjunto de sistemas de construcción creados por el hombre, pero basados en la naturaleza, como techos verdes y sistemas de ecologización vertical. UGI proporciona varios eco-servicios al entorno urbano, como la reducción de la escorrentía superficial en las grandes ciudades, la reducción del efecto isla de calor, el apoyo a la biodiversidad, la mejora de la durabilidad de las membranas impermeabilizantes y el ahorro de energía en los edificios, entre otros. Durante la última década se han llevado a cabo una serie de acciones de investigación en la Universidad de Lleida con el fin de estudiar estos sistemas constructivos, cuantificar sus beneficios y mejorar su diseño. En este trabajo presentamos estos estudios.**

Palabras Clave— Construcción sostenible; infraestructura urbana verde; techos verdes; sistemas verdes verticales; servicios de ecosistema; edificios.

Abstract — **Sustainable development requires the consideration of a whole host of interconnected elements, such as the reduction of energy demand and water consumption, minimizing waste and pollution, and providing efficient public transport. Under that "sustainable construction" approach, the closing of materials and water cycles as well as the reduction of energy consumption are the main objectives in the building sector. In this context, the concept of Urban Green Infrastructure (UGI) has been defined as a set of man-made, but nature-based, construction systems, such as green roofs and vertical greening systems. UGI provides several eco-services into the urban environment, such as the reduction of surface runoff in large cities, reduction of heat island effect, support to biodiversity, waterproofing membranes durability improvement, and building energy savings, among others. During the last decade a series of research actions have been carried out at the University of Lleida in order to study these construction systems, to quantify their benefits, and to improve their design. In this work we present these studies.**

Index Terms — Sustainable construction; urban green infrastructure; green roofs; vertical greening systems; ecosystem services; buildings.

I. INTRODUCTION

Urban green infrastructure is a set of elements that contribute to the improvement of the city's environment through the provision of multiple services to the urban ecosystem. In recent years, building vegetation integrated systems such as green roofs and vertical greening systems (Figure 1) have been incorporated into the set of traditional solutions such as urban parks, green belts, ecoducts, etc., that allow the implementation of vegetation in new areas and additionally contribute to a more efficient use of urban space in cities.

(a)

(b)

Fig. 1. (a) Roofs at Lleida Agri-food Science and Technology Park (Catalonia, Spain). (b) Green façade at 22@ district in Barcelona, (Catalonia, Spain).

Thus, beyond its incalculable aesthetic and landscape value, the urban green infrastructure contributes to the city scale by reducing the urban heat island (UHI) effect, capturing pollutants and CO, improving the control of urban run-off, decreasing noise, supporting the biodiversity, activating the economy through the generation of employment and urban agricultural production, as well as improving the health of the population thanks to the psychological effects associated to "connection with nature", among other aspects.

At the building scale, these systems also improve thermal and acoustic insulation properties, they protect building materials from weather influence, while buildings are re-valued due to their aesthetic improvements (Pérez and Perini, 2018).

However, it must bear in mind that there are some aspects that penalize the use of urban green infrastructure with respect to traditional grey infrastructure.

In this regard, the potential damages that the use of these systems can cause on the buildings, due for example to the growth of the plants or even to the irrigation systems, as well as the derived extra costs associated to the maintenance, are usually arguments that shift the choice towards solutions more inert and zero maintenance (grey infrastructure) during the design phase.

It is also necessary to consider that current systems, although already being a mature technology in the market, are still based on the use of traditional "not sustainable" materials (plastics, geotextiles, draining materials, etc.).

Finally, and perhaps the most decisive aspect lies in the difficulty to quantify some of the previously listed benefits and to link it to a single property, especially these that influence at the urban level.

Thus, on a common basis, current systems have been designed only considering the most gardening technical criteria in order to guarantee the plants survival, such as substrate composition, irrigation regimes, etc. Further R & D studies must consider also the possibility of maximizing the provision of ecosystem services to the built environment that are energy savings and UHI reduction, noise reduction, support to biodiversity, etc.

II. RESEARCH ON URBAN GREEN INFRASTRUCTURES AT THE UNIVERSITY OF LLEIDA

During the last decade, set of investigations focused on the study of green roofs and vertical greening systems for buildings have been conducted at the University of Lleida. All these research activities have materialized in two doctoral theses (and a third one in progress). During these years, more than 16 scientific articles have been published in high impact indexed journals about this topic, and about 30 contributions in international congresses have been presented.

The main objectives of this research line have been the following:

1) To study the potential of urban green infrastructure in the provision of services to the urban ecosystem:

- Passive energy saving systems in buildings.
- Passive acoustic insulation systems in buildings.

2) To design new urban green infrastructure construction systems according to sustainable criteria (materials, water and energy):

- Replacement of current materials with other more sustainable ones.
- Life Cycle Analysis (LCA) of the designed solutions.

In the following sections, a short description of these investigations as well as their most relevant conclusions will be summarized.

