UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR DE ARQUITECTURA

OPTIMIZACIÓN DE UN MÓDULO DE JARDINERÍA VERTICAL PARA LA MEJORA DEL CONFORT EN ENTORNOS URBANOS DENSOS

Tesis doctoral

Valentina Oquendo Di Cosola

Arquitecta

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DEPARTAMENTO DE CONSTRUCCIÓN Y TECNOLOGIA ARQUITECTÓNICAS

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RESUMEN

Las ciudades desempeñan un rol fundamental en la respuesta a los complejos retos medioambientales y sociales actuales como el cambio climático. El concepto de solución basada en la naturaleza (SBN), se identifica en el discurso científico y es reconocido internacionalmente como parte de la solución para abordar estos retos. Las diferentes técnicas de introducción de la naturaleza en los contextos urbanos buscan dar respuesta a problemas como la isla de calor urbana, la contaminación atmosférica o la contaminación acústica. En este contexto, los jardines verticales como parte de las soluciones basadas en la naturaleza ofrecen una serie de servicios ecosistémicos que tienen un impacto positivo en la salud y bienestar de las personas en los entornos urbanos.

Estudios previos han demostrado que la integración de la vegetación en los edificios, a través de jardines verticales, influye positivamente en el confort dentro y fuera del edificio, a la vez que provee beneficios ecológicos y medioambientales tales como: mejora de la calidad del aire y reducción de la contaminación atmosférica (Irga et al., 2017; Weerakkody et al., 2018a, 2018b), reducción del efecto isla de calor urbana debido a la reducción de calor irradiado por la vegetación y la humedad afectada por la evapotranspiración (Bartesaghi Koc et al., 2018; Imran et al., 2019; Zhang et al., 2019), ahorro de energía en los edificios (Andric et al., 2020; Cameron et al., 2015; N. C. N. H. Wong et al., 2010), o aumento de la biodiversidad (Ling and Chiang, 2018; Mayrand and Clergeau, 2018). Además de estos beneficios directos e indirectos, también produce

mejoras sociales y económicas relacionadas con la cohesión social, la generación de empleo y los beneficios psico-perceptivos (Perini and Rosasco, 2013a; Ruggeri et al., 2016; Vujcic et al., 2017).

Dado que existe un creciente interés por estas soluciones y son cada vez más las tecnologías puestas a disposición en el mercado, esta tesis doctoral propone desarrollar un análisis de las prestaciones de un módulo de jardinería vertical para establecer líneas de optimización, con el fin de incrementar su aporte en la mejora del confort en contextos urbanos densos. Este objetivo se aborda desde una visión integral, partiendo de un análisis de ciclo de vida para la selección de un sistema con el menor impacto medioambiental posible, cubriendo el análisis del impacto sobre la reducción de temperaturas y la absorción de ruido, y finalizando en una etapa analítica que permitió identificar las variables que influyen en su rendimiento.

La parte experimental de esta tesis doctoral se apoya en el desarrollo de campañas de monitorización y pruebas de laboratorio, a partir de las cuales se han obtenido los datos de las condiciones higrotérmicas y de absorción de ruido que se producen en el entorno inmediato de los módulos de jardinería vertical estudiados. Estos registros de temperatura, humedad relativa, irradiancia, y coeficientes de absorción acústica han sido útiles tanto para analizar el comportamiento del módulo, como para identificar los componentes que tienen una mayor influencia y deben ser optimizados para asegurar el máximo rendimiento.

Los resultados obtenidos muestran los beneficios de diseñar sistemas de jardinería vertical con sustratos orgánicos y sistemas constructivos a partir de materiales reciclables, para con ello garantizar un menor impacto medioambiental durante la vida útil del sistema. Asimismo, se comprobó el efecto termorregulador de los jardines verticales en su entorno inmediato, que puede llegar a reducir hasta 0.6 °C y 2.3% HR a 1.00 m de distancia. En cuanto a la absorción acústica, se identificaron cuatro variables fundamentales que garantizan y maximizan el efecto de absorción acústica:

- Sustratos orgánicos y gruesos (constituyen el 80% de la absorción),
- Vegetación de tallos gruesos y densa (suponen el 20% de la absorción),
- Saturación del sustrato (el exceso de agua disminuye un 43% la capacidad de absorción),
- Uso de materiales porosos que cumplen tanto la función de mantener la humedad en el módulo y contener el substrato, como de absorción acústica.

Este trabajo de investigación confirma la relevancia de la envolvente vegetal en el entorno urbano, así como la importancia de considerar una serie de factores como el tipo de sustrato y vegetación a la hora de diseñar y poner en funcionamiento este tipo de soluciones. Los resultados obtenidos pueden contribuir a mejorar el diseño de módulos de jardinería vertical, y a ofrecer datos concretos de los beneficios y con ello fomentar su aplicación tanto a través de su regulación en la construcción como de su consideración como un elemento del espacio urbano en la planificación de las ciudades.

ABSTRACT

Cities are essential in responding to today's complex environmental and societal challenges, such as climate change. The concept of the Nature-based Solution (NBS) is identified in scientific discourse and is internationally recognised as part of the solution to address these challenges. Different techniques for introducing nature into urban contexts attempt to respond to problems such as the urban heat island, atmospheric pollution, or noise pollution. In this context, green walls are presented as a solution offering a range of ecosystem services that positively impact the health and well-being of people in urban environments.

Recent studies have shown that the integration of vegetation into buildings through green walls positively influences comfort in and around the building and provides ecological and environmental benefits such as improvement of air quality and reduction of air pollution (Irga et al., 2017; Weerakkody et al., 2018a, 2018b), reduction of the urban heat island effect due to the reduction of heat radiated by vegetation and humidity affected by evapotranspiration (Bartesaghi Koc et al., 2018; Imran et al., 2019; Zhang et al., 2019), energy savings in buildings (Andric et al., 2020; Cameron et al., 2015; N. C. N. H. Wong et al., 2010), or increased biodiversity (Ling and Chiang, 2018; Mayrand and Clergeau, 2018). In addition to these direct and indirect benefits, it also produces social and economic improvements related to social cohesion, employment generation and psychoperceptual benefits (Perini and Rosasco, 2013a; Ruggeri et al., 2016; Vujcic et al.,

2017).

Since there is a growing demand for these solutions and the number of technologies available on the market is increasing, this PhD thesis proposes to develop an analysis of the performance of a green wall module to establish lines of optimisation to increase its contribution to improving comfort in dense urban contexts. This objective is approached from a holistic viewpoint, starting with a life cycle analysis for the selection of a system with the lowest possible environmental impact, covering the analysis of the impact on temperature reduction and noise absorption, and going through an analytical stage to identify the variables that influence its performance.

The experimental phase of this PhD thesis is based on the development of monitoring campaigns and laboratory tests, which were used to obtain data on the hygrothermal conditions and noise absorption in the immediate environment of the green wall modules studied. These records of temperature, relative humidity, irradiance, and sound absorption coefficients have served to analyse the module's behaviour and identify the components that have the most significant influence and must be optimised to ensure maximum performance.

Results demonstrate the benefits of designing green walls with organic substrates and construction systems based on recyclable materials, thus ensuring a lower environmental impact during the system's lifetime. Furthermore, the thermoregulatory effect of vertical gardens on their immediate environment was tested, which can reduce up to 0.6 °C and

2.3% RH at 1.00 m distance. In terms of acoustic absorption, four fundamental variables have been identified that guarantee and maximise the acoustic absorption effect:

- Organic and thick substrates (80% of absorption)
- Thick and dense stemmed vegetation (20% of absorption)
- Substrate saturation (excess water decreases absorption capacity by 43%)
- Use of porous materials that fulfil both a structural and an acoustic absorption function.

This research confirms the relevance of the vegetation envelope in the urban environment, as well as the importance of considering a series of factors, such as the type of substrate and vegetation, when designing and implementing this type of solution. The results obtained can contribute to improving the design of vertical gardening modules and provide concrete data on the benefits and thus encourage their application through their construction regulation and consideration as an element of urban space in city planning.

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PARTE I. INTRODUCCIÓN, HIPÓTESIS, OBJETIVOS Y METODOLOGÍA

En este primer apartado se presenta la introducción al sistema de la ciudad como contexto ideal para promover la introducción de Soluciones basadas en la Naturaleza como elemento clave en la planificación urbana para la mitigación y adaptación del cambio climático, el concepto de confort en entornos urbanos densos, y los antecedes del uso de sistemas de jardinería vertical para la mejora de la reducción de temperaturas y de la absorción de ruido en ciudades. El desarrollo de esta revisión ha contribuido a la formulación de la hipótesis y los objetivos de esta tesis doctoral.

1. **Introducción**
    - 1.1. La ciudad y el cambio climático
    - 1.2. El confort en entornos urbanos densos
    - 1.3. La implementación de Soluciones basadas en la Naturaleza como herramienta de mitigación y adaptación
    - 1.4. La envolvente vegetal en el edificio
2. **Hipótesis y objetivos**
3. **Metodología**

1. Introducción

1.1. La ciudad y el cambio climático

El crecimiento no planificado de las ciudades ha generado una desvinculación del medio urbano y la naturaleza. La ciudad contemporánea ha crecido sin relación alguna con los índices demográficos y las necesidades propias de la ciudadanía, trayendo consigo una serie de retos sociales, económicos y medioambientales como son el cambio climático, la contaminación atmosférica y los bajos índices de calidad del aire, el aumento de los residuos, la pobreza energética, la disminución de reservas de agua, entre otros. Todo esto ha puesto de manifiesto a lo largo de los últimos años la necesidad de repensar y reconfigurar el modelo de ciudad actual.

Según cifras de ONU Habitat, las ciudades son responsables del 70% del consumo de energía global y el 70% de las emisiones de carbono, aun cuando cubren solo el 2% de la superficie terrestre. Cuando además se incluyen las emisiones de gases de efecto invernadero asociadas al sector de la construcción, debido a los sistemas de calefacción y refrigeración, la producción de agua caliente sanitaria, el uso de energía para electrodomésticos y otros equipos, el promedio es del 40% de las emisiones (ONU-Habitat, 2011).

Esta problemática formó parte en 2015 de la Conferencia de las Partes de la Convención Marco de Naciones Unidas sobre Cambio Climático (COP21 – CMP11) en París, dando lugar a una declaración de principios en la que se determinó el medioambiente y el cambio climático como principales vectores de transformación del siglo XXI. Asegurando que las ciudades debían direccionar sus esfuerzos para evitar las consecuencias del cambio climático, y comprometerse a la descarbonización de la economía y el mantenimiento de la temperatura de la tierra por debajo de los 2 ºC con respecto a los niveles preindustriales (Nations, 2015a).

En el año 2016 se realizó la Conferencia de Naciones Unidas sobre Vivienda y Desarrollo Urbano Sostenible, Hábitat III, con el objetivo de debatir sobre los nuevos desafíos globales y la implementación de los nuevos Objetivos de Desarrollo Sostenible (ODS) (Habitat III Secretariat and United Nations, 2017). A partir de esta conferencia se aprueba la Nueva Agenda Urbana (NAU), intrínsecamente relacionada con el ODS11: Ciudades y Comunidades Sostenibles. Este objetivo conlleva a la solución de retos de la ciudad densa y congestionada del siglo XXI, como el cambio climático, el incremento de la desigualdad, las migraciones forzadas y el aumento de los asentamientos informales.

Alineado a esta nueva agenda, se firmó el Pacto de Ámsterdam en 2016, por el que se creó la Agenda Urbana Europea (AUE), como un nuevo método de trabajo para abordar las problemáticas actuales de las ciudades y el territorio. Dentro de los temas prioritarios destacan el uso sostenible del suelo y las Soluciones basadas en la Naturaleza, la adaptación al clima y la calidad del aire.

Este contexto de agendas y nuevos compromisos ha promovido el trabajo a nivel nacional y regional en distintos países. En España, se está promoviendo el desarrollo de instrumentos de política pública que pretenden apoyar a las ciudades y territorios a alcanzar la neutralidad climática, como la Agenda Urbana Española (AUE) (Ministerio de Transportes, 2019) o la Misión Europea de Ciudades (European Commission, 2021a). Ambas promueven el desarrollo de hojas de ruta y planes de acción climática, en las que ciudades como Barcelona, Madrid, Sevilla, Valencia, Valladolid, Vitoria-Gasteiz y Zaragoza, entre otras muchas ciudades, han apostado por introducir la naturaleza como una herramienta de planificación urbana a corto, medio y largo plazo, lo que les permitirá alcanzar nuevos modelos de ciudad sostenibles, resilientes y justos.

El concepto de ciudad sostenible lleva intrínseco otros conceptos que abarcan el ámbito social, económico y ambiental. Según el reporte Brundtland, la ciudad sostenible es "*aquella capaz de satisfacer las necesidades presentes sin sacrificar la capacidad de las generaciones futuras de satisfacer sus propias necesidades*" (United Nations, 1987). La preocupación por asegurar un futuro justo y sostenible en las ciudades ha promovido la búsqueda de una ciudad comprometida con el medio ambiente, relacionada con el clima local, autosuficiente y que gestiona su territorio de forma controlada.

Es posible ver los grandes retos a los que nos enfrentamos, como oportunidades de transformación, y así lo demuestran las agendas globales. La contaminación, la sobrepoblación, el cambio climático y sus efectos, las mejoras en la salud y el bienestar de las personas pueden promover importantes cambios que basados en la colaboración y la investigación aporten valor y den forma a un futuro de ciudades y entornos urbanos sostenibles.

1.2. El confort en entornos urbanos densos

Establecer una definición estándar de confort urbano resulta complejo y en muchos casos imposible dada la variedad de casuísticas. Se entiende el confort como el conjunto de condiciones óptimas que deben coincidir simultáneamente en un espacio para lograr su máximo aprovechamiento o disfrute en una actividad o momento concreto (Piselli et al., 2018).

El confort urbano viene determinado por distintos factores: condicionantes térmicos, escala urbana, ocupación del espacio, paisaje sonoro, calidad del aire, ergonomía de los elementos del espacio, entre otros. Dichos parámetros al estar interconectados provocan que la alteración de uno de ellos repercuta en la calidad de los demás. De todos los aspectos relevantes para el estudio del confort urbano, esta tesis doctoral considera únicamente los relacionados con el confort térmico y acústico.

El confort térmico se refiere a la condición de la mente, que expresa la satisfacción con el ambiente térmico exterior (Atmaca et al., 2007). Diferentes factores afectan a la conformidad térmica en el espacio exterior: temperatura del aire, humedad, velocidad del viento, radiación solar, radiación terrestre, calor metabólico y aislamiento de la ropa (Mazhar et al., 2015). En la evaluación del ambiente térmico exterior, la condición micro climática y los componentes fisiológicos son esenciales para un mejor confort térmico (Chan et al., 2017; Javadi, 2021). Sin embargo, es posible determinarlo de una forma objetiva utilizando diagramas climáticos y tablas de correcciones que los adaptan a distintas latitudes. Investigaciones afirman que la temperatura de confort efectiva en invierno es de 23 ºC, mientras que en verano es de 25 ºC, ambas medidas en ambientes en calma con hasta un 50% de humedad relativa (Francisco Javier Neila González, 1997).

Por otro lado, el confort acústico en una ciudad depende en gran medida del ruido provocado por el tráfico rodado. Un fenómeno producto de la integración del vehículo a motor en el paisaje urbano. En indicadores desarrollados por la Agencia de Ecología Urbana de Barcelona para ciudades grandes y medianas, se establece que las condiciones mínimas para alcanzar el confort acústico se cumplen con un 60% de la población expuesta a menos de 65 dbA, mientras que las condiciones óptimas se alcanzan con un 75% de la población expuesta a menos de 65 dbA (Rueda, 2010).

La morfología urbana juega un papel critico en los factores que influyen en el confort urbano. Aspectos como el patrón de crecimiento urbano, la orientación de los edificios, la superficie edificada, la geometría de la ciudad, y los materiales y técnicas empleadas, generan importantes variaciones en los parámetros climáticos que rigen la percepción humana. Estudios han demostrado la estrecha relación que existe entre la caracterización urbana y las modificaciones micro climáticas que pueden surgir a partir de ello (Horrison and Amirtham, 2016).

En la relación entre el medioambiente y la configuración del espacio urbano surgen una serie de problemáticas producto de las actividades humanas, como la contaminación del aire (WHO, 2003), la contaminación sónica debido al tráfico rodado (Ottelé et al., 2010), altas temperaturas y el efecto isla de calor urbana debido al tipo de materiales utilizados para la construcción y a la propia impermeabilización de la mayor parte de las superficies en la ciudad (Karakounos et al., 2018). Para asumir estos retos, será necesario transformar los modelos actuales a través del diseño de nuevas infraestructuras y la implementación de soluciones que ayuden a mejorar las condiciones climáticas de los espacios urbanos (Yahia et al., 2018).

El vínculo entre el diseño urbano, el microclima, el confort, y variables como la altura de los edificios y su orientación, el espacio entre los edificios, la incidencia solar y la velocidad del viento puede determinar la importancia de incluir vegetación, dispositivos de sombra y barreras antirruidos en las envolventes de los edificios (Yahia and Johansson, 2014). Estudios aseguran que la ventilación y la sombra son elementos cruciales para mejorar el confort (Cheng et al., 2010), condiciones que ofrece la vegetación, además de contribuir a la reducción de temperaturas externas y de flujos de calor internos.

A pesar de la tendencia al aumento de densidad en las ciudades, es necesario asegurar condiciones de vida sanas, seguras, y propicias para garantizar el desarrollo sostenible y el valor social. Aunque el bienestar humano dependa de una serie de factores externos y en algunos casos subjetivos, también está estrechamente condicionado por el diseño de los espacios, que a menudo escapan del control individual y que deben considerarse parte de una planificación urbana estratégica sostenible.

1.3. La implementación de Soluciones basadas en la Naturaleza como herramienta frente al cambio climático

La Comisión Europea define las soluciones basadas en la naturaleza (SBN) como aquellas que "*aprovechan el poder y la sofisticación de la naturaleza para convertir los retos medioambientales, sociales y económicos en oportunidades de innovación. Pueden abordar una serie de retos sociales de manera sostenible, con el potencial de contribuir al crecimiento ecológico, a la preparación del futuro de la sociedad, a la promoción del bienestar de los ciudadanos, a la creación de oportunidades de negocio, y al posicionamiento de Europa*" (European Commission and Union, 2015).

El uso de la vegetación a través de nuevas tecnologías como las soluciones basadas en la naturaleza surge a partir de la innovación en la relación clima-ciudad (Kabisch et al., 2016) – un campo de investigación que promueve el diseño y la implementación de soluciones que usan la vegetación como una herramienta, contribuyendo a alcanzar las tres dimensiones de la sostenibilidad, a través de la mitigación del cambio climático, la reducción de consumos energéticos y de emisiones, la cohesión social en espacios más habitables. y el confort urbano (Xing et al., 2017).

En la dimensión ambiental de la sostenibilidad, el resultado de estos vínculos es un modelo urbano de bajas emisiones, que actúa sobre dos principales aspectos: por un lado, sobre los edificios, su demanda de energía, materiales y diseño, fomentando las alternativas sostenibles no dependientes de energías no renovables. Por otro, actuando sobre el entorno inmediato y sobre la regeneración del microclima urbano.

En cuanto a la dimensión social, es importante considerar que la salud y el bienestar de las personas deben formar parte de la planificación de las ciudades. Diseñar sin tenerlo en cuenta, nos conduce a problemas de desigualdad y segregación importantes, ya que no solo nos enfrentamos a la contaminación y al alza de las temperaturas, sino también a la falta de interacción social y a la ausencia de espacios que promuevan el sentido de comunidad e igualdad. Incorporar naturaleza en las ciudades contribuye a promover un modelo de ciudad sostenido en espacios saludables, resilientes y justos.

El concepto de las Soluciones basadas en la Naturaleza ha sufrido una evolución importante desde el año 2000 hasta nuestros días. Ha pasado de un enfoque unilateral en el que solo se aborda la protección y conservación de áreas protegidas y especies emblemáticas, a entender la relación que esto tiene con las personas, la ecología, la economía y la sociedad. A partir de 2009 se empezaron a considerar medidas innovadoras para alcanzar economías y modelos sostenibles (Kabisch et al., 2016), y hoy en día el debate se centra en los seres humanos y los factores sociales en los que pueden influir como el bienestar humano, la reducción de la pobreza, el desarrollo socioeconómico y los principios de gobernanza (Lafortezza and Sanesi, 2019).

En ese sentido, la Unión Internacional para la Conservación de la Naturaleza (UICN) desarrolló un estándar global que lo convierte en un concepto paraguas capaz de cubrir una serie de enfoques distintos, integrar otro tipo de soluciones, y adecuar la escala de las intervenciones a la dimensión de los problemas (UICN, 2020). Todo esto con el objetivo de incorporar estas soluciones en la planificación de los territorios y en el diseño de las políticas públicas.

A partir de la evolución del propio término y del ámbito de investigación, se ha determinado que las soluciones basadas en la naturaleza no sólo tienen un valor estético, sino que además se convierten en bienes urbanos comunes que a través de una correcta experimentación y cuantificación de sus impactos, pueden ser difundidas e implementadas desde los gobiernos locales, e incluso diseñadas en procesos ciudadanos que den a conocer los beneficios de su uso, mantenimiento y replicación en las ciudades (Frantzeskaki, 2019).

1.4. La envolvente vegetal en el edificio

La evolución de la sociedad y sus necesidades ha provocado el surgimiento de nuevas técnicas y materiales en la arquitectura. En la enciclopedia "*Vernacular Architecture of the World*" (Oliver P., 1997), Paul Oliver define la arquitectura vernácula como aquella que "*comprende las viviendas y todos los demás edificios en relación con los contextos ambientales y los recursos disponibles. Todas las formas de arquitectura vernácula se construyen para satisfacer necesidades específicas, acomodando los valores, las economías y formas de vida de las culturas que la producen*". Las especificidades de esta tipología, sus parámetros de habitabilidad, el modo de vida de sus ocupantes y las técnicas de construcción tradicionales afectan al confort térmico dentro y fuera del edificio (Costa-Carrapiço et al., 2022).

Las actuales técnicas de integración del verde en la arquitectura pertenecen de alguna forma a la arquitectura vernácula o tradicional, si la consideramos una respuesta intuitiva que secunda los métodos de construcción, materiales disponibles y condiciones climáticas, en congruencia con la funcionalidad social y física de quien habita. A pesar de las carencias, la arquitectura vernácula ha logrado dar respuesta a las necesidades de protección y abrigo del ser humano, junto con una alta adaptación, integración y respeto al medioambiente.

El concepto de sistemas de jardinería vertical o "*Vertical Greening Systems* (VGS)" se ha introducido recientemente en el diseño arquitectónico, y se debe principalmente a los beneficios ambientales y psicológicos que se le atribuyen, dentro de los que destacan la mitigación del efecto isla de calor urbana (Gago et al., 2013), aislamiento de ruido (Gabriel Pérez et al., 2016a), reducción de consumos energéticos (Azkorra et al., 2015a), fijación de partículas en suspensión y gases contaminantes como los Compuestos Orgánicos Volátiles (COVs) (Liu et al., 2013), aumento de la biodiversidad (Perini et al., 2011), y el bienestar psicológico (Pioppi et al., 2020).

La vegetación ha tenido un rol importante en la evolución de la arquitectura, debido a su capacidad de transformación, no solo a nivel estético, sino a través del juego de luces, colores y sombras. El uso de la vegetación en el proyecto arquitectónico ha ido evolucionando, y, en la historia de la arquitectura se pueden encontrar diversos ejemplos de su empleo, que en la mayor parte de los casos es incorporada a superficies horizontales o verticales, como un reto de recreación de paisajes naturales dentro de una construcción artificial.

Dentro de los principales ejemplos se encuentran las *Turf House* en Islandia (Figura 1), casas realizadas en estructura de madera, con techos construidos a partir de tablas sobre las cuales se añadían estratos de corteza impermeabilizantes. Las paredes se construían con fundaciones y losas en piedra en modo tal de separar el terreno de la estructura elevada, dichas paredes se revestían de sustrato inerte de 50 a 150 cm a efectos aislantes; este sistema puede ser considerado como el predecesor de los módulos de jardinería vertical.

No existe un punto de partida preciso del uso de la vegetación como técnica constructiva, la literatura hace referencia al siglo VI y los jardines colgantes de Babilonia, en los que la vegetación proveía sombra a las fachadas, y se buscaba acentuar en algunos puntos y aligerar en otros la composición arquitectónica (Köhler, 2008). En el siglo XX, el uso de la *Hedera Helix*., como herramienta de cobertura de fachadas de ladrillo fue un concepto muy difundido (Bartfelder et al, 1987). Hoy en día el desarrollo de sistemas de verde vertical representa uno de los últimos avances tecnológicos en el campo del revestimiento de paredes a fines medioambientales (Manso and Castro-Gomes, 2015).

Figura 1: Turf House, Islandia

Fuente: treehugger.com; guidetoiceland.is *(Fecha de acceso: 06/09/2022)*

También en la cultura romana la vegetación fue protagonista, el uso de pérgolas tales como las proyectadas en la *Villa dei Misteri di Pompei* o la *Villa Adriana di* Tivoli (Figura 2), con la finalidad de integrar el edificio al paisaje por medio de galerías que albergaban jardines colgantes. En esta misma línea, durante el periodo gótico los muros de las iglesias, palacios y patios se cubrían de flores con la finalidad de aligerar el estilo.

Atravesando los distintos periodos de la arquitectura, se encuentra también el renacimiento, movimiento arquitectónico que estableció el redescubrimiento del estilo romano y con este, el paisajismo. Sucesivamente se desarrollaron corrientes de nuevos estilos que también incorporaban la naturaleza, por ejemplo, el clasicismo y el barroco, donde se buscaba instaurar el concepto de arquitectura de la naturaleza, o, en otras palabras, la naturaleza se consideraba una extensión de la arquitectura.

Figura 2: Villa Adriana di Tivoli, Roma

Fuente: www.visittivoli.eu *(Fecha de acceso: 06/09/2022)*

En siglos posteriores no se desarrollaron mayores evoluciones en el uso de la vegetación, fue a partir de la revolución industrial cuando se retoma la importancia de la naturaleza en los espacios y su rol en la salud humana y la calidad de la vida de los seres humanos (Weinmaster, 2009)

El estilo orgánico como movimiento arquitectónico derivado del funcionalismo del siglo XX, fue patentado por Frank Lloyd Wright, el termino se debe a la introducción de la arquitectura "orgánica" bajo el lema "forma y función son uno", que posteriormente se convirtió en el prólogo de la arquitectura moderna. El objetivo era mimetizar la naturaleza con el edificio, buscando reinterpretar sus principios y correspondiendo en función, forma y materiales, es decir, el proyecto debía tener las características para integrar el lugar y sus condiciones naturales.

La contribución del movimiento moderno en esta tendencia tuvo un rol fundamental, otro arquitecto que contribuyó en este periodo fue Charles-Edouard Jeanneret (Le Corbusier), quien introdujo el concepto del techo jardín con el objetivo de promover el verde en la ciudad. En su colección “*Towards a new architecture*” (1923) expuso la idea de la arquitectura moderna y estableció cinco puntos esenciales, el quinto se extendía en el uso de jardines en techos para compensar el área urbana que cubría el edificio (Carlis W., 1986) (Figura 3).

Figura 3: Casa Kaufmann (1937), Frank Lloyd Wright

Fuente: epdl.com; arqred.mx. *(Fecha de acceso: 06/09/2022)*

Después de la segunda guerra mundial y la transformación social que esta produjo, las técnicas constructivas y las estrategias de sostenibilidad que en un tiempo existieron, pasaron a un segundo plano, dando prioridad a la reconstrucción de las ciudades y a la estandarización de la arquitectura. Como resultado, el sector de la construcción pasó a ser poco responsable con el ambiente y, paralelamente, el consumo de recursos para la producción de energía y la construcción tuvo un crecimiento importante, llevando a la crisis energética de los años 70. Este contexto promovió el surgimiento de la arquitectura responsable con el ambiente, interesada en el uso de energías renovables, con el principal objetivo de contribuir a la sostenibilidad de las ciudades y el uso responsable de los recursos.

A finales de 1880 surgen las primeras investigaciones científicas sobre temas de vegetación y fachadas. Bajo el término "fachadas vegetales", desde 1880 y hasta 1940 cerca de 200 artículos fueron documentos en las revistas más importantes del momento (Sheweka and Mohamed, 2012). En 1990, y a gracias al grupo SITE (*Sculpture in the Environment*), se inicia a experimentar con la vegetación como un elemento técnico del proyecto de arquitectura con la misma importancia que podían tener otros. Surgen durante este período arquitectos como Emilio Ambasz, quien se basaba sobre premisas del SITE para proponer el concepto de "*Green Town*" en el que la relación entre lo artificial y lo natural era fundamental. Uno de sus proyectos más conocidos fue el *Fukuoaka Prefectural National Hall* (1990) en Japón (Figura 4), un edificio simbólico con amplias terrazas y jardines colgantes en cada planta.

Figura 4: Fukoaka Prefectural National Hall, Japón

Fuente: greenroofs.com *(Fecha de acceso: 06/09/2022)*

Las investigaciones recientes en este ámbito van más allá de la relación con la naturaleza, y gracias a la contribución del investigador y botánico francés Patrick Blanc, esta técnica se ha transformado en un arte difundido. Su trabajo se concentró sobre las plantas subtropicales, y la propuesta tecnológica que realizó buscaba emular el crecimiento en vertical de estas plantas en su ámbito natural, utilizando un sistema continuo de jardinería vertical separado de la estructura de soporte para dejar pasar el aire, un marco metálico, un estrato de PVC y uno de fieltro sobre los que se inserta la vegetación (Figura 5).

Figura 5: Mur Vegetal – Patric Blank, Caixa Forum, Madrid

Fuente: ingegneri.info *(Fecha de acceso: 06/09/2022)*

La investigación en el ámbito de la sostenibilidad ha llevado a la idea de un nuevo modelo de ciudad, en el que el edificio es un instrumento capaz de transformar el aire, la incidencia solar, el agua, la vegetación y otras materias primas, en recursos. Esto establece una nueva relación entre arquitectura y clima, una hibridación del verde con el ambiente edificado. Es así como la vegetación se convierte en una estrategia de eficiencia energética, un sistema pasivo, que tiene un impacto positivo en el ambiente urbano y en el interior de los edificios. El rendimiento y beneficios asociados a este tipo de sistemas se asocian a tres diferentes escalas: escala urbana, escala de edificio y a escala social.

Efectos a escala urbana:

- *Mitigación del efecto isla de calor urbana:* dicho efecto se dio a conocer a través del estudio de los patrones de viento local, la formación de nubes y neblina, el aumento de la humedad y las variaciones en las tasas de precipitaciones. Un fenómeno que ha llevado a investigar sobre la capacidad de ciertos materiales de mitigarlo, dentro de los que se encuentra la vegetación como una herramienta de gran potencial para el enfriamiento de las superficies debido a la evapotranspiración de las plantas (Mariani et al., 2016; Bartesaghi Koc, Osmond and Peters, 2018; Saaroni et al., 2018).

La combinación entre el efecto isla de calor urbana y la intensificación del calentamiento global han incrementado el interés en la vegetación como parte de las soluciones que contribuyen a alcanzar el confort urbano. Estudios demuestran cómo las temperaturas medias anuales en ciudades han incrementado en un rango de 0.12 a 0.45 ºC por década desde 1961 al 2010 (Tallis et al., 2015). Aun cuando la temperatura del aire pueda aumentar debido al calentamiento global, este aumento se da de manera gradual en comparación al incremento del calor local producido por el efecto isla de calor (Potchter and Itzhak Ben-Shalom, 2013).

Dentro de las variables climáticas más estudiadas para la mitigación del efecto isla de calor en ciudades se encuentra la temperatura del aire (Voogt and Oke, 2003). Si consideramos que el efecto de evapotranspiración asociado a la vegetación puede ejercer de regulador natural de las temperaturas del aire, se demostraría la importancia del uso de la vegetación en contextos urbanos para la mejora del confort y, en concreto, la reducción de las temperaturas (Alcázar, 2015; Saaroni et al., 2018).

- *Mejora de la calidad del aire:* estudios han demostrado que la vegetación puede contribuir a mejorar la calidad del aire de las ciudades al reducir la presencia de smog, gases contaminantes y partículas en suspensión (Klingberg et al., 2017; Mensink et al., 2011; Perini et al., 2017; Salmond et al., 2013). Los árboles y arbustos hoy en día no son suficientes para cubrir esta necesidad, debido a la densificación y reducida superficie destinada a espacios verdes en la ciudad, esto ha promovido la investigación y la implementación de envolventes vegetales (techos y fachadas vegetales) a los mismos fines.

El dióxido de carbono (CO_2) es uno de los gases más comunes presentes en las ciudades y puede ser secuestrado por el sustrato y fijado por las plantas. Investigaciones han demostrado que en un jardín doméstico una media de $2.5x10^3 g/m^2$ de dióxido de carbono puede ser fijado, con una distribución del 83% en el sustrato, 16% en árboles y arbustos, y solo el 0.6% en la hierba, por lo que el mayor beneficio se encuentra asociado al sustrato y a los microorganismos asociados a las raíces (Giordano et al., 2013). Otros resultados confirman que el uso de vegetación en contextos urbanos reduce la concentración de contaminantes a nivel peatonal en un 40% para el dióxido de nitrógeno (NO_2) y un 60% para las partículas en suspensión PM_{10} (Pugh et al., 2012).

Las capacidades de fijación de contaminantes de la vegetación dependen en gran medida de la especie, la forma y el tamaño de las hojas (Köhler, 2008).

Seleccionar plantas con ciertos criterios climáticos contribuye al aprovechamiento de sus capacidades.

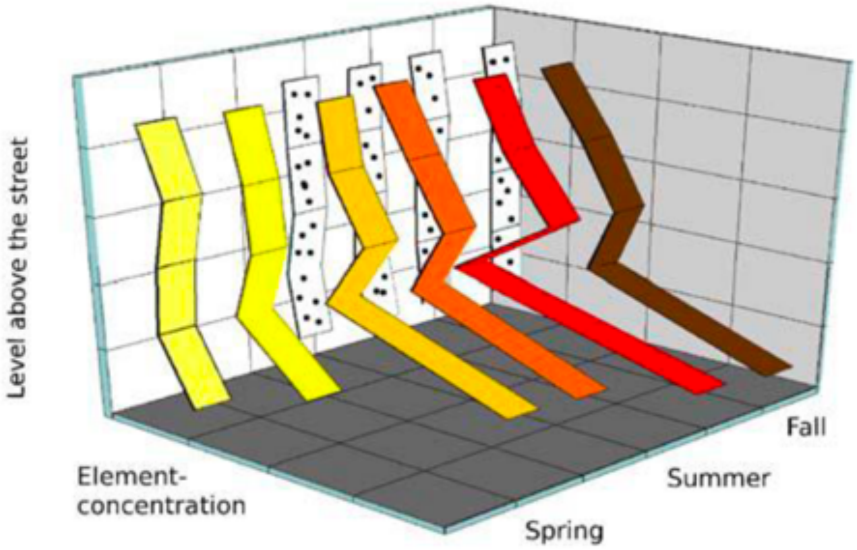


Figura 6: Concentración de cargas de polvo sobre las hojas de *Boston Ivy* durante un periodo de crecimiento comprendido entre la primavera y el otoño

Fuente: Köhler, M. “Green facades—A view back and some visions”, Urban Ecosystems. (2008)

- *Reducción de temperaturas:* dentro de los beneficios asociados a estas tecnologías, la reducción de temperaturas es una de los más relevantes (Cheng et al., 2010). La vegetación puede desempeñar un papel muy importante en el clima de las ciudades y en el microclima entre los edificios (Tan et al., 2014a). Esto se debe a la evapotranspiración de las plantas, que permite la conversión de la radiación solar en calor latente, lo que no produce un aumento de la temperatura, si no que contribuye a los procesos fisiológicos de las plantas en los que una pequeña parte de la radiación incidente es utilizada en la fotosíntesis, mientras que el resto se utiliza para la evaporación del agua presente en el sustrato, transformando este proceso en un instrumento regulador de temperatura (Charoenkit and Yiemwattana, 2016a).

Una fachada completamente cubierta de vegetación puede absorber entre un 40 y 80% de la radiación recibida en función del tipo de vegetación, lo que la convierte en un potencial instrumento de aislamiento térmico y de reducción de temperaturas (Sheweka and Magdy, 2011). Otro de los beneficios asociados a este efecto es la sombra que proporcionan, actuando como barrera a la radiación solar directa sobre la fachada (Sánchez-Reséndiz et al., 2018).

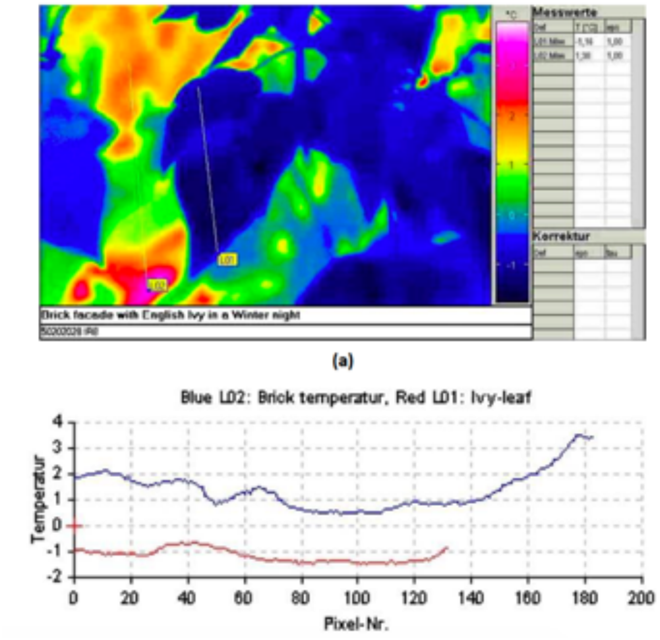


Figura 7: Análisis del efecto de aislamiento térmico de una fachada vegetal

Fuente: Köhler, M. "Green facades—A view back and some visions", Urban Ecosystems. (2008).

- *Conservación y aumento de la biodiversidad:* actualmente en las ciudades la biodiversidad se encuentra solo en los pequeños espacios verdes que cada vez están más fragmentados y aislados. Integrar soluciones basadas en la naturaleza contribuye a gestionar y aumentar la presencia de aves, abejas e insectos necesarios para el balance ecológico del medioambiente (Mayrand and Clergeau, 2018).

Efectos a escala de edificio:

- *Absorción acústica*: la reducción del ruido producido por el tráfico es uno de los beneficios asociados al uso de vegetación en ciudades (Hornikx and Van Renterghem, 2012; Lacasta et al., 2016; Ow and Ghosh, 2017). Estudios confirman la capacidad de la vegetación de aislar y absorber el sonido, debido a la presencia de las hojas de las plantas y el sustrato. Los resultados han llevado a establecer un promedio de reducción del ruido de 15 dB aproximadamente, con un coeficiente de absorción promedio de α= 0.40, lo que confirma que las fachadas vegetales aportan beneficios de reducción de ruido en contextos urbanos (G Pérez et al., 2018).

  Esta absorción se obtiene principalmente a través de tres mecanismos:

  - El sonido puede ser reflejado y difractado por las hojas, raíces y ramas;
  - La absorción del sonido por parte de la vegetación, mecanismo que varía dependiendo del tipo de vegetación y a los efectos de la capa termo-viscosa en la superficie de la planta, y su capacidad de conducir el sonido;
  - La presencia del sustrato que puede causar interferencia, este efecto se conoce como contribución de reflexión del suelo (Azkorra et al., 2015c).

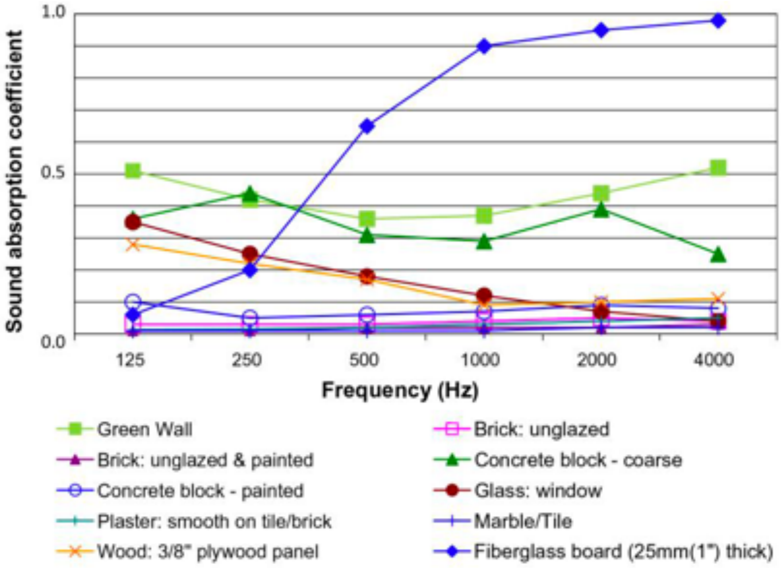


Figura 8: Coeficiente de absorción del ruido de un muro vegetal en comparación con otros materiales

Fuente: Azkorra Z., et al., Evaluation of green walls as a passive acoustic insulation system for buildings, in Applied Acoustics, n.89. pp. 46-56. (2015)

- *Recolección y gestión de aguas de lluvia*: la vegetación puede contribuir a reducir la contaminación ambiental de varias maneras, una de ellas es la gestión del agua de lluvia (Pérez-Urrestarazu et al., 2015; Perini et al., 2011; Sheweka and Mohamed, 2012; van de Wouw et al., 2017). El sistema de riego de estos sistemas se basa en tecnologías que bien pueden recuperar y reutilizar el agua de lluvia para el riego, o reutilizar las aguas grises. Las aguas grises de los edificios proceden normalmente de la descarga de fregaderos, duchas, fuentes, etc., que contienen pequeñas cantidades de nitrógeno, fósforo, detergentes, sales, bacterias patógenas, etc., que pueden influir en el crecimiento de las plantas, reducir el consumo de agua potable, además de contribuir a la reducción del tiempo de las descargas en las ciudades.

Efectos sociales:

- *Bienestar y efectos psico-perceptivos*: la presencia de vegetación en las ciudades conduce a una percepción diferente del espacio por parte de las personas, ya que contribuye a infundir una sensación de serenidad (Bit, 2010). Estudios han demostrado que la presencia de vegetación se refleja en diferentes aspectos clínico-sociales debido a que:
    - El concepto de verde se asocia al concepto de pulmón, representando la capacidad de purificación del aire contaminado;
    - La asociación a conceptos como limpieza y orden conduce a la idea de una ciudad o entorno ordenado;
    - La imagen de una ciudad sin vegetación conlleva a conceptos de caos y desorden;
    - La vegetación es capaz de reducir y absorber el ruido urbano.

- *Cohesión social y oportunidades de inversión:* la inversión en este tipo de soluciones no solo ofrece oportunidades de empleo en el ámbito de la gestión y mantenimiento, restauración, conservación, etc., sino que, además, revitaliza los espacios públicos, reactiva la economía del lugar y fomenta la cohesión social.

La introducción de naturaleza en las ciudades crea una síntesis entre paisaje y arquitectura, en la que los edificios forman parte de la solución a los problemas que enfrentan. En este sentido, se abren cada vez más oportunidades para el desarrollo de sistemas tecnológicos basados en la naturaleza y para testar su funcionamiento y maximizar su eficacia y replicabilidad.