III. EXTENSIVE GREEN ROOFS AS PASIVE TOOLS FOR ENERGY SAVINGS IN BUILDINGS

A. Recycled rubber crumbs as drainage material

This study has a twofold objective. On the one hand, it was intended to measure the potential of extensive garden roofs as a passive energy saving system in buildings under Mediterranean continental climate. On the other hand, the possibility of using recycled rubber crumbs from out-of-use tires as a sustainable alternative to conventional drainage materials such as pozzolana or alveolar plastic membranes (recycled or not) was studied.

To this end, two experiments were carried out in the laboratory in which the drainage potential of different granulometries of recycled rubber was determined and compared with the hydrologic behaviour of pozzolana in order to select the best rubber crumb granulometry to be used in green roofs (Pérez et al., 2012; Vila et al., 2012).

In the next step, two identical extensive green roofs of 9 cm thick (4 cm for drainage layer and 5 cm for substrate layer) were implemented in two identical 3x3x3 m experimental cubicles. The main aim was to characterize their contribution as passive energy saving systems in buildings (Coma et al., 2014; Coma et al., 2016). The only difference between these green roofs was the drainage material used, that was pozzolana in one and recycled rubber crumbs in the other.

These two cubicles, in which no additional insulation layer was installed on the green roof profile, were compared with a third reference cubicle with a conventional flat roof insulated with 3 cm of sprayed polyurethane, finished with gravel ballast (Figure 2). The plants used were a mixture of Sedum sp. and Delosperma sp.

From the results of this experimentation it was be concluded that a 9 cm extensive green roof without additional insulation offered better thermal insulation than a conventional isolated flat roof in cooling periods, but lower in heating periods. On the other hand, recycled rubber was shown as a material to be taken into account as a substitute for current drainage materials, offering better hydraulic and thermal performance than

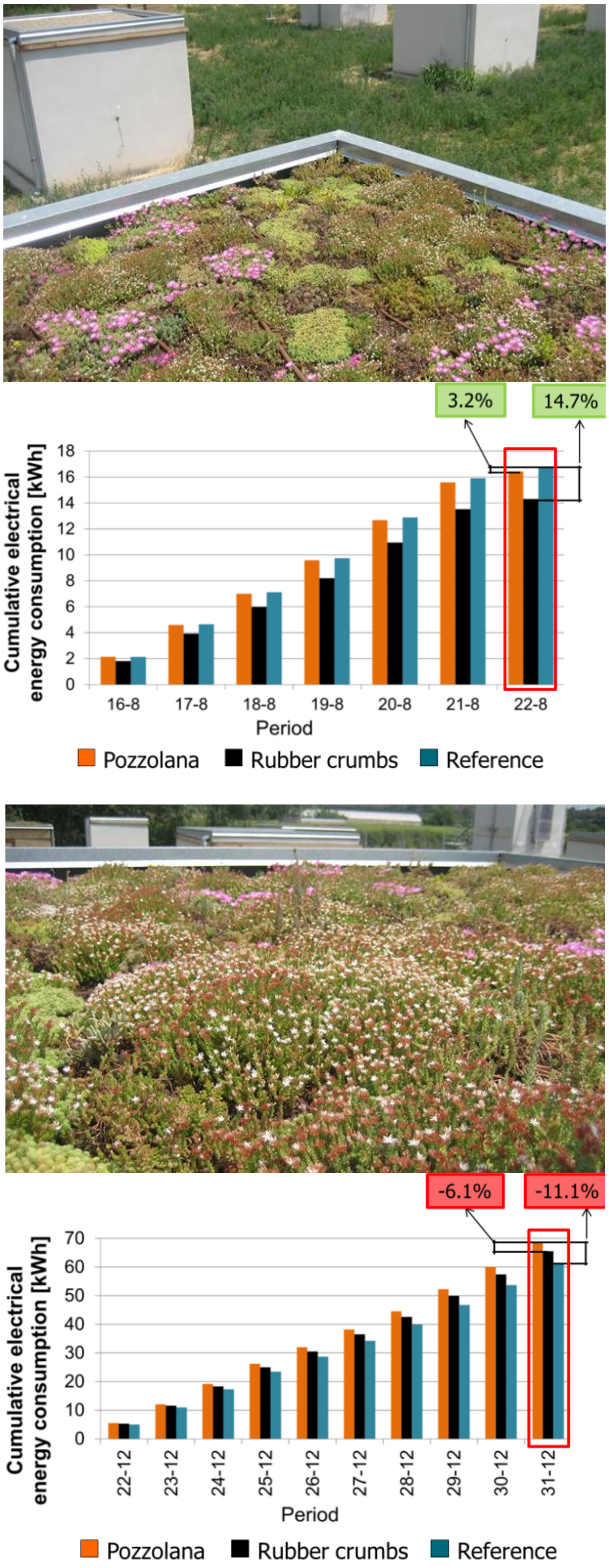


Fig. 2. Experimental extensive green roofs in the "Puigverd de Lleida" pilot plant of GREiA research group - University of Lleida. Results for the energy consumption for summer and winter (Coma et al., 2014; Coma et al., 2016).

pozzolana, while improving the overall sustainability of the construction system (Rincón et al., 2014).

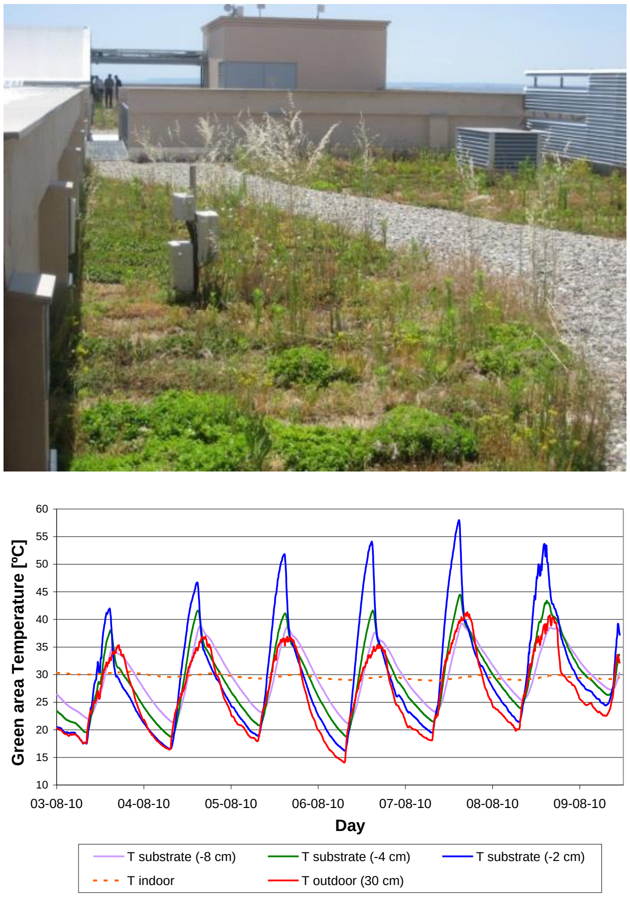


Fig. 3. Green roof "aljibe" typology on the Lleida Agri-food Science and Technology Park (Catalonia, Spain). Results for temperatures through the roof profile (Pérez et al., 2015; Bevilacqua et al., 2015).

B. Green roof case study long-term monitoring: Lleida Agri-food Science and Technology Park (Catalonia, Spain).

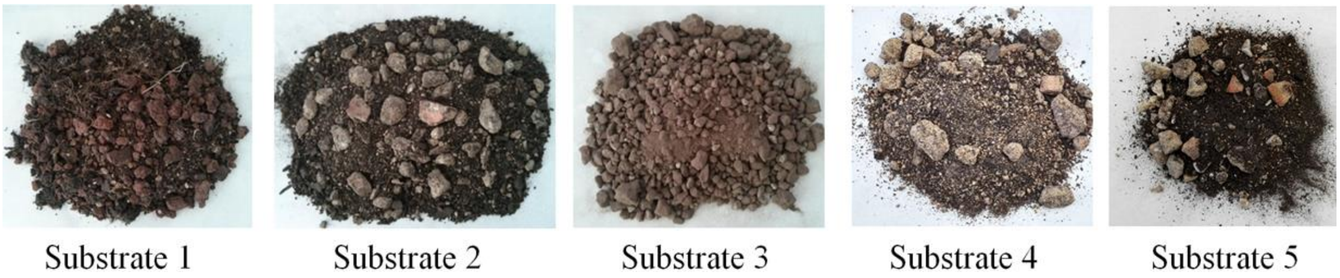
With the aim of characterizing the thermal behavior and the evolution of the plants (Sedum sp.), the extensive 2000 m^2 "aljibe" green roof type located in the Lleida Agri-food Science and Technology Park (Catalonia, Spain) was monitored during four years (Figure 3).

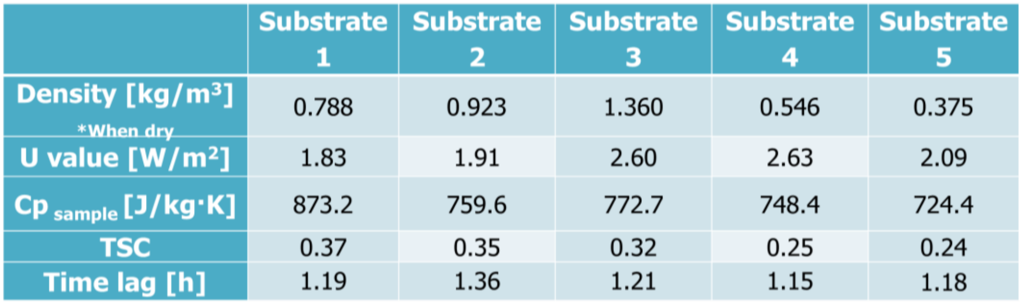
In this experimentation the importance of the substrate as a fundamental element in the thermal behaviour of the roofs was observed. Therefore, the necessity to control the composition of this substrate, not only with the objective of being the physical and nutritional support for plants, but also as a construction material that contributes to the overall functioning of the building (thermal and acoustic insulation, etc.) was highlighted (Pérez et al., 2015).