1.5. Sistemas modulares de jardinería vertical

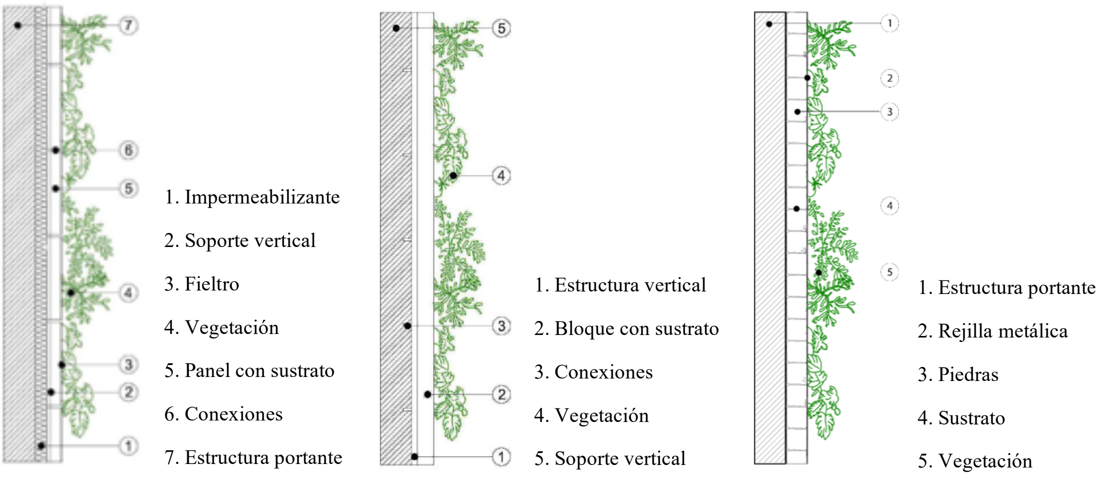
Este tipo de soluciones se reconocen en la literatura a través de los términos en inglés "*Green Wall*", "*Living Wall Systems*" (LWS) o "*Vertical Greenery Systems"* (VGS). Estructuras verticales con vegetación, un estrato de sustrato orgánico u inorgánico, y un sistema de riego y fertilización (Mayrand and Clergeau, 2018). Existe un elenco de soluciones que pueden variar según las especies utilizadas, la estructura de soporte, el tipo de sustrato y el sistema de riego. Sus características constructivas dividen este tipo de soluciones en dos macro grupos: fachadas continuas y fachadas modulares (Pérez-Urrestarazu et al., 2015). Las fachadas continuas pertenecen a las soluciones de plantas rampantes sin ninguna complejidad técnica, mientras que las modulares son paneles pre-cultivados, fijados a una estructura portante y en los que se pueden emplear materiales como el plástico, el polietileno, materiales sintéticos y metales.

En la categoría de fachadas modulares existen principalmente tres sistemas constructivos (Olivieri, 2013) (Figura 9):

- *Paneles*: sistema de módulos prefabricados de dimensiones variables que permiten cubrir superficies verticales a pequeña y gran escala.

- *Bloques*: sistema de paneles pre-fabricados y pre-cultivados que cubren superficies verticales a pequeña y gran escala. La modularidad permite la sustitución de las plantas en caso de daños. Tienen una baja permeabilidad, por lo que suelen tener una estratigrafía compleja y, por tanto, mayor peso.

- *Gaviones*: sistema desarrollado a partir de la creación de paneles con gaviones, utilizando una malla metálica, piedra y sustrato, añadiendo en algunos casos hormigón para rigidizar el sistema. También es un elemento constructivo, sin embargo, la opacidad y la permeabilidad limitan su uso.



(a) (b) (c)

Figura 9: (a) Sistema modular de jardinería vertical de paneles (b) Sistema modular de jardinería vertical de bloques (c) Sistema modular de jardinería vertical de gaviones.
Fuente: Elaboración propia

Estos sistemas pueden variar en base a las condiciones climáticas, el tipo de proyecto, la orientación y los requisitos de diseño. Sin embargo, cuentan con una serie de rasgos comunes y de prestaciones asociadas a la presencia del sustrato y la vegetación que se mantienen a pesar de la solución constructiva.

Dentro de la categoría de sistemas modulares predominan dos soluciones constructivas: módulos construidos a partir de textiles o fieltros y módulos construidos a partir de cajas prefabricadas con materiales poliméricos. Ambos ofrecen la posibilidad de introducir las especies previamente cultivadas directamente en el módulo, por lo que el sustrato se encuentra alojado en el interior de los bolsillos o cavidades según el tipo de sistema. Asimismo, cuentan con una serie de elementos constructivos o rasgos comunes que se describen a continuación (Bit, 2010).

- *Estructura de soporte:* es uno de los principales componentes de cualquier sistema y requiere de un cierto nivel de rigidez para garantizar la estabilidad desde el punto de vista estructural. La resistencia mecánica es otro aspecto fundamental, la estructura de soporte debe ser capaz de resistir el esfuerzo mecánico ejercido por el crecimiento de las raíces de las plantas y el aumento del peso del sustrato cuando está saturado. Este elemento pude ser elaborado en materiales como aluminio, plástico reciclado, fieltros, acero, entre otros.

- *Capa de absorción y retención de agua:* el objetivo de este componente es conservar la humedad del sistema y evitar pérdidas, además de evitar el paso de la humedad a capas externas que entren en contacto con el edificio. Suele ser la última capa del sistema y los materiales utilizados pueden ser membranas bituminosas, membranas de PVC o fieltros.

- *Sustrato:* el sustrato puede ser orgánico, compuesto por materiales como fibras vegetales, humus, arcilla, perlita, etc., o hidropónico, compuesto por sales minerales como potasio, calcio, magnesio y nitrógeno. La mezcla obtenida a partir de estos materiales debe ser adecuada para el tipo de plantas seleccionadas, debe tener un peso apropiado para el sistema constructivo y una capacidad de retención de agua adecuada, además de ser compatible con el contexto climático en el que se encuentre. Las necesidades hídricas y nutricionales de todo el sistema se establecerán en función del tipo de sustrato.

- *Vegetación:* representa el elemento más importante del sistema. Un sistema óptimo debe tener en cuenta los requisitos agronómicos de las especies vegetales seleccionadas, si esto no se cumple, se tendrán necesidades de mantenimiento extraordinario, y, en consecuencia, un aumento de los costes.

  La selección de las especies se debe hacer en función del ciclo de las estaciones, los requerimientos hídricos, la exposición solar de la fachada y el clima. Estas pueden ser epifitas, es decir que crecen sobre otras plantas para el apoyo mecánico, o litofitas, aquellas plantas que crecen en asociación con rocas o sustratos rocosos.

- *Sistema de irrigación y fertilización:* para el correcto funcionamiento de esta tecnología es necesario un correcto suministro de agua y nutrientes que garanticen la salud de las plantas. La frecuencia de riego se establece según el tipo de especie vegetal, el tipo de sustrato y la estación del año. El sistema de irrigación y fertilización puede ser manual o automático y suele estar compuesto por un controlador electrónico, filtro, electroválvula, tubos, sondas, sistemas de recuperación de agua y reutilización de la fertilización, conexiones y goteros.

El sistema seleccionado para el desarrollo de esta tesis doctoral es un sistema modular compuesto por una estructura tridimensional de polietileno reciclado con diseño celular. Esta estructura se rellena con sustrato y plantas. La última capa del módulo es de fieltro y cumple dos funciones, mantener la humedad del módulo y evitar el desprendimiento de la vegetación. Cada unidad de cultivo modular se rellena con sustrato orgánico compuesto por fibra de coco, turba y humus. Cuenta con un consumo de agua de 8 l/m^2 en días muy calurosos y hasta 2 l/m^2 en días normales, y unas necesidades de mantenimiento reducidas ya que el sustrato natural mantiene un equilibrio en la nutrición y el crecimiento de las plantas que conlleva a realizar podas una o máximo dos veces al año.

2. Hipótesis y objetivos

2.1. Hipótesis

En la introducción se ha puesto de manifiesto que el uso de sistemas modulares de jardinería vertical en la envolvente del edificio es una práctica relativamente nueva y con muchas posibilidades de mejora, ya que estas soluciones se encuentran aún en una fase de desarrollo tecnológico que se espera contribuya a la optimización de los sistemas existentes y futuros. A partir de este contexto, la hipótesis que se plantea para el desarrollo de la investigación es: **"Es posible optimizar módulos de jardinería vertical para mejorar su efecto sobre el confort urbano entendido como confort higrotérmico y confort acústico".**

La hipótesis propuesta contiene dos aspectos relevantes sobre la optimización. En primer lugar, es de naturaleza empírica. Es decir, basada en datos obtenidos a partir de mediciones experimentales desarrolladas en condiciones reales y a escala de ciudad. Aunque los resultados de la monitorización del comportamiento del módulo de jardinería vertical estarán sujetos a las características constructivas del sistema y del contexto en el que se desarrollan, contribuyen a la definición de líneas de optimización que pueden ser extrapolables a otros sistemas.

En segundo lugar, se reconocen únicamente dos aspectos dentro del confort urbano: el confort higrotérmico y el confort acústico. Es decir, entendiendo que el confort responde a un conjunto de condiciones óptimas que deben coincidir simultáneamente en un espacio y que vienen determinadas por una serie de factores como la temperatura, la escala urbana, la ocupación del espacio, el paisaje sonoro, la calidad del aire, entre otras, esta tesis doctoral se centra en estudiar únicamente la temperatura y el paisaje sonoro. Esto significa que las líneas de optimización buscan mejorar el aporte que la envolvente vegetal puede tener en la reducción de temperaturas y en la absorción de ruido en entornos urbanos densos.

2.2. Objetivos

A partir de la hipótesis planteada, el objetivo general de esta tesis doctoral es **establecer líneas de optimización de un sistema modular de jardinería vertical con el fin de incrementar su aporte en la mejora del confort urbano en contextos urbanos densos**.

Es importante destacar que la finalidad de esta tesis doctoral no solo está en analizar el impacto que tiene la envolvente vegetal en la reducción de temperaturas y absorción de ruido en la ciudad, sino en identificar a partir de ese impacto las posibilidades de mejora para futuros desarrollos tecnológicos que contribuyan a la difusión de este sistema como una herramienta de adaptación del cambio climático. En este sentido, a continuación, se plantean una serie de objetivos específicos que han contribuido a estructurar las distintas fases de este trabajo de investigación.

1. **Estudiar el estado del arte de la tecnología y su aplicación en entornos urbanos densos.** Dado que la implementación de envolventes vegetales en los edificios como medida de mitigación del cambio climático es una práctica en constante evolución, se plantea este objetivo con la finalidad de comprender el escenario actual e identificar las variables que aún no han sido estudiadas en el impacto sobre la reducción de temperaturas y absorción acústica en entornos urbanos. Este objetivo constituye la primera fase de esta tesis doctoral: *Análisis del uso de sistemas modulares de jardinería vertical en la ciudad como herramienta para la mejora del confort urbano*.

2. **Identificar el sistema modular de jardinería vertical más adecuado para el estudio.** Dicha identificación tiene la finalidad de seleccionar dentro de los sistemas constructivos disponibles en el mercado, el que cumpla en mayor medida con parámetros de sostenibilidad medioambiental. Este objetivo da lugar a la segunda fase de esta investigación: *Análisis del ciclo de vida de dos sistemas modulares de jardinería vertical.*

3. **Cuantificar e identificar las variables que influyen sobre la reducción de temperaturas.** Con este objetivo se pretende monitorizar el comportamiento de un módulo de jardinería vertical en condiciones reales, a través de la medición de variables como la temperatura, la humedad relativa y la irradiación. Estos valores permitirán estimar el impacto del sistema sobre la reducción de temperaturas e identificar las variables que mayor influencia tienen y cómo pueden contribuir a

la definición de líneas de optimización del sistema. Este objetivo constituye la tercera fase de esta investigación: *Análisis del impacto de los sistemas modulares de jardinería vertical en la reducción de temperaturas*.

4. **Cuantificar e identificar las variables que influyen sobre la absorción de ruido.** Esta cuantificación pretende evaluar los niveles de absorción acústica de un módulo de jardinería vertical en condiciones controladas y en condiciones reales. La finalidad es evaluar los componentes y el sistema en su conjunto para identificar las variables que mayor influencia tienen en la reducción del ruido y cómo éstas pueden contribuir a la definición de líneas de optimización del sistema. Este objetivo da lugar a la última fase de esta investigación: *Análisis del impacto de los sistemas modulares de jardinería vertical en la absorción acústica.*

5. **Definir las líneas de optimización de un módulo de jardinería vertical para la mejora del confort higrotérmico y el confort acústico en contextos urbanos densos.** Este último, a pesar de ser un objetivo en sí mismo, se cumple a lo largo de las conclusiones obtenidas en las fases previamente descritas. Además, en el apartado de conclusiones de esta tesis doctoral se recogen las características de optimización del módulo exponiéndolas como parte del producto final del trabajo de investigación.

3. Metodología

El desarrollo de esta tesis doctoral se ha planteado por compendio de artículos. El trabajo de investigación se desarrolla a partir de la publicación de varios artículos científicos en revistas de alto impacto, en los cuales se profundiza en los objetivos específicos y generales propuestos. Los resultados parciales de la tesis se incluyen en otras publicaciones en revistas indexadas y han sido incluidas como anexos. En este apartado se explican las fases en las que se ha estructurado la investigación y la relación entre los artículos científicos incluidos.

La tesis doctoral se estructura a partir de cuatro fases y se plantea como una investigación por agregación de partes, en las que las dos primeras fases son necesarias para poder llevar a cabo la tercera, y las tres anteriores para conseguir desarrollar la cuarta. En esta última se cumple con el objetivo general y la hipótesis de la investigación. A su vez, en las tres primeras fases se da respuesta a los objetivos específicos planteados en este trabajo y que han sido expuestos en el apartado anterior. A continuación, se expone un esquema metodológico que explica gráficamente la metodología propuesta.

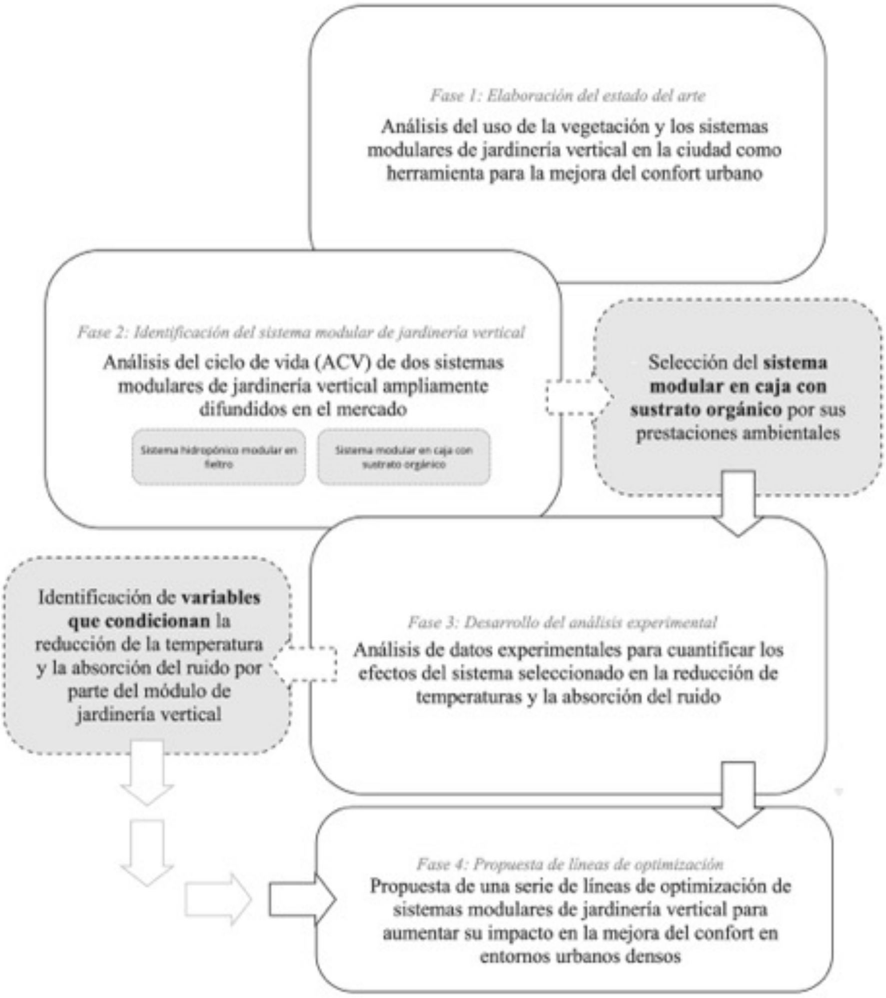


Figura 10: Esquema de la metodología utilizada para el desarrollo de la investigación

En la **primera fase** se presenta el estudio del estado del arte del uso de la infraestructura verde en entornos urbanos densos, y, en concreto, la aplicación de envolventes vegetales para la mejora del confort higrotérmico y acústico. El objetivo es *analizar el uso de sistemas modulares de jardinería vertical en la ciudad como herramienta para la mejora del confort urbano*, con el fin de contar con una revisión sistemática del estado del arte del uso de esta tecnología para la reducción de las temperaturas y la absorción de ruido en entornos urbanos densos; identificar los factores que influyen en el confort urbano mediante el uso de vegetación; e identificar los aspectos aún no profundizados en investigaciones precedentes que pudieran ser estudiados en esta tesis doctoral.

El trabajo realizado en esta fase se desarrolló a partir de tres proyectos de investigación que dieron lugar a tres publicaciones indexadas, dos que cumplen con la normativa aprobada por el Consejo de Gobierno de 30 de noviembre de 2017 de la Universidad Politécnica de Madrid al ser la doctoranda primera autora y se presenta como parte del compendio de esta tesis, y otra que se incluye como publicación complementaria por no cumplir con la normativa al ser una publicación indexada en el cuartil 3 de Scopus.

Proyectos de investigación:

- Proyecto del Programa EIT Climate-KIC Pathfinder (MUAC Modules for Urban Air Cleaning – nº referencia: EH1803020290), financiado por el Instituto Europeo de Innovación y Tecnología (EIT), 2018. La coordinación del proyecto la realizó la profesora Francesca Olivieri, directora de esta tesis doctoral.

- Proyecto del Programa Retos-Colaboración 2017 (Powertree – nº referencia: RTC1803020133), financiado por el Ministerio de Ciencia, Innovación y Universidades, 2018 – 2020. La coordinación del proyecto la realizó el profesor Lorenzo Olivieri.

- Proyecto del Programa EIT Climate-KIC Demonstrator (Bluebloqs Circular Water System – nº de referencia: EH1903020348), financiado por el Instituto Europeo de Innovación y Tecnología (EIT) 2019 – 2021. La coordinación del proyecto la realizó la profesora Francesca Olivieri, directora de esta tesis doctoral.

Artículos científicos:

- Valentina Oquendo-Di Cosola, Jorge Adán Sánchez-Reséndiz, Lorenzo Olivieri, Francesca Olivieri (2021). *Actions for adaptation and mitigation to climate change: Madrid case study.* Revista Facultad de Ingeniería, Universidad de Antioquia, No.101, pp. 84-99, Oct - Dec 2021. Q3 (SJR – Scopus) DOI: 10.17533/udea.redin.20200795.

- Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Jorge Adán Sánchez-Resendiz (2021). *Towards urban transition: implementing nature-based solutions and renewable energies to achieve the Sustainable Development Goals (SDG).* TECHNE Special Series Vol. 2. Q2 (SJR – Avery) DOI: 10.13128/techne-10691

- Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García (2022). *A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation.* Renewable and Sustainable Energy Reviews, 162, 112463. Q1 (JCR). DOI: 10.1016/j.rser.2022.112463

En la **segunda fase** se identifica el sistema modular de jardinería vertical que se utilizará a lo largo del trabajo de investigación. Para la selección de este sistema se realizó un *análisis del ciclo de vida de dos sistemas modulares de jardinería vertical* disponibles en el mercado, con la finalidad de evaluar el impacto en las fases de fabricación, construcción y mantenimiento, y su contribución tanto al balance energético como al ciclo de vida del edificio.

El trabajo realizado en esta fase se desarrolló a través de una breve estancia en la Università degli Studi di Milano (UNIMI) y de la colaboración en un proyecto de investigación, lo cual dio lugar a un artículo científico publicado en una revista científica indexada en JCR.

Proyectos de investigación:

- Proyecto del programa LIFE (Lugo+Biodinámico: planificación de un barrio multi-ecológico como modelo de resiliencia urbana – nº referencia: E160017380), financiado por la Comisión Europea 2016-2020. La coordinación del proyecto la realizó el profesor Luis Ruiz García, director de esta tesis doctoral.

Artículos científicos:

- Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García, Jacopo Bacenetti (2020). *An environmental Life Cycle Assessment of Living Walls Systems*. Journal of Environmental Management, 254, 109743. Q1 (JCR). DOI: 10.1016/j.jenvman.2019.109743

En la **tercera fase** se desarrolló una metodología de análisis de datos experimentales para cuantificar los efectos del sistema seleccionado en la reducción de temperaturas y la absorción del ruido, con el fin de definir un patrón de comportamiento que permitiera definir líneas de optimización y maximizar su rendimiento en la mejora del confort urbano.

En una primera etapa se tomaron datos de temperatura, humedad relativa e irradiación frente al sistema seleccionado a distancias progresivas (0.25 m, 0.50 m, 0.75 m, y 1.00 m), los cuales fueron analizados para determinar el impacto que supone la presencia de la vegetación en la temperatura del entorno inmediato, así como la identificación de la influencia de cada uno de los componentes del sistema (sustrato, vegetación y materiales del sistema). Esta parte de la investigación experimental cumple con el objetivo de *cuantificar e identificar las variables que influyen sobre la reducción de temperaturas.*

En una segunda etapa se llevaron a cabo mediciones de absorción acústica mediante sonda PU – sonda de intensidad acústica para la identificación de fuentes sonoras y la determinación de potencia acústica-, con la finalidad de identificar el coeficiente de absorción acústica del sistema seleccionado en ambientes no controlados (ciudad) y en condiciones de laboratorio controladas, así como las variables que provocan dicho efecto, como la densidad de vegetación, la presencia y saturación del sustrato, o las características de determinados materiales del módulo. Esta segunda parte responde al objetivo de *cuantificar e identificar las variables que influyen sobre la absorción de ruido.*

El contenido de esta fase se presenta a través de tres artículos científicos. Dos artículos enviados a revistas indexadas en JCR, cuyos resultados se incluyen en la discusión de esta tesis doctoral, pero no en el compendio de artículos por no cumplir con los parámetros de la Universidad Politécnica de Madrid, ya que aún no se encuentran aceptadas.

Artículos científicos:

- Valentina Oquendo-Di Cosola, María de los Ángeles Navacerrada, Francesca Olivieri, Luis Ruiz-García (enviado abril 2023). *Impact assessment of green walls on sound absorption.* Applied Acoustics.

- Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Luis Ruiz-García (2023). *Assessment of the impact of green walls on urban thermal comfort in a Mediterranean climate.* Energy and Building, 296, 113375. Q1 (JCR). DOI: https://doi.org/10.1016/j.enbuild.2023.113375

Y un artículo publicado en revista indexada en JCR, que contribuyó al análisis del comportamiento térmico de la fachada, pero que no cumple con la normativa al ser la doctoranda segunda autora, por lo que se incluye como publicación complementaria:

- Rafael Sendra-Arranz, Valentina Oquendo-Di Cosola, Lorenzo Olivieri, Francesca Olivieri, César Bedoya, Álvaro Gutiérrez (2020). *Monitorization and statistical analysis of south and west green walls in a retrofitted building in Madrid.* Building and Environment, 183, 107049. Q1 (JCR). DOI: 10.1016/j.buildenv.2020.107049

En la **cuarta y última fase** se cumple con el objetivo principal de la tesis, identificando una serie de líneas de optimización de un módulo de jardinería vertical para la mejora del confort en entornos urbanos densos. El contenido de esta fase se incluye a lo largo de las publicaciones de la tercera fase en las que la doctoranda es primera autora, y en las conclusiones de esta tesis doctoral, que posteriormente dan lugar a las futuras líneas de investigación.

PARTE II. PUBLICACIONES

En este apartado se presentan las publicaciones que constituyen esta tesis por compendio, tal y como recoge la normativa aprobada por el Consejo de Gobierno de 30 de noviembre de 2017 de la Universidad Politécnica de Madrid. Se incluyen tres artículos científicos de alto impacto publicados en los que la autora de esta tesis figura como primera autora cumpliendo así con la normativa, y cuatro artículos complementarios. De los artículos complementarios, dos ya están publicados y dos están en fase de publicación habiendo sido enviados en abril 2023. En total, la doctoranda figura como primera autora en 6 artículos y como segunda autora en 1 de ellos. Los artículos se presentan siguiendo el orden que establece el hilo argumental de la tesis doctoral y las fases propuestas.

LISTADO DE PUBLICACIONES

A continuación, se recogen todas las publicaciones que estructuran esta tesis doctoral. Han sido dispuestas según el hilo argumental de la investigación destacando su cumplimiento con la normativa aprobada por el Consejo de Gobierno de 30 de noviembre de 2017 de la Universidad Politécnica de Madrid para el desarrollo de tesis por compendio de artículos.

Publicación	**Cumple con la normativa UPM y se incluye en el compendio**	**No cumple con la normativa UPM**
Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Jorge Adán Sánchez-Reséndiz (2021). *Towards urban transition: implementing nature-based solutions and renewable energies to achieve the Sustainable Development Goals (SDG).* TECHNE Special Series Vol. 2. Q2 (SJR - Avery). DOI: 10.13128/techne-10691	X	
Valentina Oquendo-Di Cosola, Jorge Adán Sánchez-Reséndiz, Lorenzo Olivieri, Francesca Olivieri (2021). *Actions for adaptation and mitigation to climate change: Madrid case study.* Revista Facultad de Ingeniería, Universidad de Antioquia, No.101, pp. 84-99, Oct - Dec 2021. Q3 (SJR – Scopus). DOI: 10.17533/udea.redin.20200795		X *Publicación del cuartil 3*

Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García, Jacopo Bacenetti (2020). *An environmental Life Cycle Assessment of Living Walls Systems*. Journal of Environmental Management, 254, 109743. Q1 (JCR). DOI: 10.1016/j.jenvman.2019.109743	X	
Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García (2022). *A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation.* Renewable and Sustainable Energy Reviews, 162, 112463. Q1 (JCR). DOI: 10.1016/j.rser.2022.112463	X	
Rafael Sendra-Arranz, Valentina Oquendo-Di Cosola, Lorenzo Olivieri, Francesca Olivieri, César Bedoya, Álvaro Gutiérrez (2020). *Monitorization and statistical analysis of south and west green walls in a retrofitted building in Madrid.* Building and Environment, 183, 107049. Q1 (JCR). DOI: 10.1016/j.buildenv.2020.107049		X *Doctoranda como segunda autora*
Valentina Oquendo-Di Cosola, María de los Ángeles Navacerrada, Francesca Olivieri, Luis Ruiz-García (enviado abril 2023). *Impact assessment of green walls on sound absorption.* Applied Acoustics. Q1 (JCR).		X *Enviado y en proceso de revisión*

Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Luis Ruiz-García. *Assessment of the impact of green walls on urban thermal comfort in a Mediterranean climate*. Energy and Buildings. Q1 (JCR). DOI:https://doi.org/10.1016/j.enbuild.2023.113375	X	

PARTE III. ANÁLISIS DE RESULTADOS Y DISCUSIÓN

Este apartado resume los principales resultados obtenidos a lo largo del trabajo de investigación, desde la contextualización del uso de la naturaleza en la ciudad, hasta el análisis de ciclo de vida y los resultados experimentales obtenidos a partir del sistema modular de jardinería vertical seleccionado para esta investigación. Se estructura en cuatro capítulos, una por cada fase de la investigación, vinculados además a las publicaciones científicas incluidas en esta tesis doctoral.

1. Análisis del uso de sistema modulares de jardinería vertical en la ciudad como herramienta para la mejora del confort urbano
2. Análisis de ciclo de vida de dos sistemas modulares de jardinería vertical
3. Análisis del impacto de los sistemas modulares de jardinería vertical en la reducción de temperaturas
4. Análisis del impacto de los sistemas modulares de jardinería vertical en la absorción acústica

Análisis del uso de sistema modulares de jardinería vertical en la ciudad como herramienta para la mejora del confort urbano

La complejidad e interconexión de sistemas que caracteriza a las ciudades, requiere promover innovaciones sistémicas que den respuesta a los problemas complejos que perjudican la salud y calidad de vida de la ciudadanía. Promover dicha innovación necesita de cambios estructurales profundos y sostenidos en el tiempo en el campo tecnológico, social, medioambiental, económico y cultural. Cambios que sólo serán posibles a través de la implementación de acciones que generen cambios visibles y permanentes en el tejido urbano, conduciendo a su transformación.

Las ciudades responden a un modelo complejo no solo desde el punto de vista de los sistemas que la componen, sino también desde la red de actores que actúan en ellas, lo que exige enfoques integradores y amplios a la hora de pensar en la transformación del modelo actual en uno más sostenible, resiliente y justo. Dicha integración puede venir dada por tecnologías capaces de activar simultáneamente distintas palancas de transformación urbana como son la tecnología, la gobernanza, la innovación social y la regulación, entre otras.

Un ejemplo de la interconexión de los sistemas en las ciudades puede verse en la pérdida de biodiversidad debido a la pavimentación e impermeabilización de la mayor parte de la superficie urbana, que conlleva a dinámicas que afectan, por ejemplo, la calidad del aire y del agua, el confort acústico y el confort higrotérmico. Esto demuestra que las decisiones no se deben tomar de forma aislada, sino desde una visión holística y transversal.

En el marco de ese complejo modelo de funcionamiento, la naturaleza, las personas y el espacio urbano se encuentran dentro de los elementos interconectados que componen una ciudad, que planificados en conjunto son capaces de aportar una serie de beneficios medioambientales como la mitigación del efecto isla de calor urbana, la absorción de ruido, la mejora de la calidad del aire, la gestión del agua de lluvia, el aumento de la biodiversidad y la absorción de gases de efecto invernadero (GEI).

Las soluciones basadas en la naturaleza (SBN) son consideradas un elemento de planificación urbana estratégica y la columna vertebral de las agendas urbanas en el ámbito de la recuperación de espacios públicos en las ciudades. No sólo por los potenciales beneficios medioambientales antes mencionados, sino por los impactos sociales, económicos y de gobernanza asociados a su implementación, que han demostrado que pueden ser una herramienta clave para la transformación.

El trabajo en la dimensión económica y social de las soluciones basadas en la naturaleza en Europa ha sido introducido por la Comisión Europea, la cual a través de informes y estrategias (European Commission, 2022, 2021b) ha promovido su implementación como una herramienta que debe formar parte de las políticas medioambientales basadas en una economía sostenible, la conservación de la biodiversidad, la adaptación al cambio climático, la reducción de catástrofes naturales y el bienestar humano. Dicha implementación requiere tener en cuenta no sólo los beneficios y costes directos, sino también las interacciones y co-beneficios. Algunos indicadores como la tasa de empleos verdes, el porcentaje de superficie verde total en la ciudad y los m^2 por ciudadano, la reducción de los índices de inseguridad vinculados a la recuperación de espacios degradados, la reducción de enfermedades vinculadas a la calidad del aire, y la mejora de la calidad del agua, pueden convertirse en demostradores del potencial que posee la infraestructura verde en la ciudad.

El incremento del capital natural y la implementación de soluciones basadas en la naturaleza en la ciudad tendrán que venir acompañados de un esfuerzo de cuantificación y monetización de los impactos directos e indirectos. Una tarea en la que la investigación está llamada a tener un papel fundamental, ya que puede asumir el reto de desarrollar, supervisar e implementar métodos, herramientas y tecnologías que demuestren la viabilidad técnica, económica y medioambiental de estas soluciones a corto, medio y largo plazo.

Esto de alguna forma ya está sucediendo y el valor de la infraestructura verde está siendo cada vez más reconocido por las autoridades, las empresas y la ciudadanía. Prueba de ello es el creciente número de iniciativas locales, nacionales e internacionales que destacan principalmente por potenciar la urbanización sostenible mediante nuevas tecnologías y modelos de negocio que utilizan la naturaleza para garantizar el bienestar humano y la salud pública, y promover la regeneración de ecosistemas degradados mediante la restauración ambiental.

Este es el objetivo del artículo científico: Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Jorge Adán Sánchez-Reséndiz (2021). *Towards urban transition: implementing nature-based solutions and renewable energies to achieve the Sustainable Development Goals (SDG).* TECHNE Special Series Vol. 2. Q2 (SJR - Avery). DOI: 10.13128/techne-10691, que aporta una visión transversal y estratégica de la transformación del espacio urbano, destacando el potencial de las soluciones basadas en la naturaleza y la oportunidad que supone reverdecer la infraestructura gris ante un panorama en el que los asentamientos urbanos y la actividad humana está siendo responsable de acelerar las consecuencias del cambio climático.

Contrarrestar esta realidad sólo será posible si se promueven soluciones que reduzcan emisiones, preserven la biodiversidad y mejoren la calidad de vida de las personas, desde una visión integradora que active procesos de transformación social, económica, política y de gobernanza para acelerar el cambio que necesitamos.

La Agenda 2030 (Nations, 2015c), como hoja de ruta hacia el desarrollo sostenible, ha dejado en evidencia que reforzar la adaptación y mitigación a las consecuencias del cambio climático frente al desarrollo masivo de las ciudades es crucial para evitar impactos socioeconómicos. Esto se fundamenta en dos principios transversales a todas las metas y objetivos: (i) garantizar que los cambios promovidos estén diseñados por y para fomentar la equidad y la inclusión social, y en particular, los servicios públicos y las infraestructuras; (ii) asegurar que toda iniciativa contribuya a reducir la vulnerabilidad de la humanidad, su huella ambiental, el uso de recursos y la contaminación.

En su ODS 11: Ciudades y Comunidades Sostenibles, la agenda contempla la acción climática urbana y establece la inversión e innovación en infraestructura verde en ciudades, pueblos y comunidades, como un medio para hacer frente al cambio climático. Dicha innovación debe partir de la cultura de la experimentación, el pensamiento creativo y la intersección de áreas de conocimiento, dejando a un lado las soluciones aisladas y los enfoques sectoriales, y dando paso a la investigación e innovación experimental basada en enfoques interdisciplinarios e intersectoriales.

Esta apuesta por la sostenibilidad y la naturaleza sitúa a las soluciones basadas en la naturaleza como una herramienta de innovación capaz de generar impacto y promover la transición hacia modelos de ciudad más saludables, resilientes, inclusivos y justos. El impacto y la eficacia de estas soluciones puede evaluarse a través de: (i) la cuantificación de los beneficios y co-beneficios; (ii) la viabilidad e impacto económico; (iii) la capacidad de integrar a diferentes sectores de la sociedad e influir en el diseño de nuevas políticas públicas.

La evaluación de los beneficios de las soluciones basadas en la naturaleza puede hacerse teniendo en cuenta la escala a la que se implementan, la cual varia desde el micro-nivel de un edificio, el meso-nivel de toda una ciudad, o el macro-nivel de un país entero. Sin embargo, la evaluación también depende del tipo de servicio ecosistémico que se ofrece, que se agrupan en torno a tres categorías: (i) servicios de aprovisionamiento (de comida, agua potable y biomasa), (ii) servicios de regulación (de temperatura, ruido, calidad del aire y del agua); (iii) y servicios culturales (de cohesión social y recreación en espacios públicos).

A pesar de la inmensa variedad de beneficios, la difusión de este tipo de soluciones se ha visto afectada principalmente por la dificultad de proveer información que permita estimar el valor de dichos beneficios y que ayude a establecer marcos de rentabilidad económica. Esta dificultad de cuantificar los beneficios supone una gran oportunidad para la investigación, en concreto, a través del desarrollo de metodologías que contribuyan a acelerar su implementación.

En ese sentido, el artículo científico: Valentina Oquendo-Di Cosola, Jorge Adán Sánchez-Reséndiz, Lorenzo Olivieri, Francesca Olivieri (2021). *Actions for adaptation* *and mitigation to climate change: Madrid case study.* Revista Facultad de Ingeniería, Universidad de Antioquia, No.101, pp. 84-99, Oct - Dec 2021. Q3 (SJR – Scopus). DOI: 10.17533/udea.redin.20200795, demuestra la importancia de la cuantificación de los beneficios de las soluciones basadas en la naturaleza en términos medioambientales y socioeconómicos y la oportunidad que esto supone para la investigación. Dicha cuantificación puede ser beneficiosa tanto para la inclusión de estas tecnologías en la regulación y políticas pública, como para la monetización de sus beneficios y co-beneficios, ambas condiciones contribuirían a su difusión.

El objetivo de esta tesis doctoral es contribuir a la cuantificación de dichos beneficios, centrándose concretamente en los sistemas modulares de jardinería vertical y la capacidad que poseen para regular temperaturas y ruido ambiental en entornos urbanos densos. Los jardines verticales pertenecen al grupo de soluciones basadas en la naturaleza y destacan por su gran potencial de enfriamiento de superficies y regulación de temperaturas.

Así, por último, en el artículo científico: Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García (2022). *A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation.* Renewable and Sustainable Energy Reviews, 162, 112463. Q1 (JCR). DOI: 10.1016/j.rser.2022.112463, se lleva a cabo una revisión sistemática del estado del arte de la tecnología para reducir temperaturas y absorber ruido, con la finalidad de identificar los factores que influyen en dicho comportamiento, así como los ámbitos inexplorados o poco profundizados en los que esta tesis doctoral podría contribuir.

La selección de la temperatura y el ruido como variables para el desarrollo de la tesis doctoral viene dada por la relevancia que tienen para la adaptación al cambio climático en ciudades y la mejora del confort urbano. Bajo el concepto de confort se encuentran las condiciones ambientales, arquitectónicas, sensoriales e incluso socioculturales que un individuo puede percibir, y entre los parámetros que pueden afectar esta percepción se encuentran la temperatura del aire, la humedad relativa, la velocidad del viento, la radiación solar y los niveles de ruido. En el marco de la tesis doctoral, este análisis bibliográfico estudia en profundidad únicamente dos de esos parámetros: la temperatura del aire y el ruido ambiental. Ambos aspectos han sido estudiados utilizando una única metodología y criterios de evaluación (sistema constructivo, tipo de experimento y clima). A continuación, se presentan los principales resultados de cada parámetro:

- *Resultados en el ámbito de la reducción de temperaturas*

  El estudio del impacto de los sistemas de jardinería vertical en la reducción de temperaturas ha sido desarrollado a través de la evaluación de: i) los efectos en el entorno inmediato; ii) los aspectos que contribuyen al efecto de enfriamiento de superficies; iii) la influencia de la orientación de la fachada; y iv) la correlación entre la reducción de temperatura y los procesos de fotosíntesis y evapotranspiración. La mayoría de los estudios realizados internacionalmente han sido desarrollados utilizando métodos experimentales con recogida de datos a partir de prototipos, siendo escasos los estudios que evalúan el efecto de regulación de temperaturas exteriores en condiciones reales, lo que se constituye como uno de los objetivos para el desarrollo de esta tesis doctoral.

  La revisión muestra las principales conclusiones de una evaluación sistemática de los estudios previos, en el que se identificaron una serie de condiciones esenciales para el rendimiento térmico del sistema:

- El efecto regulador térmico se debe principalmente al proceso de fotosíntesis y evapotranspiración de las hojas de las plantas, lo que se denomina equilibrio térmico de la vegetación. Los resultados muestran reducciones de hasta 2.7 ºC en comparación con la temperatura del aire, debido principalmente a la absorción de la radiación solar y la transferencia de calor por convección.

- El efecto de la combinación de la sombra y la evapotranspiración de las plantas reduce la temperatura del aire entre 1 ºC y 3 ºC, aunque esto puede variar en función del clima y la composición del sustrato. La mayoría de los resultados obtenidos son atribuibles a la presencia del sustrato y su inercia térmica.

- El tipo de especie, el índice foliar, la superficie cubierta y el espesor de la planta influyen significativamente en el rendimiento de los sistemas de jardinería vertical. Cuanto mayor sea la cobertura, mayor será el impacto de reducción.

Tras el análisis de los resultados se identificaron dos aspectos que requieren mayor investigación: (i) el efecto de la distancia de medición como una variable para determinar el radio de acción de este tipo de soluciones en la ciudad, y en concreto, a nivel de calle; y (ii) la importancia de extrapolar y contrastar los resultados obtenidos en prototipos realizados a escala y en condiciones controladas, a jardines verticales instalados en edificios que se encuentren expuestos a las condiciones reales de la ciudad.

- *Resultados en el ámbito de la absorción acústica*

El estudio de la capacidad de absorción acústica de los sistemas de jardinería vertical ha sido mayormente desarrollado en condiciones de laboratorio controladas (cámaras de reverberación y tubos de impedancia), con el objetivo principal de identificar el coeficiente de absorción a partir de variables como: el sustrato, las plantas, la configuración y materiales del sistema o la influencia de la distancia del emisor de ruido. Sin embargo, la evaluación de las propiedades acústicas de estas soluciones a escala real sigue siendo un ámbito de estudio poco explorado.

La revisión recoge las principales conclusiones de una evaluación sistemática de los estudios previos, en el que se identificaron una serie de condiciones esenciales para garantizar la absorción acústica:

  - Los sistemas de jardinería vertical cuentan con una mayor capacidad de absorción a frecuencias medias y altas, lo que los convierte en una solución eficaz para el control de ruido ambiental en espacios públicos.
  - La absorción del ruido proviene fundamentalmente del sustrato, el cual absorbe el 80% de la energía recibida a frecuencias superiores a 1000 Hz. Estas características lo convierten en un material tan útil como cualquier otro material poroso utilizado normalmente para el aislamiento en la construcción (como lana de roca o fibra de coco).
  - El espesor del sustrato es una variable relevante para garantizar las prestaciones acústicas del sistema, cuanto más grueso el sustrato, mayor es la reducción de ruido.
  - La densidad de la masa vegetal también supone un condicionante para el aumento de la absorción de ruido, siendo de hasta un 20% con respecto a la capacidad de absorción del sustrato.

- La configuración o sistema constructivo del módulo puede influir en la capacidad de absorción acústica, principalmente debido al espesor y la composición del sustrato, la densidad de la vegetación, la impedancia de las juntas entre los módulos y el aislamiento de la estructura de soporte.

Tras la revisión sistemática de los resultados obtenidos por los distintos estudios, se identificaron dos aspectos que requieren mayor investigación: (i) el estudio de la influencia de variables como la saturación, el tipo y densidad de vegetación, y los materiales del módulo en la capacidad de absorción acústica; (ii) la importancia de extrapolar y contrastar los resultados obtenidos en prototipos realizados a escala y en condiciones controladas, a jardines verticales instalados en edificios que se encuentren expuestos a diversas fuentes de ruido y en condiciones reales de ciudad.

El análisis del estado del arte del impacto de los sistemas de jardinería vertical en la regulación de temperaturas y la absorción acústica ha arrojado conclusiones que dan forma a los objetivos generales de esta tesis doctoral. Así, los objetivos responden fundamentalmente a la necesidad de evaluar el comportamiento de esta tecnología a escala real y expuesta a fuentes de ruido y condiciones climáticas no controladas, para con ello validar la capacidad de mitigar y adaptar el entorno urbano a los efectos del cambio climático.

Artículo 1

Towards urban transition: implementing nature-based solutions and renewable energies to achieve the Sustainable Development Goals (SDG)

Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Jorge Adán Sánchez-Reséndiz (2021).