On the other hand, during these four years of continuous monitoring, the floristic composition evolution was also studied. From the results the heterogeneity on the microclimate generated in a roof was observed. Thus, the influence of differences on the substrate composition and depth, the shadows from the different building elements and facilities, the air currents, etc., led to a different evolution of the floristic composition by zones in the green roof, and consequently differences on the thermal behaviour (Bevilacqua et al., 2015).

C. File Formats For Graphics

One general conclusion derived from previous research was that the substrate in a green roof cannot be considered only from the agronomic point of view, that is, as a physical and nutritional support for the plants. Considering the multi-functionality of green roofs in the built environment, substrate





	Substrate 1	Substrate 2	Substrate 3	Substrate 4	Substrate 5
Density $[kg/m^3]$ *When dry	0.788	0.923	1.360	0.546	0.375
U value $[W/m^2]$	1.83	1.91	2.60	2.63	2.09
Cp_{sample} [J/kg·K]	873.2	759.6	772.7	748.4	724.4
TSC	0.37	0.35	0.32	0.25	0.24
Time lag [h]	1.19	1.36	1.21	1.15	1.18

Fig. 4. Thermo-physical properties of green roof substrates analyzed at the University of Lleida (Coma et al., 2017a).

becomes a key construction material that must be designed taken into account the provision of all these ecosystem services.

For this reason, it is very important to improve the composition of these substrates, so that the provision of these other capacities (thermal, acoustic, etc.) becomes an added value, as stable as possible, for the whole construction system.

With this objective and as a starting point, different laboratory experiments were carried out to characterize the thermal and acoustic properties of different substrates (Figure 4) (Coma et al., 2017a; Fabiani et al., 2018). From the first results of these studies it could be concluded that current substrate compositions contribute positively to improving the thermal and acoustic insulation of the roofs, being the moisture content one of the most critical factors, since by increasing the thermal conductivity compromises the substrate layer insulating capacity.

IV. Vertical Greening Systems as Passive Tools for Energy Savings in Buildings

A. Case study monitoring. Golmés green facade (Golmés, Catalonia, Spain)

In this study, a glycine double-skin green façade (Wisteria sinensis) located in the village of Golmés, Lleida was monitored during two years. From this case study, interesting conclusions regarding the potential of green facades as passive systems of energy saving in buildings were obtained.

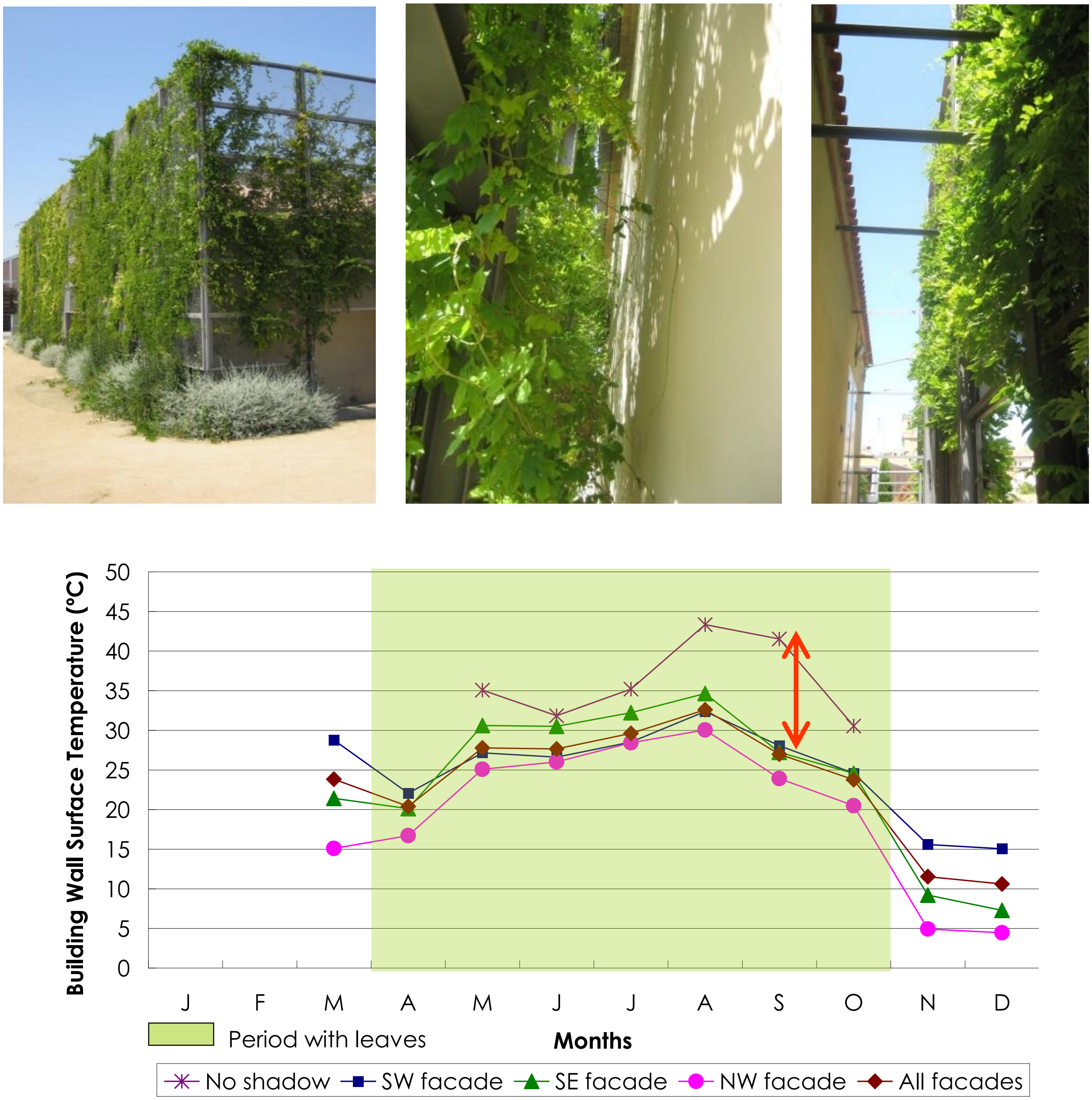
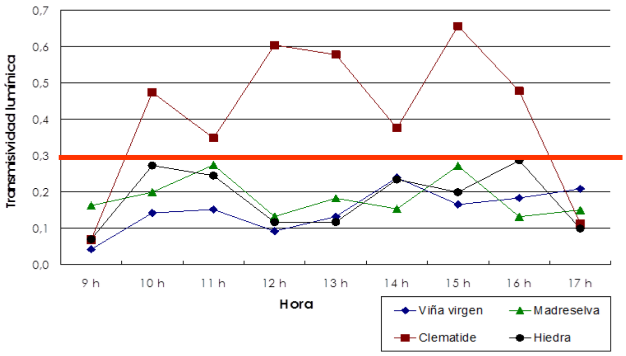