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Q2 (SJR – Avery)

Towards urban transition: implementing Nature-Based Solutions and renewable energies to achieve the Sustainable Development Goals (SDG)

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Abstract: Cities today are the scene of major problems linked to air pollution, resource consumption, and inequality. The 2030 Agenda for Sustainable Development proposes a roadmap for the transition to more resilient and sustainable city models. This challenge can only be met through systemic innovation, which produces technological, social, environmental, and cultural changes. The integration of nature-based technologies is a tool for the transformation of the current city model. This essay analyses the international context of sustainable development in cities, and the different possibilities for transforming urban space, with the final aim of making a concrete contribution to solutions that guarantee the fulfilment of the Sustainable Development Goals (SDGs), decarbonize the current model, and ensure the participation of citizens in the process.

Keywords: Cities, Nature-Based Solutions, Renewable energy, Sustainable Development Goals, Systemic approach.

Research and innovation to achieve the Sustainable Development Goals (SDG’s)

The United Nations ensures a population growth from 55% today to 75% in 2050, which means that vulnerability to the consequences of climate change will increase and there will be a greater need to ensure economic productivity, social inclusion and resilience (Nations, 2015b). The importance of the social, economic, and environmental effects of urbanization, such as the lack of education and inequity in access to services; the gap between the health and well-being of people linked to population growth; the energy consumption and the emissions associated, among others, are evidence of the challenges we face. Against this background, cross-cutting measures are needed, with emphasis on the multi-stakeholder approach.

These challenges are addressed in the Agenda 2030 through the 17 Sustainable Development Goals (SDGs) (Nations, 2015c) and the Paris agreement, in which members of the United Nations have developed a framework for action and international cooperation to achieve sustainability through a systemic approach that encompasses prosperity, people, the planet, peace, and partnerships. This will require profound changes and the participation of all sectors of society: governments, universities, businesses, and civil society. Jeffrey Sachs in his work "*Six transformations to achieve Sustainable Development Goals",* argues the importance that SDGs have over global development, and how the goals set can achieve a complex model beyond mere objectives. However, for this to happen it is necessary to promote deep structural changes (Sachs et al., 2019).

Along these lines, on 3 December 2013 the Horizon 2020 Programme (H2020) was approved, the main source of European funding for research and innovation in the European Union (European Commission, 2014) with a mission-oriented approach. Theorised by Mariana Mazzucato (Mazzucato, 2018), Professor of Economics of Innovation and Public Value at the University College of London (UCL), the approach is based on an innovative policy, which must be oriented towards one or more specific missions, in order to define an ambitious objective and long-term policies.

Sustainability-oriented missions in the urban environment will require investments in energy, transport, health, water management, and waste reduction. Cities, because of the complexity involved and the crucial role they play in the transition towards a more desired future, offers an extraordinary opportunity for experimental research based on interdisciplinary approaches, aimed at finding solutions to the complex problems we face.

It is well known that the urban space and the energy model we have must change. In this sense, we should reflect on lines of action that generate visible and permanent changes. On the one hand, the decarbonisation of the current energy model requires holistic approaches to the generation, transmission and use of energy, which is framed by three different levels of action: the substitution of fossil fuels by zero carbon sources (solar photovoltaic, wind, geothermal), energy efficiency in the final use of energy (heating and cooling of buildings and transport) and the electrification of motorised mobility and industrial processes (Renewable and Agency, 2018). On the other, achieving resilient and sustainable cities requires investment and development of urban infrastructure, services, and technologies, in which nature-based solutions can play a key role.

Research through the scientific community hence plays a key role in this process, as it can take up the challenge of developing, monitoring and quantifying tools, methods and technologies that demonstrate the technical and economic feasibility of certain actions in the medium and long term. It is therefore the aim of this paper is to define the framework for international action in terms of innovation and sustainable development in cities and to analyse the lines of action that are being implemented today in the field of nature-based technologies, in order to finally make a concrete contribution to urban space design models that meet the global agenda and demonstrate that the design of isolated actions does not produce a real transformation.

Fostering the nature and energy values

Urban space is made up of a complex network of actors and elements that require a broad integration approach when thinking about transforming it into a sustainable model. Some authors such as Tara Mothtadi call this systemic approach "*hedonistic sustainability*"(Mohtadi, 2016).

Addressing climate change issues will highlight the role of architects and urban planners in shaping the city and building resilience.

Urban space, nature and people are interconnected, which is confirmed by the proven benefits of nature in cities, ranging from mitigating the urban heat island effect, to absorbing sound waves, improving air quality, managing rainwater, increasing biodiversity, and reducing carbon emissions. In addition, they provide psycho-perceptual benefits that improve people's well-being and health (Lee et al., 2015). Considering that cities must work to mitigate climate change and, at the same time, taking into account the relationship with the urban landscape and citizens, it is necessary to devise solutions that provide cross-cutting values, such as nature-based solutions and the use of renewable sources.

Green infrastructure*:* The changes that cities are undergoing today mean that Nature-Based Solutions can have a fundamental role to play through the implementation of green and blue infrastructure, due to their capacity to restore ecosystems and at the same time provide benefits to society.

In 2015 the European Commission published the report "Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions and Re-Naturing Cities", a document that presented the opportunities for innovation and research in the use of nature as an instrument for urban planning for sustainability. This highlights the growing value that nature has acquired in facing the environmental, social and economic challenges that we face, defining them as "*solutions inspired and supported by nature, which are cost-effective, provide simultaneous environmental, social and economic benefits and help build resilience*" (European Commission and Union, 2015).

The term Nature-based Solutions (NBS) arises through the concept of ecosystem, used by the scientific community since 2000, considered as a tool to solve social and environmental problems. Through the European Commission's new approach, the economic dimension is increasingly part of this concept, thus becoming part of European policies and strategies based on biodiversity conservation, climate change adaptation, natural disaster reduction, and human well-being (Lafortezza and Sanesi, 2019).

The quantification and evaluation of the benefits provided by the NBS to address the challenges we face is part of current research. It is important to identify not only benefits and costs, but also interactions with social, cultural, economic, biodiversity and climate factors. Cities therefore need to be rethought through sustainable planning that takes into account these complex interactions. Under this approach, NBS can be seen as a technological innovation focused on nature and on the objective of improving the natural capital of cities (Frantzeskaki, 2019).

Energy infrastructure: to achieve the main objective of decrease the temperature of the earth below 2 ºC in relation to the pre-industrial levels fixed by the Paris Agreement, renewable energies must be climbed six times faster than what has been doing.
The urban model is the inflection point on which the parameters, dimensions, and methodology necessary for a large-scale energy transition can be established, allowing the current energy model to be modified.

The concept of the energy transition, in addition to being technological, puts the citizen at the centre of the system, transforming his or her role as a passive consumer into an active actor, capable of rationalising, self-producing and managing his or her energy needs. This transition must consist of aligning public policies with private investments in a framework of cross-cutting action.

The growing role of cities in climate action

The introduction of sustainable solutions in cities depends largely on new models of governance, through which innovation is encouraged, whether through long-term funding programmes in collaboration with businesses; the creation of an economic framework; or the monetisation of the benefits offered by nature.

Some indicators such as: the rate of growth of jobs related to green infrastructure; access to energy from renewable sources; the percentage of total surface area of green spaces; reduction of the rates of insecurity linked to the recovery of degraded spaces; levels of population exposed to outdoor air pollution; waste water treatment; the proportion of renewable energy produced and investment capacity, can be public policy instruments for quantifying the effectiveness of these solutions.

The value of green infrastructure and the reconfiguration of the current energy model are increasingly recognized by civic authorities and local citizens. Evidence of this is the growing number of local, national, and international initiatives for the sustainable use of natural capital in urban areas, among which some priority lines of action have been developed, linked to:

- Enhancing sustainable urbanization through new technologies and business models*:* sustainable urban planning requires the development of technologies focused on human well-being and public health. An example of this is green roofs, which are capable of providing benefits in reducing energy consumption, contributing to rainwater management, reducing the urban heat island effect, creating opportunities for work and social interaction, as well as improving public health (Xing et al., 2017).

- Restoring degraded ecosystems by environmental restoration*:* As a result of human activities, some ecosystems have been degraded or lost, especially due to air and soil pollution, the modification of water bodies and the intensity of forestry practices, resulting in the interference of the functions that nature exercises in urban environments such as water purification, carbon sequestration, flood and drought prevention among others (Kabisch et al., 2016).

  Some NBS such as Sustainable Urban Drainage (SUD) can contribute to flood mitigation and water quality, as well as reduce the risk of flooding in cities.

Some solutions, such as plant facades, can contribute to generating economic and environmental value. The opportunities to green the grey infrastructure, the design of exterior and interior spaces, the development of business models around spaces such as urban gardens, can guarantee a positive and multiplying effect in the search for sustainability and urban resilience (Nesshöver et al., 2017).

- Power grid decarbonization*:* energy transition must be drawn inside and out from the cities, from their different consumer sectors, buildings, industry, and services. The transport sector is one of the most influential, and the promotion of electrification of mobility can be one of the strategies that can help the decarbonization.
  Some estimates claim that a combination of solar, wind and hydropower by 2030 would capture between 35 and 45% of the sector's total emissions. Therefore, without promoting demand for renewables and energy efficiency through utilities and policymakers this won't be possible (McKinsey Center for Business and Environment, 2017).

- Promote the expansion of distributed renewable energies*:* Solar energy is considered one of the main strategies for sustainability in cities and forms part of only 0.1% of the world's electricity mix. Despite development and innovation, there are still barriers in the renewable energy market such as lack of legislation, tax incentives and the exhaustion of available areas adaptable to solar energy production.

  Photovoltaic technologies are a potential contributor to both small- and large-scale energy in response to the challenges of 2050. Unlike centralized renewable energies, smaller and more distributed installations can be more economical for public services and can be faster to implement. Energy resilience is important, not only at the scale of buildings but also in urban space (Renewable and Agency, 2018).

  In the building sector worldwide, heating and cooling accounts for 35% to 60% of total energy demand and is expected to increase by 70% by 2050, despite the energy efficiency measures that have been implemented. Several opportunities such as Building

Integrated Photovoltaics (BIPV) offer the possibility of reducing emissions from buildings (Kiss, 2012).

Building the urban transition: the holistic of urban space

A great deal of the scientific research developed so far has focused on identifying the causes of urban social inequality and the unsustainability of the current urban model, and on understanding the connections that there are between these problems.

While certain tensions in cities are considered to be connected, the loss of biodiversity, air quality, the impacts this has on water quality, climate, and human health, are part of a chain of consequences that lead us to reflect on the need for holistic and cross-cutting solutions that can address these interconnected problems.

We are convinced that NBS's are a tool that can contribute to the improvement of urban environments in vulnerable neighbourhoods. Among other ways, through citizen participation and attention to the specific needs of disadvantaged groups. One evidence is the European project CLEVER Cities. In which it was proposed the rehabilitation of an area of the city of Madrid through the creation of "habitable itineraries" in the Usera neighbourhood.

Similarly, projects such as Nature4Cities, Naturvation, or Think Nature, investigate the new political and economic models of NBS to provide evidence at European level of the scalability potential of NBS, as well as to provide a sound assessment framework for spreading the value of nature in cities. Such projects contribute to synthesising current knowledge and influencing local and European policies towards more sustainable and resilient cities.

Likewise, if we look at the field of renewable energies. Nowadays, there is a significant disproportion between population density, the energy intensity this entails, and the surfaces available for the installation of technologies such as solar photovoltaic. This scenario raises the question that beyond the installation of systems on roofs and facades, it is necessary to promote another type of innovation and technology in the field of distributed energy offering alternatives to the current market under the premise of more production and efficiency with less surface area.

The incessant growth of the cities requires a commitment to the development of new systems that can be adapted to the territory, not dependent on the surface area of the buildings, and which can also offer different systemic and transversal solutions, including light, urban furniture, charging points for electric vehicles, contact with nature, and recovery of the sense of belonging to a community. The design of complex and interconnected urban spaces that have solutions based on nature and energy production technologies from renewable sources can become tools, among many others, capable of activating a series of social, ecosystemic and economic mechanisms and processes, valuable for the transformation of the cities of today and tomorrow.

Addressing the current complexity of urban spaces requires the definition of spaces that, on the one hand, define strategic actions in cities, and on the other, involve cross-cutting solutions to address current challenges. Considering the city as an ecosystem allows us to achieve models of efficient, complex, interconnected, and socially cohesive cities.

Conclusion

In this study, a reflection is made on distinct aspects that characterize the current urban scenario. It starts with the awareness that urban settlements have the most important environmental impact in terms of energy consumption, natural resources, and CO_2 emissions. For this reason, the challenge of climate change must be met by promoting economic, social, environmental, and political initiatives, involving society and government in co-creation models aligned with the SDGs. Through this work, the aim is to provide a strategic and interdisciplinary vision in the transformation of urban space, giving rise to concrete actions focused on processes of an ecosystemic and social nature.

The creation of an innovative model requires the creation of spaces for debate and consultation processes that are the basis of collaborative design. This requires, on the one hand, promoting solutions compatible to achieve zero net emissions, preserve biodiversity, and improving citizens' well-being in the short term. On the other hand, it is necessary to promote the integration of renewable energies through innovative technologies necessary to reduce emissions. As architects, we are called upon to promote urban planning approaches that allow citizens to enjoy the benefits and services that nature offers, without prejudice to the environment.

Indeed, one of the main challenges of our time is to achieve sustainable urban ecosystems. Although much progress has been made in recent years, we can consider that we are only at the beginning of a long journey. In this sense, the study supports the hypothesis that the combination of nature-based solutions and renewable energy production technologies can give rise to integrated urban spaces, potentially activators of social, ecosystemic, and economic processes functional to the transformation of today's and tomorrow's cities.

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Artículo 2

Actions for adaptation and mitigation to climate change: Madrid case study

Valentina Oquendo-Di Cosola, Jorge Adán Sánchez-Reséndiz, Lorenzo Olivieri, Francesca Olivieri (2021).

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Actions for adaptation and mitigation to climate change: Madrid case study

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Abstract: Systemic innovation must be the driving force behind actions to transform cities to address climate change. It includes transformations of environmental, social, economic, financial, technical, regulatory, and governance nature, supporting the permanent change of cities. Nature-based Solutions (NBS) can be part of the tools to address the challenges ahead. This research aims to define a framework of action in cities for the implementation of NBS, demonstrating the importance of quantifying its benefits in environmental and socio-economic terms, to boost public policy design and investment in this field. This work is divided into two parts. The first part, analyses some of the European measures in the field of sustainable development in cities, focusing the research on the case of Madrid. And in the second part, some case studies are presented to reflect the measures and actions taken to promote the implementation of NBS in the city of Madrid. As a result, the potential levers of change for the implementation of NBS are identified, highlighting the importance of quantifying their effects to demonstrate the potential value that can be generated in the cities. within cities.

Keywords: Nature-Based Solutions, Sustainable cities, Innovation, Climate change

1. Introduction

1.1 Innovation through Sustainable Development Objectives (ODS)

In 2015, 193-member states of the United Nations unanimously adopted Agenda 2030 for Sustainable Development, made up of 17 Sustainable Development Goals (SDGs), and 169 goals to be achieved by 2030 [1]. These universally applicable goals set quantitative results in the three dimensions of sustainable development: social, economic, and environmental. They address critical issues related to human development such as energy poverty, climate change, economic development, protection of ecosystems, and cities. However, this agenda has been more ambitious and comprehensive than the previous ones, since it integrates dimensions that had been absent until now, such as governance, gender equity, and peace.

The international community, through the 2030 agenda, has changed its vision of how to tackle development problems. This approach implies taking on challenges on a global scale in a much more complex and interdependent world, which sometimes implies significant resource management. Although, it requires the collaboration of different actors in society - governments, citizens, investors, civil society - who seeks to connect demand with action. The transition to a more desirable world for all should go beyond independent initiatives and partial approaches and must be characterized by a new narrative that encompasses the growth of the entire economy [2].

Cities play a fundamental role in the path to achieve Sustainable Development Objectives. Any vision of the future that seeks to design sustainable scenarios must consider the social, economic, and environmental aspects involved. By 2050 it is projected that more than half of the world's population will live in cities, accounting for 90% of urban expansion in developing countries [3]. The interpretation of these data leads to estimates that the growth rate of cities will be 1 million people per week. Becoming one of the main challenges of the 2030 agenda, since population growth is intrinsically related to energy consumption and pollutant emission.

Cities occupy only 3% of the earth's surface and account for 80% of energy consumption and around 75% of the planet's CO_2 emissions. Many cities are also highly vulnerable to climate change, and natural disasters mainly due to their location, so strengthening adaptation and mitigation to the vast consequences of massive city development is crucial to avoid negative socio-economic impacts.

With the Agenda 2030 and the Sustainable Development Goals, countries have committed themselves to set a goal for prosperity, people, peace, and partnerships in favour of moving towards a stable and long-term development scenario. To achieve this, not only are technological developments or scientific advances needed, transformations are needed that develop technologies capable of promoting public and private investments and stimulating governance mechanisms.

In response to this scenario, the Sustainable Development Solutions Network, in its report, 2019 [4], refers to six main changes to achieve the SDGs, based on two cross-cutting principles. The first is related to governments and the need to ensure that each change promoted is designed by and to encourage equity and social inclusion, applying particularly to public services and infrastructure. The second argues that any transformation must reduce humanity's vulnerability, i.e., the environmental footprint, resource use, and pollution caused by human well-being.
Among the 6 transformations, the proposal of the SDG 11 stands out: Sustainable Cities and Communities, which contemplates within its action the investment in green infrastructure in cities, towns, and communities that contribute to face climate change. Although this is a specific objective, its impacts indirectly affect all the SDG targets, mainly those related to transport, urban development, and water resources.

The development of public policy and increasing research has demonstrated the milestone cities represent in the global urban transformation and in the development of innovative solutions. Proof of this has been the implementation of the New Urban Agenda and the Spanish Urban Agenda, as well as statements such as those of sociologist and economist Saskia Sassen who states that "cities will be more important than states" [5].

In the field of research and its main funding programmes at the European level (Horizon Europe) and in Spain (State Research Plan 2021 - 2027) the focus is on systemic innovation. This approach is being promoted by the European Commission [6,7] and has been theorised by Mariana Mazzucato [8,9], professor of Economics of Innovation and Public Value at University College London (UCL), who states that on the basis of innovative policies, oriented towards one or more specific missions, it is possible to define ambitious, long-term political objectives.

These missions oriented towards sustainability in the urban environment will require investment in areas such as energy, transport, nutrition, health, and waste reduction. This approach offers a massive opportunity to increase the impact of research and innovation, capture the collective imagination, and make real progress in complex challenges. Whether it is to achieve lower pollution levels in congested cities, have access to digital technologies that improve public services, or better treatments for the sick.

A crucial element within this theory of innovation in cities is the culture that supports experimentation, risk-taking, original, and creative thinking aimed at finding new solutions to existing problems. To this end, it requires interdisciplinary academic work, the intersection between knowledge sectors, a collaboration between different segments of the industry, alliances between the public-private sector and civil society organizations, to identify cross-cutting solutions to complex problems.

Due to their complexity and the fundamental role they play in the transition towards a more desirable future, cities offer us an extraordinary scenario to accommodate experimental research based on interdisciplinary approaches. As cities are places where negative impacts occur from a social and environmental point of view, there are issues such as atmospheric pollution and climate change, which have a direct incidence of cardiorespiratory diseases, rising temperatures, among others. In contrast, cities by their very nature can favour the search and joint identification of solutions to these problems.

According to weather forecasts and reports, the long-term climate will be characterized by a predominance of extreme weather events, as well as a general increase in temperatures and a decrease in precipitation. Addressing current needs for adaptation and mitigation of climate change impacts is therefore critical. Along these lines, nature-based solutions, among many others, are shown to be solutions that promote the transition to healthier, more resilient, sustainable, inclusive, and friendly city models.

This article is adapted from the work done for the ICSC-CITIES 2019 congress "Nature-Based Solutions for Cities Resilience: opportunities for action in Madrid" [57]. In this work, we have deepened in one of the practical cases, specifically, the quantification of the effects of the vegetal facades installed in the building of the Innovation in Technology for Human Development Centre (itdUPM).

1.2 Nature-Based Solutions: goal and challenges

Climate change is affecting ecosystems, and, in this scenario, future environmental challenges are expected to increase [10]. The densification of cities, the degradation of soils, and natural areas are part of the challenges we face today. These processes lead to the loss of biodiversity and the biological processes necessary for the survival of the planet.

If these challenges are seen as opportunities for innovation, Nature-Based Solutions can achieve biodiversity conservation, but also bring environmental, economic, and social benefits, and foster climate change mitigation and adaptation [11].

The term Nature-Based Solution emerges around the year 2000 as a perspective of the relationship between people and nature, focusing specifically on the use of nature to address social and environmental challenges such as climate change. The European Commission defines them as "those that can turn nature into opportunities for social, economic and environmental innovation" [11]. However, the affirmation of the concept as a means of providing solutions to the problems posed by climate change is very recent [12].

NBS are solutions capable of interpreting complex processes of nature, such as the absorption of carbon dioxide, the treatment, and management of rainwater, the fixation of atmospheric particles, among others, to reduce environmental risks and achieve human well-being. Therefore, maintaining and improving the natural capital is the principle of this type of solution.

The benefits provided by nature in urban spaces have always been related to environmental and social sustainability. This concept has evolved as public policy on environmental issues has been transformed, shaping research programmes such as the European Union's Framework Programmes for Research (Horizon 2020) [13], which incorporate narratives on ecosystem services that respond, among other things, to the Sustainable Development Goals [1]. The current calls allocate an important part of the funds to the recovery of the urban ecosystem, through green infrastructure, seeking to promote the monitoring of pilot experiences to quantify their benefits and contribute to pilot-based decision-making in cities [14].