Fig. 5. Surface temperature evolution of the different façade walls in a detached building in Golmés under a double-skin green facade, Lleida (Spain).

The good thermal performance was due to, not only the shadow effect, that is the direct interception of the solar radiation, but also as a consequence of the microclimate generated in the intermediate space between the green screen and the building facade wall. In this sense, the contribution of the cooling effect by means of evapotranspiration from plants was very significant (Figure 5) (Pérez et al., 2011a).



Artificial barrier	shadow factor
Cantilever	0.16 – 0.82
Setback	0.17 – 0.82
Opaque awnings	0.02 – 0.43
Translucent awnings	0.22 – 0.63
Horizontal slats	0.26 – 0.49
Vertical slats	0.32 – 0.44

Fig. 6. First: Evolution of the shadow factor of different plant species used in green facades. Second: Shadow factor provided by different artificial barriers included in the Spanish Technical Building Code.

B. Shadow factor assessment for different climber plants to be used for green facades

In order to characterize the shade factor of different climbing plant species, a specific experimentation was carried out in which four plant species were compared (Pérez et al., 2011b).

From the results it was concluded that the shade factor provided by the green facades is equal, even higher, than the shadow factors proposed by the Spanish Technical Building Code for any of the artificial solar barriers that can be used in buildings (blinds, awnings, setbacks, etc.) (Figure 6). Moreover, it could be taken into account that greenery systems also provide other complementary effects in addition to the shadow effect, such as the cooling effect due to the transpiration of the plants, the wind barrier effect and the insulating effect provided by the intermediate air layer.

C. Comparative study between green facades and Green walls as passive systems for energy savings in buildings.

In a more complete experimentation than the previous ones, two different vertical greening systems were installed in two identical experimental cubicles of 3x3x3 m with the objective of evaluating their potential as passive systems of energy saving in buildings. In the first cubicle, a green facade was implemented in the East, South and West orientations, by means of a steel mesh separated 20 cm from the building facade and Boston ivy (Parthenocissus tricuspidata). On the second cubicle, a green wall, constituted by modules of recycled plastic and aromatic shrubs (Rosmarinus and Helicrissum) was also placed on the same three orientations. A third identical cubicle in which no one greening system was placed was used as reference for the experimentation.

In this experiment, positive results were obtained so that the ability to save energy during summer periods was really very high. The relationship between the vertical solar irradiation and the reduction of the energy consumption provided by the two vertical systems was also found (Figure 7).

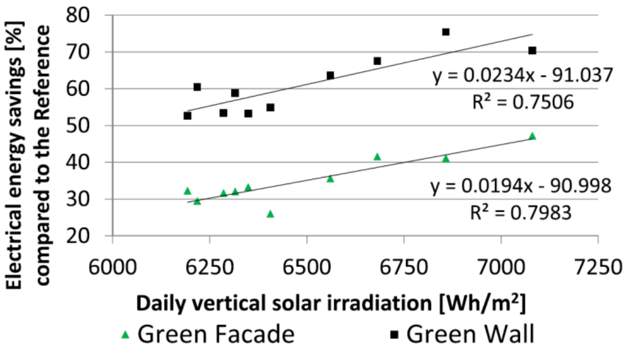


Fig. 7. Relationship between solar irradiation and the reduction on energy consumption due to the effect of vertical greening systems (Pérez et al., 2014; Coma et al., 2017b).

In winter, unlike what is usually said in the non-specialized bibliography, very promising results were observed. Thus, relating to green facade, the cubicle on which this system was placed, behaved equal to the reference cubicle as it was expected, due to the deciduous condition of Boston ivy. On the other hand, the green wall cubicle recorded a slight reduction of 4%, which means a slightly insulating capacity but with a large margin for improvement in the design of these construction system (Figure 8) (Pérez et al., 2014; Coma, J.; Pérez et al., 2017b).

D.Research about the correlation between the foliar density of vertical greening systems and the provided energy consumption.

Given the difficulty to characterize the behavior of these systems, due to the multiple plant species that can be used and considering the great variability of their growth depending on the climatic zone, or even, on the specific micro-climatic conditions, it becomes necessary to look for universal measurement methodologies of their contribution to each service provided to the urban ecosystem.

According to this idea and considering the clear co-relation between leaf volume and the ability of the system to provide

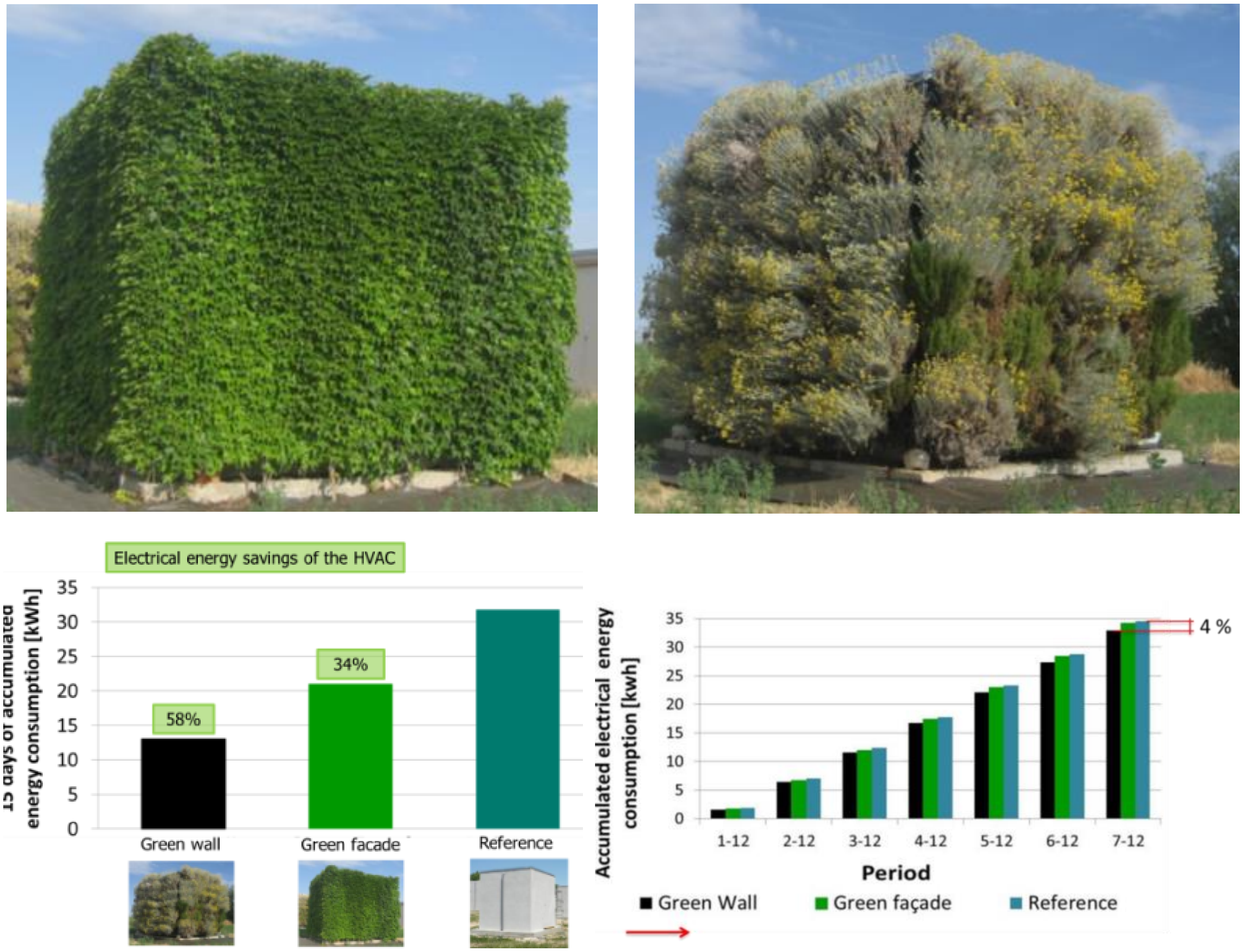


Fig. 8. Left: Green facade on the experimental cubicle and results of summer energy consumption. Right: Green wall on experimental cubicle and winter results (Pérez et al., 2014; Coma et al., 2017b).

energy savings in buildings, a new research line was started. The main objective of this research was to establish and characterize the relation between foliage density and energy savings provided.