According to a group of experts from the European Commission [11], nature-based solutions should be developed within the framework of 4 main objectives and 7 actions in the field of research and innovation. These include "(I) urban regeneration through nature-based solutions; (II) nature-based solutions for improving well-being in urban areas; (III) establishing nature-based solutions for coastal resilience; (IV) multi-function nature-based watershed management and ecosystem restoration; (V) nature-based solutions for increasing the sustainable use of matter and energy; (VI) nature-based solutions for enhancing the insurance value of ecosystems; (VII) increasing carbon sequestration through nature-based solutions". These actions would lead to the promotion of international cooperation in the development of sustainable solutions that would help Europe achieve its objectives of sustainable urbanisation, adaptation, and mitigation of climate change, risk management, and resilience.

Taking advantage of the impulse of big problems to bet on change seems to be the way. Face current challenges based on studies already carried out on how nature works and how many benefits, including innovative developments of alliances between governments, companies, and investors. There is today a real awareness of the value of nature, and the growing number of international organizations, policy initiatives for conservation and sustainability is proof of this.

2. Evaluating the effectiveness of Nature-Based Solutions

The impact and effectiveness of nature-based solutions can be analysed from three main concepts including quantification of the benefits obtained, mapping and evaluation of the profitability of these solutions, and finally the capacity to integrate different sectors of society and assimilate it into their city management policies.

This paper evaluates the effectiveness of NBS from three fundamental aspects: the monitoring of their behaviour, the capacity to provide profitable ecosystem services, and finally, the importance it has in the framework of action of the decision-makers in the cities. The final aim is to build a comprehensive narrative on their capacity for systemic transformation in response to the challenges faced by cities, demonstrating the value of quantifying performance and benefits.

2.1 Monitoring and analysis

One of the most important challenges of NBS is to make its effects become visible. They have a number of benefits designed to produce changes in the context in which they are found, varying in scale from a micro-level of the building, a meso-level of an entire city or country, or a macro-level of the entire planet [15]. One possible way to quantify their effects may be to evaluate their impact on a given space, through the use of indicators.

Therefore, taking into account the different scales of action and capabilities of these solutions it is possible to assess the impact through:

- Increase of green areas for the evaluation of, carbon absorption and improvement of air quality [16–20], reduction of temperatures [21–25], and acoustic absorption [26–30];
- Increase the use of façades and plant covers to mitigate the effect of urban heat island, through the management of shade and the effect of evapotranspiration of plants and substrate [24,31–37].

- Reduction of emissions and energy consumption through the study of solutions that contribute to the ene(Liu et al., 2013)rgy balance of buildings [21,38–42].

2.2 Economic valuation: NBS as a business model

Nature-based solutions are a form of eco-innovation that seeks to address climate change from the mitigation and adaptation of its effects on cities and people, such as improving air quality (Liu et al., 2013)(Salmond et al., 2013)(Abhijith et al., 2017), reducing biodiversity loss (Francis and Lorimer, 2011; Mayrand and Clergeau, 2018; Säumel et al., 2015) , reducing the urban heat island effect (Chun and Guldmann, 2018; Imran et al., 2019; Mariani et al., 2016), among others. Part of these solutions has to do with green infrastructure that adapts to the current grey infrastructure, such as green facades and roofs, rainwater recycling systems, parks, and forests. These can provide value to society, whether economic, environmental, or social.

From a socio-economic perspective, NBS can be interpreted as natural capital, which provides services to current ecosystem problems [43]. These services can be classified into three categories, according to The Economics of Ecosystems and Biodiversity (TEEB) [44]. First, they provide "provisioning services" such as food, biomass, clean water, and medical resources. Second, they provide "regulating services" such as temperature regulation, air quality, biodiversity protection, noise reduction, atmospheric carbon reduction, and water purification. Finally, they provide "cultural services" through recreation in public spaces and the psychological well-being of people.

Innovation as a business model has been widely studied [45-47], and in its development proposes three main areas: (i) the value proposition for customers in the form of service; (ii) how the value is delivered, i.e., the partners; (iii) and the component that captures the value, i.e., the revenues and costs. These concepts translate into NBS, specifically, those related to buildings: facades and roofs, as well as those related to water management, can be framed in a sustainable business model.

An example of this is green roofs, which provide insulation and protection to buildings, which leads to maximizing energy efficiency. For the owner of a building, the investment in this type of solutions will be felt if one takes into account the reduction in expenses related to the conditioning of the internal spaces, as well as those of maintenance. Also, these solutions can use the building's water, heat, and organic waste to maintain themselves. This type of technology can be developed in the model of passive solutions for reducing energy consumption (de Munck et al., 2018; Taleghani, 2018a), recycling rainwater (van de Wouw et al., 2017), improving air quality (Gourdji, 2018), increasing biodiversity (Mayrand and Clergeau, 2018), among others.
However, these benefits are difficult to capture through private investments, so their monitoring and quantification would establish a framework for profitability and investment.

Another important example would be the management of water flows in densely urbanized areas. Water management through NBS provides an alternative to prevent flooding in cities, as opposed to creating a grey infrastructure based on pipelines. Sustainable drainage systems can generate numerous benefits, however, the lack of quantification of these benefits becomes a barrier to diffusion in cities and adaptation by authorities.

One of the main obstacles in investing in green infrastructure is the economic return, and this is due to the lack of tools that capture the value and service they offer. The success of innovation through nature can go hand in hand with the quantification of its benefits and public-private investment.

2.3 Policy implications

The insertion of these solutions in cities depends to a great extent on a new model of governance, i.e., coordination between administrations is essential when it comes to tackling problems that affect society. This is proposed in the European Urban Agenda [48], through the establishment of global and integrated strategies that provide solutions to common challenges.

Part of these strategies could be materialized in the emergence of new organizations in the form of innovation laboratories driven by the local administration that allow to prototype and evaluate actions and solutions, that in turn, respond to current challenges and are developed in open collaboration with the citizenry. The development of technology and interdisciplinary collaboration can be transformed based on acceleration towards the resilience of cities.

There are several options through which policymakers at a local, regional, or national level can foster innovation through NBS in cities. Either through long-term funding, establishing an accounting framework for the services nature provides, such as, improving air quality, and developing public-private partnerships with incentives that benefit all actors: academic, business, and government. To give to NBS a value that allows them to be integrated into government decision-making.

Indicators such as the growth rate for jobs related to green infrastructure, access to energy from renewable sources, the percentage of the total area of green spaces, the reduction in insecurity rates linked to the recovery of degraded spaces, the levels of the population exposed to outdoor air pollution, wastewater treatment, the percentage of solid waste recycling, the proportion of renewable energy, and the investment capacity of public-private cooperation, can be instruments of public policies for quantifying the effectiveness of these solutions.

3. Nature-Based Solutions in practice: the case of Madrid city

Madrid is a city with a great deal of experience in innovation and transformation of its urban fabric, as well as in the development of public policies that respond to the economic and environmental commitments acquired at the European level. It has demonstrated this through its work towards a low-carbon, circular, ecosystem-friendly economy, which highlights NBS as a lever towards resilience in the face of climate change.

3.1 Government and regulations

Today, urban nature has taken on the role of an instrument for adapting the city to the effects of climate change. In the international context and at the European level, different cities are developing programmes for the integration of nature into urban contexts as a way of adapting cities to climate change [49-51].

Concerning these plans, the commitments made by Madrid City Council on climate change have been on the rise, demonstrating this through adherence to the European New Covenant of Mayor's initiative; the participation in the Paris Conference of the Parties (COP21); the adherence to international networks such as the network of cities for climate C40; and the development of concrete plans for the implementation of NBS and the improvement of air quality.

To identify the threats and vulnerability of the city of Madrid to climate change, the General Directorate for Sustainability and Environmental Control carried out an analysis [52], based on the Energy and Climate Change Plan for the city of Madrid - Horizon 2020. This identifies the main climate trends and the impacts derived which the city will have to face throughout this century. Including a decrease in rainfall, an increase in average monthly and annual temperatures, as well as an increase in the duration of heatwaves. These changes can affect public health and the loss of biodiversity. Since it not only increases air pollution but also diminishes water resources reserves and increases the risk of flooding from heavy rainfall.

To respond to these challenges, the Energy and Climate Change Plan establishes a strategic framework for developing a low-carbon city, which promotes energy efficiency and the use of renewable energies, the optimisation of municipal energy and environmental management, and the planning of adaptation to climate change.

The Madrid + Natural Plan was born out of the commitment to advance municipal policies [53]. To promote the development of green urban infrastructure, the programme was structured on three scales: the building, the neighbourhood, and the city, in such a way that the actions lead to specific and common objectives. These include improving the energy performance of buildings, regulating rainwater flow, making green spaces available, mitigating the urban heat island effect, improving air quality, and monitoring facilities to quantify the cost-benefit ratio, maintenance, and operation of these solutions.

Plan A: Air Quality and Climate Change Plan for the City of Madrid is part of this strategy, a tool for reducing air pollution, contributing to the prevention of climate change, and defining adaptation strategies [54]. It is structured in four key areas: sustainable mobility, urban regeneration, adaptation to climate change, public awareness, and collaboration with other administrations. It has an ecological vision of the city, both in terms of mobility and public awareness, and in the rehabilitation of buildings, public spaces, local energy production, water management, and the renaturation of the city.

In the context of the programmes and initiatives previously discussed, and with the assumption that the city needs to establish new models of relationship with the climate and the environment, we present below a series of case studies carried out in the city of Madrid and coordinated from the Universidad Politécnica de Madrid, establishing the main objective of introducing NBS as a tool for mitigating and adapting to climate change.

3.2 Case studies

The following are different research projects whose main objective is to quantify the effects on buildings and the urban environment of different nature-based solutions. The quantification was carried out through the use of predictive models, the use of specific computer tools, and the analysis of the data obtained.

It is important to note that the results presented here apply only to the city of Madrid. And although this type of solution can be extrapolated to other geographical contexts, as they are natural processes of exchange with the environment, the results and effectiveness of these will vary accordingly.

Several variables are analysed in detail:

- Energy efficiency
  - To quantify, by monitoring and data analysis, the effect provided by vertical gardens on the indoor thermal conditions of a building.
  - To quantify, by predictive models, the energy behaviour of façades and plant roofs, the effect that the installation of a plant roof and roof would provide on the internal thermal conditions of a building and its energy demand.

- Reduction of temperatures at street level
  - To quantify the effect of different Nature-Based Solutions in reducing outdoor temperatures at street level during the warm season.

- Reduction of air pollutants
  - To quantify the effect of a tower with vegetation in the absorption of polluting gases and the capture of suspended particles.

- Sustainable use of rainwater in the built environment

  To quantify the effect of a circular system for integrated water management in built environments on the temporary retention of runoff water and the elimination of pollutants.

Energy efficiency through analysis of experimental data: vertical gardens on itdUPM

The study is being carried out in the maintenance building of the Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas (ETSIAAB) of the Universidad Politécnica de Madrid, the current headquarters of the Centro de Innovación en Tecnología para el Desarrollo Humano (itdUPM).

In 2016, the building was renovated to become the headquarters of the itdUPM and was set up as an experimental building to promote sustainable development within a programme of new strategies and technologies **(Fig.1).** The building has a rectangular floor plan and measures approximately 21.38 m x 9.35 m. There are two floors: basement and ground floor, each with 199.90 m^2 built, with a height of 4.70 m. The total area of the building is 399.80 m^2.

The building's requalification proposal is based on the integration of a vegetal envelope that occupies part of the south, east and west facades. The façade system is based on a recyclable plastic module belonging to the continuous plant façade systems with an organic substrate. This system allows savings in water consumption and low fertilizer use.

The metal skin has been made through a ventilated façade in three of the four walls of the building (south, east, and west), and consists of modules 2.4 m long x 0.6 m high, supported on vertical uprights. These uprights placed every 2.4m, do not rest on the ground but are anchored to the envelope of the existing building using metal plates screwed to the wall. Each upright rest at three points on the wall. This metal façade, with its structure, allows the vertical garden modules to be placed on top of it, making it very quick to install. The vertical garden modules are made up of pre-cultivated panels fixed to the metal enclosure. These façades currently cover an area of 11.25 m^2 on the south façade, 6.25 m^2 on the east façade, and 10 m^2 on the west façade.

The system used is a commercial product *Biofiver* [55], which has the following characteristics:

- Size: 50 cm x 50 cm x 10 cm
- Weight (without plants): 2 kg
- Number of floors/m^2: 48
- Static system: simple anchorage
- Irrigation system: integrated exudate pipe
- Module material: recyclable polyethylene
- Substrate: organic (coconut, peat, humus clays)

It is composed of two three-dimensional polyethylene structures, including a hydrophilic layer for the distribution and drainage of the irrigation water. One of the structures is filled with a substrate for cultivation, and the other remains empty, creating a hollow space for air circulation. The irrigation system is internal and is done through self-compensated dripping, which means that the water is always in circulation generating a humid environment.

Fig. 1. Headquarter of Innovation and Technology for Development Centre (itdUPM)

Reductions of temperatures at street level: renaturation of Matadero

This second case study is part of the “Matadero Acción Mutante” project an initiative carried out by Matadero in collaboration with a group of researchers from the UPM, the Sub Directorate-General for Energy and Climate Change, and the Directorate General for Intervention in Urban Landscape and Cultural Heritage of the Madrid City Council and other agents such as architects, engineers, artists, botanists. This aims to raise awareness of the environmental crisis with strategies for mitigation and adaptation to climate change and through the relationship culture-nature.

The exterior space of the enclosure occupies 34.330 m^2, so it is significant to think about treating these spaces that form part of the complex. The spaces without vegetation and shade suffer enormously from extreme temperatures and especially the heat waves that are occurring more and more frequently in Madrid. It is for this reason that Matadero has become a case study to apply Nature-Based Solutions and thus test responses to adapt to climate change while transforming Matadero in a friendlier and fresher space. The solutions based on nature will be the result of a creative process involving five artists from different parts of the world.

As a first step of the work, in the summer of last year, five sensors were installed in different external spaces of Slaughterhouse or near it for the measurement of temperatures and humidity of the air in the current state before the interventions of urban naturalization **(Fig.2)** The sensors used were the HOBO MX2301A Temperature/RH Data Logger [56].

Fig. 2. Location of the sensors, from the top right clockwise: Plaza de Legazpi, Plaza de acceso, Calle Matadero, Casa del Lector (north access), “No huerto”.

Reduction of air pollutants: modules for urban air cleaning (MUAC)

This case study is based on the installation and monitoring of two identical experimental prototypes of the *MUAC* (*Modules for Urban Air Cleaning*) tower with vegetation **(Fig 3**). The first was installed in October 2018 in the vicinity of the former maintenance building of the Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas (ETSIAAB) of the Universidad Politécnica de Madrid, current headquarters of the Centro de Innovación en Tecnología para el Desarrollo Humano (itdUPM); and the second will be installed in the vicinity of the Escuela Técnica Superior de Ingenieros Industriales (ETSII) of the Universidad Politécnica de Madrid in autumn 2019.

MUAC vegetation tower is an air decontamination system that reproduces the biological and microbiological purification processes carried out in forests. The tower is 2.8 m high and has a square floor area of 0.7 m on each side, with a total surface area of 0.49 m^2. It consists of 16 plant panels from the Biofiver system. The purification of the air is carried out outside and inside the tower. Outdoors, the leaves capture and absorb suspended particles ($PM_{2.5}$/PM_{10}), as well as generate an exchange of gases (CO_2 for O_2) through the process of photosynthesis. In the interior, the air is filtered through a process where the roots and the microorganisms that inhabit the substrate absorb and feed themselves with polluting gases such as COx, NOx, O_3, or SOx.

Fig. 3. A prototype of the MUAC installed at the entry of the itdUPM headquarters.

This system has been designed to easily adapt to different types of environments and climates, using native vegetation. Furthermore, the MUAC is equipped with an autonomous energy system that, through a photovoltaic panel and a storage battery, allows it to operate 24 hours a day, even in conditions where there is no connection to the electricity supply. Electrical energy is used to power both the irrigation system and the air circulation system inside the tower.

The two vegetation towers are equipped with two types of sensors for the measurement of suspended particles and polluting gases. These are the Uhooair sensors, which measure NO_x, CO_x, COV_x, O_3, $PM_{2.5}$, etc. **(Table 1)** and Purpleair sensors, which measure particles in suspension PM 0.3, 0.5, 1.0 2.5 and 10 μm **(Table 2)** tower, where the composition of the air is measured after the decontamination process.

Table 1: Actual measurement values by sensor type (Source Uhooair.com)

	Temperature	**RH**	**PM2.5**	**CO_2**	**TVOC**	**CO**	**NO**	**Air Pressure**	**O_3**
Units	°C / °F	%	µg/m^3	ppm	ppb	ppm	ppb	mBar	ppb
Range	-40°C / -40°F to 85°C / 185°F	0 to 100	0 to 200	400 to 10.000	0 to 1000	0 to 1000	0 to 1000	300 to 1100	0 to 1000
Resolution	0.1 °C	1%	0.1 µg/m^3	1 ppm	1 ppb	1 ppm	1 ppb	1 mBar	1 ppb
Tolerance	± 0.3°C	± 3%	± 20 µg/m^3 or ± 20 %	± 50 ppm or ± 3%	± 5%, based on the types of VOC in the air	± 10 ppm	± 5%	± 1 mbar	± 5%

Table 2: Actual measurement values of PM particles (Source purpleair.com)

Laser Particle Counters	
Type	(2) PS5003
Range of measurement	0.3, 0.5, 1.0, 2.5, 5.0, & 10 µm
Counting efficiency	50% at 0.3µm & 98% at ≥0.5µm
Effective range ($PM_{2.5}$ standard) *	0 to 500 µg/m^3
Maximum range ($PM_{2.5}$ standard) *	≥1000 µg/m^3
Maximum consistency error ($PM_{2.5}$ standard)	±10% at 100 to 500µg/m^3 & ±10µg/m^3 at 0 to 100µg/m^3
Standard Volume	0.1 Litre
Single response time	≤1 second
Total response time	≤10 seconds

The monitoring period shall be one year (limited to the lifetime of the measurement sensors). The data obtained will be used to measure the efficiency of the system, in addition to allowing us to estimate the impact that the implementation of towers would have on the urban fabric of cities.

Sustainable use of rainwater in the built environment: Bluebloqs circular water system.

This last case study consists of the installation and monitoring of the *Bluebloqs* system. It is an innovative solution developed by the Dutch Start-up Field Factors for the management and sustainable use of rainwater in the built environment, which integrates natural techniques for the retention, treatment, storage and reuse of rainwater in a circular system of flexible implementation in urban design, with the aim of restoring the natural water cycle in cities.

Bluebloqs biofilter is a modular system that combines hybrid technology using biological purification, using the proven purification power of wetland plants (68-72), as well as mineral purification using sand filters (73-77) to achieve highly efficient water treatment **(Fig.4).** *Bluebloqs* integrates natural purification processes in a controlled environment, eliminating the need for large infrastructures or chemical substances.

The system has distribution channels and water level and flows control mechanisms. The biofilter can be adapted to remove specific contaminants: organic matter, metals, and high levels of nitrogen usually found in runoff water (samples of water quality are currently analysed weekly, with results showing purification of more than 90% of impurities). The biofilter is optimized to work in combination with technologies for water injection and extraction in aquifers, guaranteeing high levels of water quality to comply with infiltration regulations and avoiding obstruction of facilities.

Bluebloqs presents a comprehensive solution for multiple challenges in water management. First, it aims to prevent flooding. The urban space is full of buildings and infrastructure that limit the infiltration of rainwater into the terrain. *Bluebloqs* makes use of the natural capacity of the subsoil to purify and store excess rainwater. This slows runoff infiltrates surface water and recharges groundwater levels, providing the retention capacity needed to prevent flooding.

Secondly, it contributes to combating drought. Longer periods of drought, loss of infiltration, and exponential population growth force us to use drinking water differently. With *Bluebloqs,* rainwater can be used when it's needed most: in times of drought. By creating a high-quality local water source, purified water stored in the subsoil can be used for numerous applications, including water parks, sports fields, and gardens, combating the heat, stabilizing surface waters, and industrial processes.

Finally, improving water quality. Urban currents carry pollutants present on the surface and in the environment, especially in large cities. Pavements, roofs, and the use of the environment emit pollutants that include metals, nutrients, and pathogens. To make safe use of rainwater and avoid the dispersion of pollutants, it must be treated. *Bluebloqs* makes use of natural purification systems, removing organic matter, solids, metals, and nitrogen levels typically found in urban runoff.

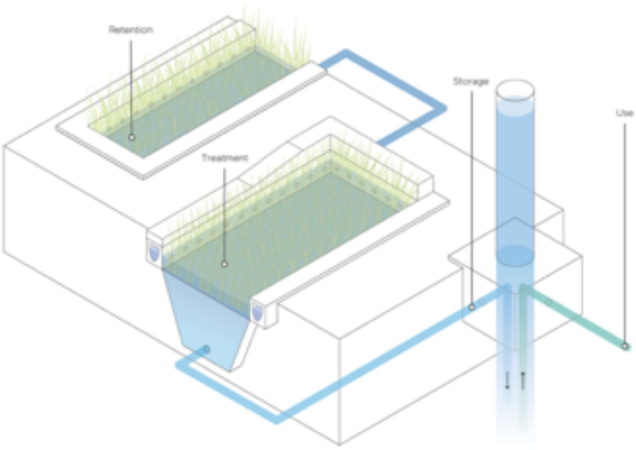


Fig. 4. Water cycle in the Bluebloqs system.