For this purpose, the first approach was to measure the Leaf Area Index (LAI) of the green facade used the previous experiments by means two different methodologies. The first one was the direct or destructive method in which all leaves in an square meter must be harvested and individually measured. The second one was the indirect method by means of a ceptometer to measure the light extinction capacity of the foliage as a parameter closely linked to the LAI of this canopy (Pérez et al., 2017).

The results allowed the establishment for the first time of a direct relation between these two parameters, LAI as descriptor of foliage density and external building wall surface temperature as representative passive energy saving potential.

In addition, during the experiments and from the results it also was observed the relationship between the energy savings provided by the green systems and the contribution from each facade orientation. These results will be of great interest to engineers and architects to be used during the design phase (Figures 9 and 10).

V. ACOUSTIC INSULATION PROVIDED BY VERTICAL GREENING SYSTEMS

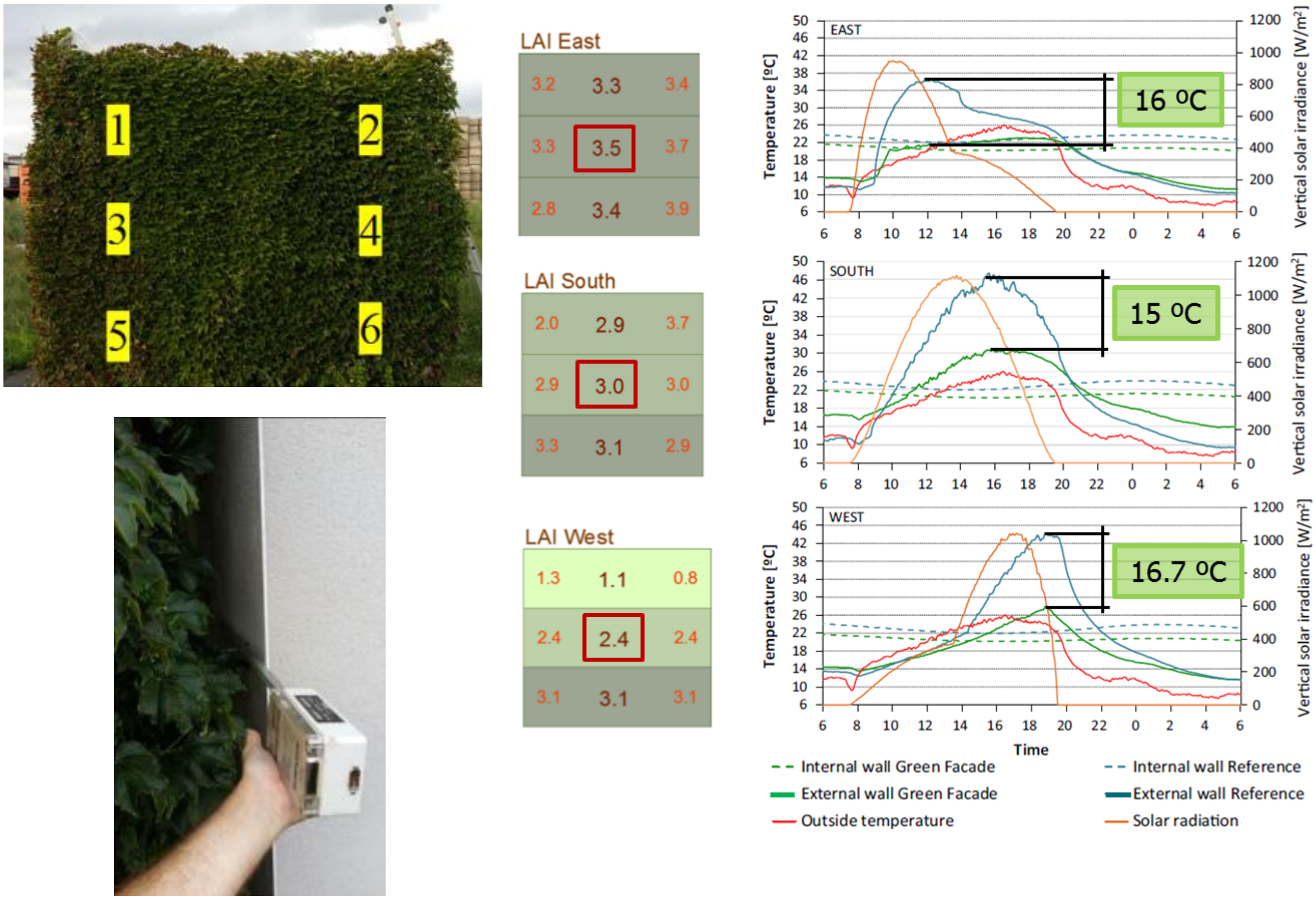
In this research the study of the acoustic performance of the vertical greening systems described in the previous sections was carried out.

The obtained measurements showed that there was an acoustic insulation contribution from the evaluated systems, basically due to the diffraction of the sound waves due to the vegetation, as well as by means of the absorption of the sound in the case of substrate in the green walls. However, the limited thickness of the foliage and the transmission of sound, both by vibration and through the gaps in the systems, make it impossible to obtain better results.

Consequently, there is a great potential for improvements of

	Number of leaves	Leaf average surface (cm²)	Measured leaf area (cm²)	LAI
Upper level	1387	15.08	20914.64	2.1
Middle level	1224	26.29	32185.04	3.2
Lower level	992	39.60	39283.75	3.9

Fig. 9. Direct measurement (destructive) of LAI in a Green façade (Pérez et al., 2017).



LAI East

3.2	3.3	3.4
3.3	3.5	3.7
2.8	3.4	3.9

LAI South

2.0	2.9	3.7
2.9	3.0	3.0
3.3	3.1	2.9

LAI West

1.3	1.1	0.8
2.4	2.4	2.4
3.1	3.1	3.1

Fig. 10. Indirect measurement (ceptometer) of LAI in a Green facade and co-relation with the building facade wall exterior surface temperature (Pérez et al., 2017).

these systems as passive tools for acoustic insulation, especially in the case of the design of green walls (Figure 11) (Azcorra et al., 2015; Pérez et al., 2016).

VI. CHALLENGES FOR THE FUTURE RESEARCH

The results obtained from the research conducted at the University of Lleida and many others carried out worldwide, showed the great potential of the urban green infrastructure in the provision of several and diverse services to the urban ecosystem.

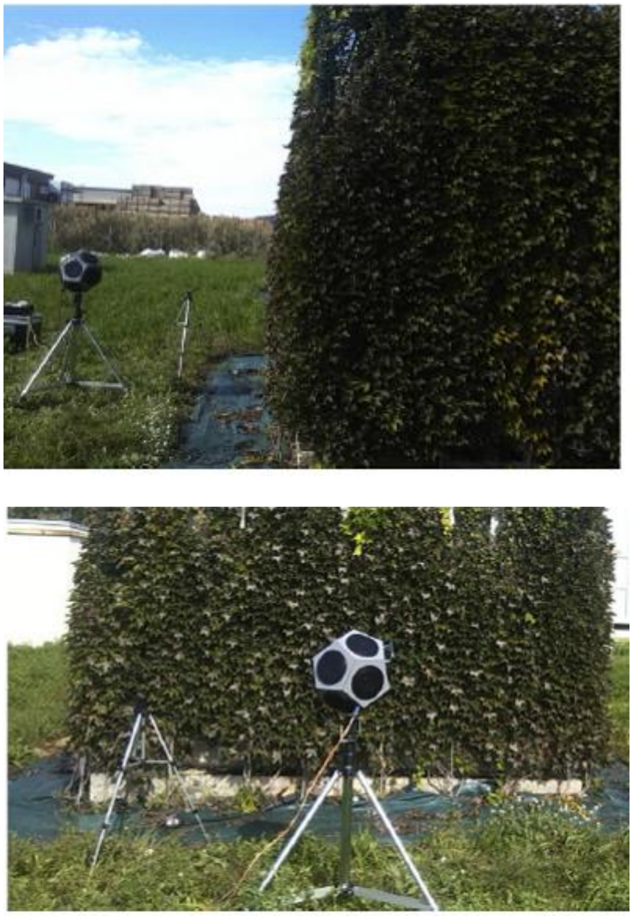


Fig. 11. Data collection for the evaluation of the acoustic insulation capacity of vertical greening systems for buildings (Azcorra et al., 2015; Pérez et al., 2016).

In a society in which environmental criteria are being added to traditional design criteria, that are the aesthetic, functional and economic criteria, nature-based solution are currently increasingly included in engineering, architecture and urban planning projects. For this reason it is necessary to continue investigating and improving these solutions in order to offer a real alternative to the traditional gray infrastructure solutions.

The challenges faced by these constructive systems are especially aimed at overcoming the barriers that are currently limiting their full deployment in urban environments.

Specifically, two of these challenges stand out:

1) The quantification of all the provided benefits provided (ecosystem services), but also the negative impacts (disservices), in order to obtain an adequate catalog of indicators and realistic and useful metrics to be used by the end users (designers, engineers, architects, city planners, manufacturers, etc.).
2) The improvement and design of new solutions considering not only the survival and good development of the plants, but the provision of multiple services to the urban ecosystem.

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