4. Quantification of effects: the case of the Innovation and Technology for Human Development Centre (itdUPM)

The vegetal facades installed in the itdUPM are monitored to study the performance and its influence on the improvement of the environmental conditions and the energy consumption of the building. There is a total of eight sensors on the façade, four in each orientation. Of these four, one pair measures the surface temperatures of the vertical garden (A and B, E and F), while the other pair is placed on the metal skin (C and D, G and H). Both pairs of sensors measure the surface temperature on the envelope and the immediate wall **(Fig.5).**

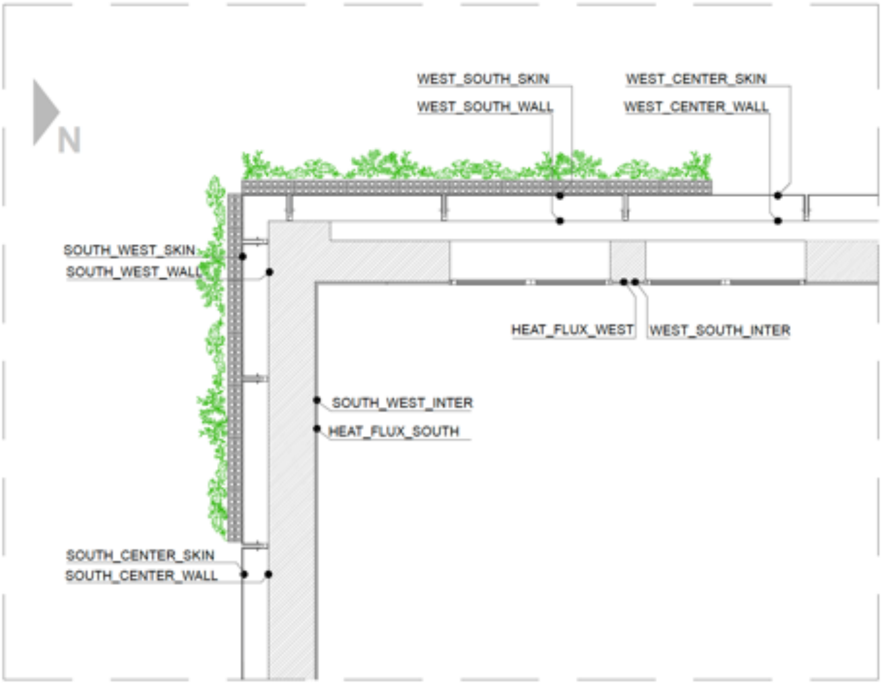


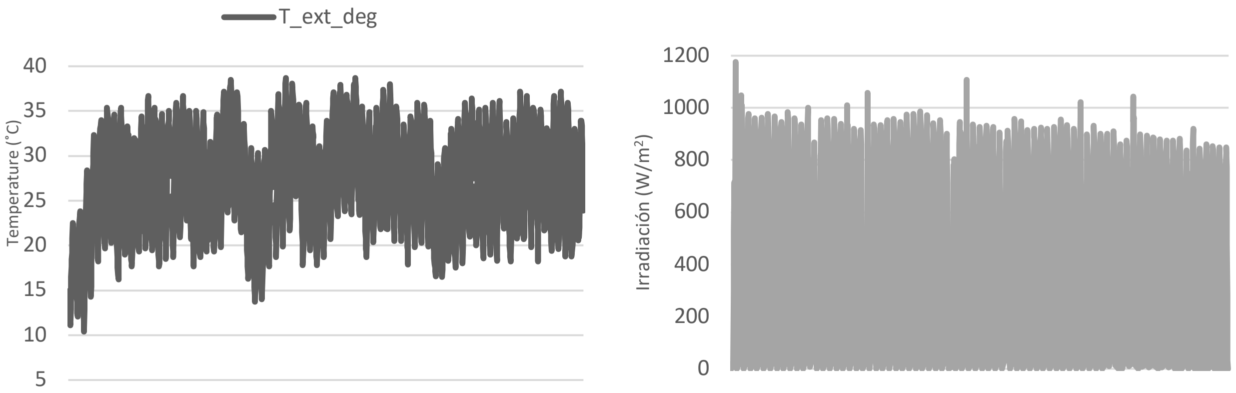
Fig. 5. Distribution in plant of the temperature sensors installed on the facade.

4.1 Local climate conditions in summer

Madrid's climate is in a semi-arid to Mediterranean transition. Due to its altitude of 650 m above sea level, great differences in temperatures are experienced between winter and summer. Summers are usually hot, with average temperatures above 25 ºC in July, with average temperatures between 32 ºC and 33.5 ºC. The annual thermal amplitude is also high: between 19 and 20 ºC.

To identify the most representative days of the year in terms of weather, a study was carried out of the data collected by the weather station located on the roof of the building, which collects data linked to atmospheric pressure (mmHg), outdoor temperature (ºC), wind speed (km/h), wind direction, relative humidity (%), UV index, irradiation (W/m^2) and rainfall (mm/h).

In this case, irradiation has been selected as the most significant parameter, since solar radiation **(Fig.6-a)** and outdoor temperature **(Fig.6-b)** will be the variables that will most directly influence the behaviour of plant facades.



(a) (b)

Fig. 6. (a) Average temperature during the summer; (b) average irradiance during the summer.

4.2 Experimental design and data acquisition

The real-time monitoring system has been installed through the use of thermocouples, type K with an error range between 0.1 ºC and 0.3 ºC, installed inside and outside the facades, and connected to a distribution system that allows obtaining information every minute, which can be visualized in streaming.

The network of sensors installed in the building is taking data since July 2016, recording the values in one-minute intervals during the twenty-four hours of the day. For this reason, the first step in interpreting the data has been to classify them into half-hour intervals. After classification, the previously selected days are evaluated.

To select the most representative days was considered a database of irradiation data for 12 months, from July 2016 to July 2017. The objective was to choose the days that represent most of the climatic conditions that occur throughout the year in the environment of the vegetal façade.

A total of eight typical days were selected, due to the influence it has on the behaviour of vertical gardens:

- Sunny days: 15/07, 19/07, 11/08 and 05/09
- Cloudy days: 20/07, 22/07, 09/08 and 02/09

4.3 Experimental results

In the different selected days, the registered values are very similar, so this work presents the results of one specific day, a sunny day, which achieve represent the behaviour of the facade during the summer.

Sunny day: July 19, 2016

July 19 has been a sunny summer day, in which the average temperature is 29 ºC, with a maximum temperature of 38.1 ºC at 17:30h and a minimum temperature of 21.7 ºC at 8:30h. As can be seen in the graph **(Fig. 7)** the solar radiation incident on the building begins at 7:30 am, reaching its maximum at 14:00, where a value of 902 W/m^2 is recorded. From that point on, the radiation begins to decrease, until it becomes null at 21.00h.

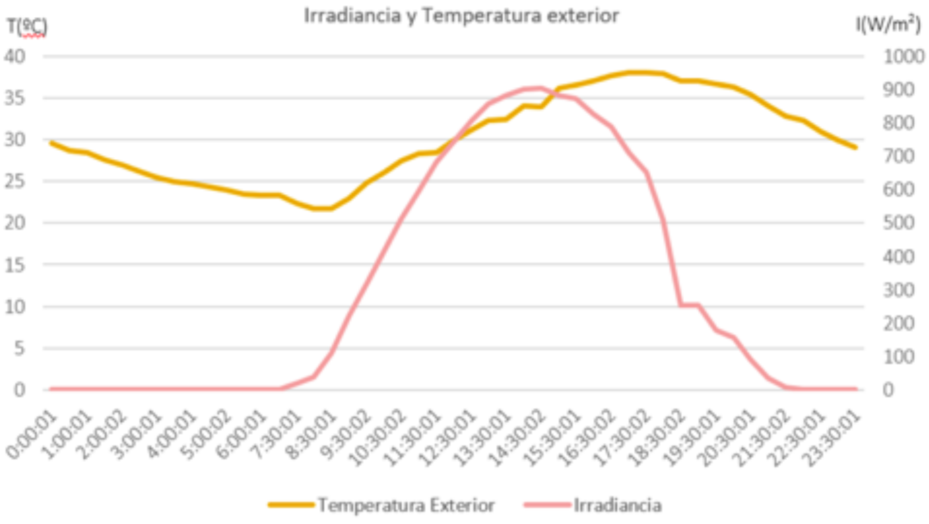


Fig. 7. Irradiance and outdoor temperature chart for July 19, 2016.

To understand the behaviour of the vertical gardens, a study was carried out of the shadows themselves and projected onto the building. It is observed that the modules oriented to the east receive solar radiation during most of the day, except the last hours of the afternoon. For its part, the western façade begins to receive solar radiation at around 11.30 a.m, and from 2.30 p.m. onwards, the shadow of the adjacent building begins to project onto it. From 18:30h, the whole building is in shadow.

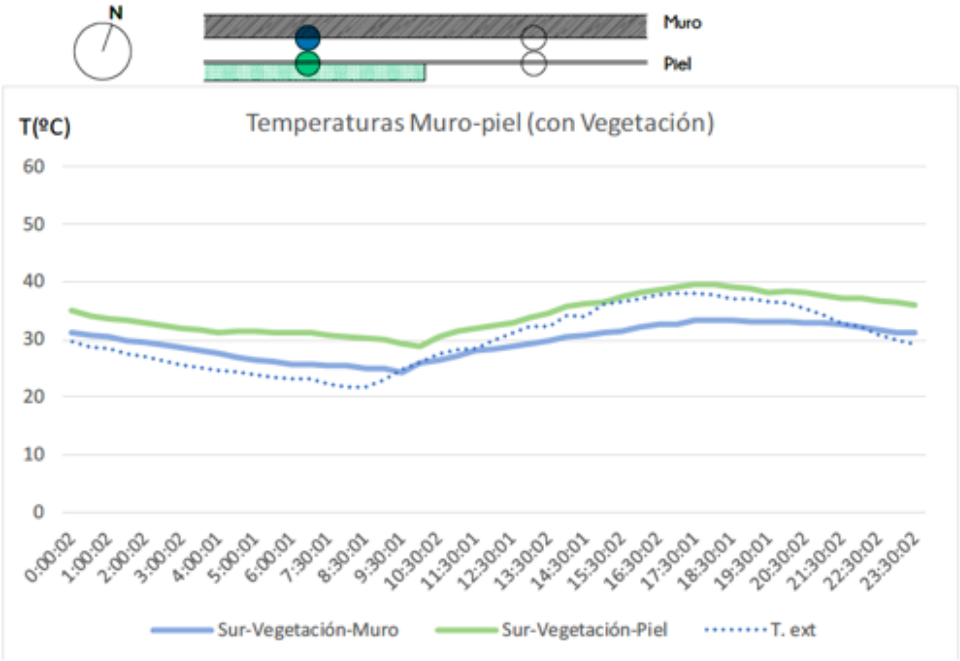


Fig. 8. Graph of temperature on the plant facade facing south.

In the graph **(Fig.8)** it is observed the comparison between the temperatures recorded in the wall and the skin in the vegetated zone. It can be noticed how the difference in temperature is constant throughout the day, reaching the greatest difference of 6 ºC at 17.30h. This difference is due to the ventilated façade and to the fact that the vegetation absorbs part of the solar energy received to carry out photosynthesis. By means of this effect, fresh air is obtained in the interior of the chamber, which will serve for aside, to regulate the temperature of the wall, managing to reduce its thermal load. On the other hand, this fresh air is distributed in the façade of the building, achieving a notable reduction of temperatures in the adjacencies of the building, thus improving the microclimatic conditions of the place.

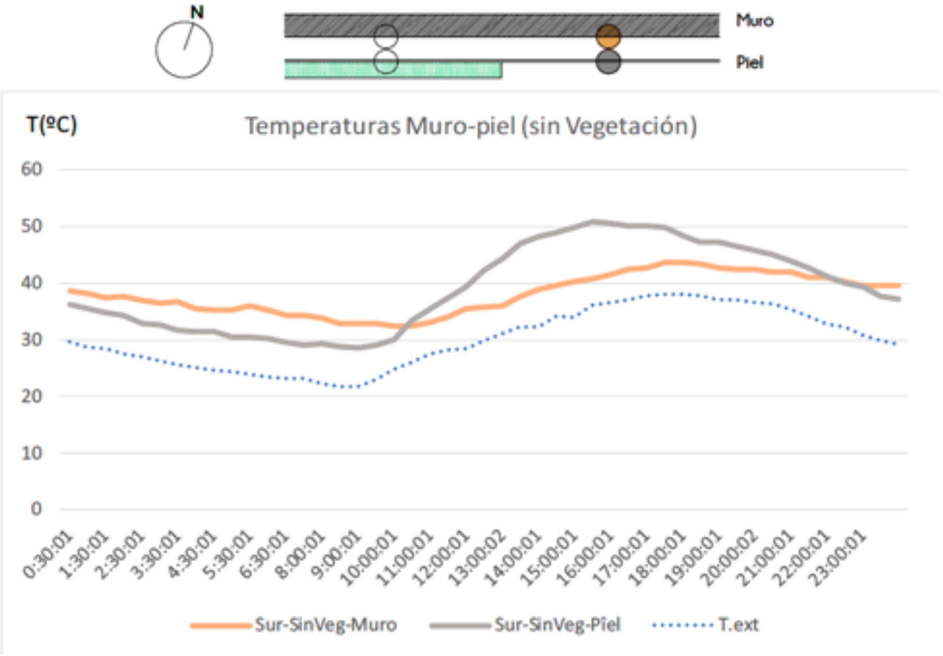


Fig. 9. Graph of temperature on the metal envelope facing south.

Fig. 9 expresses the comparison between the temperatures recorded on the wall and the metal enclosure. At night, with the decrease in outside temperatures, the temperature of the enclosure also decreases considerably. In the same way, as the temperature increases during the day, so does the surface temperature of the enclosure, reaching 50 ºC in the hours of maximum irradiance. In contrast, the wall maintains its temperature constantly, registering maximum differences of 10 ºC throughout the day, as opposed to more than 20 ºC of difference in the metallic mesh.

In general, data analysis allows us to demonstrate that a vertical garden, on a sunny summer day, is capable of absorbing part of the incident solar radiation, achieving a much cooler temperature at the back. On 19 July, at the point of maximum irradiance, an outdoor temperature of 37.7 ºC was recorded, while in the vertical garden it was 38.7 ºC, and in the wall area at the back of the garden, it was 32 ºC. This allows us to affirm that the temperature of the environment 1.5 meters away from a vertical garden can reduce up to 5 ºC the temperature concerning the temperature of the air, which leads us to conclude that this type of solutions allow us to improve the hygrothermal conditions of the surrounding environment, and affect the energy consumption of the buildings linked to the air conditioning of the spaces.

The main objective of this project was to quantify the benefits in buildings and urban environment provided by the use of green facades. It also aims to contribute to the use of innovative and replicable technologies as possible responses to some of the problems arising from climate change in urban areas, identifying them as adaptation and mitigation strategies.

This project is considered to be in line with the thematic priorities of the State Plan for Scientific and Technical Research and Innovation and Programme H2020 mentioned previously. Likewise, it is considered that the project responds to the guidelines set by the new European programme Horizon Europe and by the new State Research Plan 2021-2027 mentioned in section 1.1.

5. CONCLUSIONS

The main objective of the study carried out is to demonstrate the importance of quantifying the benefits of NBS in buildings and the urban environment. At the same time, it proposes the use of innovative and replicable technologies as possible answers to some of the problems derived from climate change in urban areas, identifying adaptation and mitigation strategies.

From the critical evaluation of the current European context and that of the city of Madrid, as well as from the different case studies in development, it is concluded that the potential benefits and beneficiaries of the results of this project are:

- The quantification of the effects and benefits of nature-based solutions in urban environments would allow establishing their value and potential as tools to increase the resilience of cities.
- Public administrations, which thanks to the results obtained from the analysis of the monitored data, will be able to have a clear idea of the effectiveness and efficiency of the different systems and thus be able to assess to what extent they could be interesting to be taken into consideration in the development and promotion of local plans for adaptation and mitigation of climate change.

- The private companies that commercialize the technologies involved in the study will be able to use the analyses carried out to provide potential clients with reliable data on the operation of these technologies.
- Potential investors who, with data in hand, will be able to assess the profitability of the investment.

This research work, based on the study of the social, economic, and environmental opportunities offered by solutions based on nature, has allowed us to corroborate the importance of quantifying the associated effects to consolidate the fact that they are tools capable of improving both the conditions of the building in which they are installed and those of their surroundings.

DECLARATION OF COMPETING INTEREST

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Artículo 3

A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation

Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García (2022).

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A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation

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Abstract: Achieving sustainable urban development requires a reorientation in the planning, management, and design of cities based on the use of cross-cutting solutions that can systematically address urban problems. The implementation of Nature-based Solutions (NBS) such as green walls in cities contributes to reducing the effects of a systemic issue: climate change. This field of research is constantly evolving, and there is a growing need for systematic analysis to understand the current scenario, identify gaps, and accelerate new lines of research. This review aims to demonstrate the impact of green walls on urban comfort by providing a systematic review of the state of the art in the field of temperature reduction and acoustic absorption; identifying the factors that influence urban comfort through the use of vegetation; and highlighting research gaps that can be further explored. The most relevant results have shown that the temperature reduction is mainly influenced by the shading capacity of the selected vegetation type, the natural evapotranspiration process of the plants, and the presence of substrate; that the acoustic absorption capacity is influenced to a greater extent by the configuration of the system, the characteristics of the substrate, and the density of the vegetation; and that in both cases the environmental conditions in which they are found can vary the impact to a greater or lesser extent. The results of this research are relevant for the implementation of green walls as a climate change mitigation tool in cities and the development of new research approaches.

Keywords: Vegetation; Green wall; Environmental comfort; Hygrothermal comfort; Urban noise; Sustainability.

Abbreviations:

- **SDGs:** Sustainable Development Goals
- **NBS:** Nature-based Solutions
- **EPA:** United States Environmental Protection Agency
- **WHO:** World Health Organization
- **UN**: United Nations
- **LAI:** Leaf Area Index
- **UHI**: Urban Heat Island
- **HI:** Thermal stress
- **dB:** Decibels
- **Hz:** Hertz
- **ºC:** Degree Celsius
- **α:** Sound absorption coefficient

1. Introduction

Climate change represents an unprecedented challenge for humanity. In recent years, remarkable efforts have been made at the global level both to identify these challenges and to promote solutions that contribute to the adaptation and mitigation of their effects. The most recent step in favour has been the definition and implementation of Sustainable Development Goals (SDGs) (Nations, 2015c), which, together with the Paris agreement on climate change (Nations, 2015a), form the new global agenda, the 2030 Agenda (Nations, 2015b). One of the SDGs is "sustainable cities and communities", which aims to "make cities and human settlements inclusive, safe, resilient, and sustainable". In the quest for a more sustainable planet, cities have a significant role to play, as they are currently home to more than half of the world's population, and this figure is expected to increase by 2030 (United Nations Department of Economic and Social Affairs-Population Division, 2018).

Accelerated urbanisation of cities has led to an increasing fragmentation of nature both in cities and in peri-urban areas. Consequently, impacts on the environment, such as the urban heat island effect, the progressive loss of the benefits of plant shade and evapotranspiration, as well as other impacts on society and the economy, have resulted (Smith and Levermore, 2008). A clear consequence of these effects is the urban heat island effect and associated temperature increases, amplified by the prevalence of reflective building materials. These surfaces in cities absorb and retain heat, which, in addition to the absence of vegetation and emissions, intensifies the effects of global warming (Stone Jr., 2012).

Improving outdoor comfort conditions in cities is one of the most significant environmental challenges for city sustainability and resilience. Climate change brings about a series of problems to the urban environment, among which the urban heat island phenomenon stands out. The United States Environmental Protection Agency (EPA) classified this phenomenon into two categories: that which affects surfaces and that which affects the air (United States Environmental Protection Agency (EPA), 2008). High temperatures are part of the variables of urban comfort, which are considered as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Atlanta: American Society of Heating, Refrigerating, and Air-conditioning Engineers. Inc., 2004). In this field of relationships between the built environment and environmental conditions, nature can be considered a technique that contributes to perceived temperature reduction and the regulation of bioclimatic parameters (Karakounos et al., 2018)

Some nature-based climate change mitigation and adaptation strategies have the potential to cushion these impacts and improve people's quality of life (Lafortezza and Sanesi, 2019). Not only are they capable of regulating temperatures, improving air quality, or reducing urban noise, but they also offer economic benefits related to reducing energy consumption, which affects the balance of emissions locally and globally (Perini and Rosasco, 2013b). Nature can be seen as a tool that provides ecosystem services (cultural, regulatory, and provisioning) that systematically contribute to reducing carbon emissions, solving problems of social inequality through job creation or food production, improving people's well-being and health by being taken into account early on in urban planning (Fabbri et al., 2020; Sharifi and Khavarian-Garmsir, 2020).

Taking into account this assumption, the use of vegetation as a natural temperature regulator through processes such as evapotranspiration becomes an optimal means of mitigating UHI (Afshari, 2017). Furthermore, the demand for building cooling is proportional to the increase in temperature in cities. The use of air conditioning is increasing. Without energy efficiency measures, the energy demand for space cooling will more than triple by 2050, consuming as much electricity as the whole of China and India today. By 2050, around 2/3 of the world's households could have an air conditioner. Such worldwide increases are leading to a rise in the average temperature of the Earth and hence the possibility of suffering the consequences of climate change (International Energy Agency (IEA), 2018).

On the other hand, environmental noise has become an aspect of great relevance to public health, as it has several negative impacts on human health and well-being. This topic has raised awareness among researchers, planners, and governments, resulting in decisions and guidelines that help control it (Héroux et al., 2020). According to the World Health Organization (WHO), noise is the second most important cause of health problems due to environmental factors after air quality. The adverse effects caused by noise will depend on its intensity and exposure. Following the WHO, 0 dB is considered the hearing threshold at which it is possible to hear a signal, 50 dB level of acoustic comfort, 65 dB desirable limit, 85 dB damage to the ear, and 120 dB pain threshold. In terms of frequency, values from 20 Hz to 20 kHz were usually taken for signals that can be perceived by the human ear (Van Den Berg, 2007).

Studies by the United Nations show that the world population will increase by two billion people in the next 30 years, from 7.7 billion today to 9.7 billion in 2050 (Nations, 2015b). If we also consider that road traffic is one of the main contributors to noise pollution in the urban environment, we face the growing need to mitigate the impacts to reduce the detrimental effects they can have on urban areas (Piselli et al., 2018).

Road, air and rail traffic, and commercial activities are among those responsible for noise emissions in urban environments, which at high levels can have a direct impact on the health and quality of life of city dwellers (Magrini and Lisot, 2015). Addressing the growing need to generate tools that regulate noise emissions, different countries and regions have created directives and legislation that evaluate and control environmental noise levels and establish some common approaches to avoid, prevent, or reduce harmful effects related to exposure to environmental noise (Europeo, 2002).

These noise regulation models, with a predominant focus on the control of sound pressure levels, have been widely used in urban planning. Within the framework of urban planning and acoustic comfort lies the concept of soundscape, understood as the human perception of the sound environment according to the surrounding context (Brown et al., 2011). Under this concept, it is essential to consider that each context will have different visual and architectural configuration aspects, as well as a sound taxonomy, various energy descriptors, and psychoacoustic parameters, which together with a series of subjective factors of people's attitudes and behaviours will affect the noise perception of the space.

Along these lines, some research states that the positive perception of the acoustics of a public space will depend on many factors, which do not necessarily have to do with the sound itself, but the demographic characteristics of the user, the activity carried out in that space, the time it is spent there, and the physical characteristics of the place where the user is located (Jennings and Cain, 2013).

Within this framework, this paper aims to provide a broad perspective on the positive impacts of one of the many nature-based solutions, such as green façades. Focusing on some of the benefits they bring to cities: external temperature reduction and noise absorption. To transform cities and contribute to achieving climate neutrality, it is necessary to employ solutions that act in an interconnected way on the complexity of urban systems, and one possible way is through integrated solutions capable of providing ecosystem services.

The purpose of this review is to study current knowledge about the impact of green walls on urban comfort. Thus, the objectives of this work are (i) to provide a systematic review of the state of the art in the field of temperature reduction and acoustic absorption offered by vegetation façades, (ii) to identify the factors that influence urban comfort through the use of vegetation, and (iii) to identify research gaps that can be further explored. Furthermore, this review aims to elaborate some recommendations on possible research lines that can be applied in future urban studies.

In addition to modular green walls, studies focusing on plant species or substrates have been considered in this review due to their relevance as the main components of the system. Analysis of these components will help us determine the key factors that affect the ability of green walls to reduce temperature or absorb noise.

2. Materials and methods

Through this research work, the literature on the effect of green walls on urban comfort was reviewed. The authors conducted a systematic review of the state of the art regarding the capacity of green walls to reduce temperature and absorb acoustic waves in urban environments and evaluated the scope of studies carried out to identify gaps in the field of research. This review differs from previous reviews on green walls since green walls are investigated in a holistic way, and the selected topic is analysed by splitting the scope into two subtopics: temperature reduction and noise absorption.

As a basis for the study, the following questions were established:

- What is the state-of-the-art in the use of green walls to improve urban comfort?
- What kinds of studies have been conducted on the benefits of green walls for improving urban thermal comfort and noise absorption?
- What are the most relevant influencing factors that affect urban comfort through the use of vegetation?

For the assessment of the resources, the following information was considered: type of experiment; duration of the test; measurement time; sample size; location and type of climate; measurements taken on a prototype or real scale; type of environments (controlled or natural).

2.1 Search strategy

Following the methodology of other review articles (Besir and Cuce, 2018; Hunter et al., 2014; Manso and Castro-Gomes, 2015)(Koch et al., 2020), Scopus, Elsevier, and Google Scholar databases have been used for the literature search. The objective was to identify all available studies on green walls and their influence on urban comfort, including those that had been developed taking into account thermal and acoustic comfort.

In the first phase of this review, different sources of information were considered (peer-reviewed journals, conference articles and books, research reports, and research articles). The searches were conducted through predetermined fields such as title, abstract, and keywords, and using the option "articles with these terms". **(Table 1)** shows the word base used for the search. Boolean operators such as +, ", AND, NOT were used during the research. In the review process, the literature was classified according to the following topics: review of green wall systems, urban comfort, reduction in temperature, and acoustic absorption.

Since the literature research reveals different terms assigned to green walls, the search terms for studies related to green walls were extended to the following: 'green façade' (Besir and Cuce, 2018; Tamási and Dobszay, 2015; Zaid et al., 2018), 'green wall' (Weerakkody et al., 2018b; Xing et al., 2017; Zaid et al., 2018), 'living wall system' (Oquendo-Di Cosola et al., 2020; Ottelé et al., 2011; Tedesco et al., 2016), 'vertical garden' (Giordano et al., 2017; Kmie, 2014; Scarpa et al., 2014), 'vertical greenery system' (Azkorra et al., 2015b; Daemei et al., 2018; uklje et al., 2016), “VGS” (Gabriel Pérez et al., 2018; Wang et al., 2014; N. C. N. H. Wong et al., 2010). Combined with the following terms: "urban comfort", "urban microclimate", "outdoor thermal comfort", "outdoor temperature reduction", "acoustic absorption", "noise reduction" and "pedestrian level measurement". These resulted in a total of 2306 articles found; 7 aspects searched; 24-word combinations for each aspect; and 6 terms referring to green walls. The search was first conducted in February 2020 and renewed in June 2021 to cover additional studies published by the end of 2020.

Table 1: Keywords and number of results from bibliography review.

Keywords	Type of search	No. of results
Urban comfort	Keywords, abstract, title	64
	'Articles with these terms'	17
Urban microclimate	Keywords, abstract, title	62
	'Articles with these terms'	219
Outdoor thermal comfort	Keywords, abstract, title	32
	'Articles with these terms'	145
Reduction of outdoor temperature	Keywords, abstract, title	218
	'Articles with these terms'	1104
Acoustic absorption	Keywords, abstract, title	38
	'Articles with these terms'	40
Noise reduction	Keywords, abstract, title	31
	'Articles with these terms'	191
Measurements at pedestrian level	Keywords, abstract, title	9
	'Articles with these terms'	136

2.2 Selection criteria

During the search, a total of 2306 articles related to green walls were identified. Of these, 1488 sources were related to energy efficiency in buildings, indoor comfort, or duplicate resources that emerged despite changing search terms. Based on these results and to evaluate the most interesting studies, a criterion was established by which only studies focusing on the effects of green walls on the outdoor environment, conducted at the pedestrian level, or performed on prototypes designed to assess impacts at the street scale were included.

The selection of the articles comprising this review was structured in 3 phases **(Fig. 1).** In the first phase, 1488 duplicate sources, articles from non-peer-reviewed journals, conference contributions, or articles from books and nonindexed journals were excluded, leaving a total of 818 sources. In the second phase, a total of 778 articles were excluded based on the study of the contribution of green walls to the energy efficiency of the building and indoor comfort, as these topics do not belong to the subject of the study of this review, leaving a total of 40 sources. These 40 sources were categorised in the last phase according to the two main aspects of this review: temperature reduction and sound absorption.

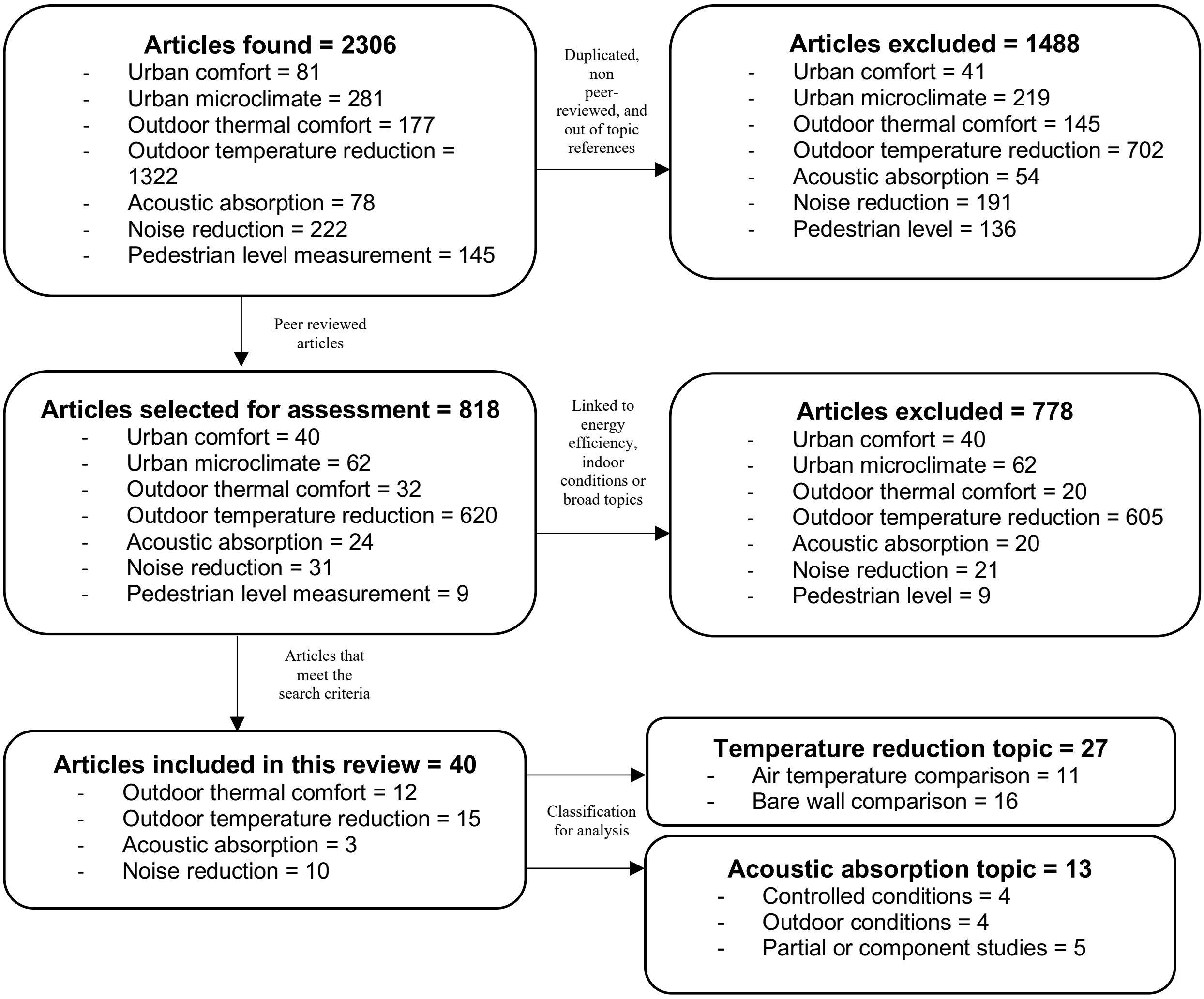

Figure 1: Flow diagram of the bibliography selection process

2.3 Classification

The selected articles were classified into those investigating the capacity of green walls to reduce temperatures outside the building and those studying their potential to absorb sound waves. Some works that considered both the interior and exterior of the building offering substantial results for the review were considered. The subject classification was established to demonstrate the research approach in each article. For each subject, the literature was divided into two broad and determining subthemes for analysis, which include, for example, the method of measurement and the type of instrument used.

- Outdoor temperature reduction
    - **Air temperature comparison**: including analysis of outdoor temperature reduction due to the presence of vegetation in correlation with air temperature.
    - **Bare-wall comparison:** it was assigned for studies that analysed the reduction of the outside temperature due to the presence of vegetation in correlation with the temperature of a reference wall without vegetation.

- Outdoor noise reduction
    - **Controlled conditions**: this classification covers all studies carried out in spaces with controlled conditions such as reverberation chambers for the calculation of the absorption coefficient of a vegetal facade.
    - **Outdoor conditions**: includes all studies carried out in exterior spaces under natural conditions for the calculation of the absorption coefficient of a vegetal facade.
    - **Partial or component studies**: studies carried out in a laboratory or through computerized models for the calculation of the absorption coefficient for an element of the green wall (type of substrate, vegetal species).

2.4 Analysis framework

This review of the state-of-the-art in the use of green walls in cities involves two main areas: the potential to reduce external temperatures and the potential to absorb noise. Both aspects have been studied under the same criteria. Despite being two different areas of knowledge, they are presented as part of the same system: building environment.

Most of the reviews conducted previously in the area of green walls or mitigation measures in cities (Hooftman et al., 2018; Moya et al., 2018; Schindler et al., 2016; Taleghani, 2018a) focus on a single aspect. However, regarding urban comfort, it refers to those environmental, architectural, personal, and even socio-cultural conditions that can affect an individual's sense of comfort (Javadi, 2021). Among the environmental parameters that can affect this perception are air temperature, relative humidity, wind speed, solar radiation, and noise levels, among others.

The framework of this review's literature analysis considers some of the aspects of urban comfort to be studied in depth and identifies the capacity of green walls to contribute to achieving a thermally ideal urban environment with controlled noise levels.

3. Overview of selected studies

To assess the current state of research on the impact of green walls on the reduction of temperature outside the building and the potential to absorb sound waves, we have made a synthesis of 27 and 13 peer-reviewed papers, respectively. The set of papers analysed presents experimental, observational, or modelling studies. These studies were treated separately for this review and totalled 40 studies (38 experimental studies and 2 modelling studies), which are summarized in Tables 1 to 5.

3.1 Impact of green walls on the reduction of outdoor temperature

Green walls are used for two reasons: first, because they provide an aesthetic value to the building or shade and second, because they are capable of creating a microclimate in the zone adjacent to the building. These thermal regulations are mainly due to the shading of the building's façade, the transpiration of water through the leaves, and the loss of water from the substrate through evaporation. In addition, benefits are associated with it, such as the retention of rainwater and the capture of polluting particles (Sheweka and Magdy, 2011). Some studies have identified how certain characteristics such as foliage density (LAI > 3), leaf cover (100% coverage) and branch type (woody branches) increase temperature reduction capacity. (Charoenkit et al., 2020).

Urban paving and the use of materials such as concrete, glass, and bricks contribute to increased heat. This, added to the loss of shade and the loss of green space, contributes to the formation of urban heat zones (Afshari, 2017). In this context, vegetation is used as living media, providing ecosystem services and capable of mitigating the effects produced by the current city model (Bartesaghi Koc et al., 2018; Meili et al., 2021). A study in Beirut, an urban dense environment with UHI value of 7 °C, showed that the insertion of 7% vegetation in a 73.5 km^2 district contributes to a 2°C reduction in air temperature. (Fahed et al., 2020).

Most of the reviewed literature suggests that green walls have great potential to cool surfaces and save energy consumption during the summer and mainly in humid subtropical climates (Cheung and Jim, 2018; Galagoda et al., 2018; Pan et al., 2018). However, the effectiveness of green walls in regulating external temperatures according to the climatic conditions and the type of construction system was not studied.

The analysis carried out in the following includes 10 studies of modular green walls and 15 studies of continuous green walls. Most of them were carried out during summer (14), 3 were carried out in winter, 2 in winter and summer, 4 during all seasons of the same year, and 2 were not specified. All of them were carried out mainly in four climatic regions: (1) humid subtropical climate, (2) arid, (3) Mediterranean continental, and (4) oceanic, which have been studied taking into account the characterisation made by the Koppen-Geiger classification (Kottek et al., 2006).

In this review, green walls can take two forms:

- *Continuous green walls*: This classification includes systems developed to cover continuous facades that provide the building with a homogeneous green enclosure solution. This category comprises those systems that are an integral part of the enclosure, constituting the same support structure for the development of the vegetation, those formed by vertical structures (cables, meshes) that are the structure in which the vegetation grows, the systems made up of pots added to the building's finish, also in which the plants grow in pots and develop vertically due to the support structures, and those formed by support structures covered with synthetic felt in which the plants take root.

- *Modular green walls:* this category includes all those solutions whose constructive characteristics allow their use in a discontinuous way. The effect achieved is that of a continuous covering of the facade through modular pieces. These include systems with pre-vegetated lightweight modular boxes of different sizes and materials, modular units into which plants can be inserted, and modular concrete units made up of several layers.

The analysis of the studies considered in this review has also been classified according to the type of experimentation.

- *Real scale*: In this category are all those studies carried out under real conditions, controlled or not. And whose scale corresponds to that of the city.
- *Prototypes*: in this category, we grouped all studies in which measurements are made from small samples.

The following sections analyse the most relevant findings from the literature on the reduction of outside temperature produced by green walls, which has been constructed essentially along with three principal characteristics, the type of study, the climate, and the sample size.

As mentioned before, the literature was subdivided into two categories for analysis. The first corresponds to studies that correlate their temperature reduction results with air temperature, which focus on demonstrating the capacity of green walls to reduce temperature in their immediate context and the benefits that this brings for urban comfort. The second corresponds to those studies in which temperature reduction correlates with the surface temperature of a bare wall, which, in some ways, although passive, also affects urban comfort.

3.1.1 Air temperature correlation studies

Green walls in a city tend to store heat, cool surfaces, and reduce maximum daytime temperatures, not only due to reduced heat flow on the surface, but also due to the effect of evapotranspiration. Studies claim that a lack of vegetation in cities would lead to an increase in air temperature, and therefore a massive use of vegetation in the urban environment would lead to a reduction of the urban heat island (Erell, E., Pearlmutter, D., Williamson, T., 2012).

The combined effect of shade and evapotranspiration can produce a reduction in air temperature between 1 °C and 3 °C, which could vary depending on the climate and substrate conditions (Wong et al., 2016). Similarly, a study by (Tan et al., 2014b) on a continuous façade in a humid subtropical climate demonstrates the effect of shade on the reduction in the temperature of the adjacent environment by between 1.1 °C and 1.5 °C on the air temperature.

The thermal regulating effect of plants is mainly due to the photosynthesis and transpiration of the plant's leaves, a process which could be called thermal equilibrium of vegetation. (Zhang et al., 2019) researched this equilibrium to estimate the thermal effect of plants' physiological activities and to evaluate the overall effects on indoor and outdoor environments in humid subtropical climates. Their results show a reduction of 2.7 °C compared to the air temperature due to (i) solar radiation absorption, (ii) heat transfer by convection between foliage and air, (iii) transpiration in plant leaves, and (iv) the thermal effects of photosynthesis.

Most of the studies in this field were conducted during the summer. However, studies have been conducted to evaluate the performance of a continuous green wall during winter (Bianco et al., 2017; Castiglia Feitosa and Wilkinson, 2018; Jim, 2015a). The results showed a variation in temperature mainly on sunny days within 3 °C – 4 °C on the east facing wall, and between 1 °C – 2 °C on the north and west facing walls, and was due to the radiation received, which could not be less than 500 W/m^2 to achieve remarkable solar heating and cooling surfaces by transpiration (Jim, 2015a). These results turn green walls into a passive heating measure during the winter.

Temperature reduction has a significant impact regarding modular green walls that have a substrate. (Pan and Chu, 2015) demonstrated the effect of orientation in a humid subtropical climate with a modular green wall, which obtained a reduction of approximately 10.1 °C in its northern exposure. On the other hand, (Cheng et al., 2010) evaluated the thermal performance of a modular vegetal façade in a humid subtropical climate that showed a cooling effect of the substrate and a consequent reduction in air temperature around 14 °C.

The study of the influence of green walls on the adjacent microclimate requires an accurate assessment not only of the orientation and type of walls, but also of the distance at which the data are collected. A study by (Razzaghmanesh and Razzaghmanesh, 2017a) showed that green walls may not have any cooling effect on the surrounding microenvironment at a distance greater than 1.00 m.

For continental climate, few studies have been carried out to determine the efficiency of temperature regulation in urban microclimates. Studies carried out in continental weather with continuous green walls (de Jesus et al., 2017; Susorova et al., 2014) demonstrate reductions in temperatures ranging from 2 ºC to 5 ºC in the presence of vegetation.

Less common are studies performed in oceanic climates. The only source found during this literature review (Cameron et al., 2014), analyses the ability of climbing plants and wall bushes to reduce the temperature of the adjacent air. The results show reductions of around 3 °C due to the high solar radiation outside and the type of vegetation used, *Prunus laurocerasus* species being the most efficient. As a result, different species vary in their cooling capacity; some are more likely to provide cooling by evapotranspiration and others are more likely to provide cooling by shade.

Studies reviewed throughout this section have provided consistent data on the performance of outdoor green walls **(Table 2),** regardless of the configuration of the system and the arrangement of the sensors **(Fig.2).** Therefore, it can be stated that, through the use of continuous green walls outside, it is possible to achieve reductions in the temperature of the adjacent air between 2 ºC and 5 ºC, while modular walls with substrate reach much higher reductions between 10 ºC and

14 ºC. Gaps such as the influence of measuring distance and the study of variables that influence the behaviour of modular green walls on a real scale have been found.

Table 2: Air temperature correlation studies

Air temperature correlation studies									
Author	***Location***	***Season***	***Orientation***	***Type of study***	***Type of system***	***Temperature reduction***	***Duration***	***Sample size***	***Sensor distance***
Humid Subtropical									
(1) Chun Liang Tan., et al.	Singapore, Singapore	Autumn and Winter	*Not specified*	Experimental	Continuous green facade	1.1ºC to 1.5ºC	Green wall A: 27 September 2011 to 13 March 2012 Green wall B: 4th January 2012 to 13th March 2012	Two green walls A: (2.27m x 1.90m) B: (3.18m x 2.40m)	2m away at intervals of 0.5m
(2) Lan Pan., et al.	Hong Kong, China	All seasons	North and West	Experimental	Modular green facade	8.4ºC	12 months	Two testing rooms (1.3 x 1.2 x 1.3m) as mockup. Green wall area of 1.3m2. 54 planting pots.	Wall surface temperature and air temperature at 40cm from the substrate surface. All sensors 60cm above ground level. 30 min intervals.
(3) Lei Zhang., et al.	Guangzhou, China	Summer	All orientations	Modelling	Continuous green facade	2.7ºC	*Not specified*	A planting rack of 20.1cm width x 20.1cm height.	Pyranometer and pyrgeometers placed 1.35m above the roof surface. 3 thermocouple temperature sensors 1.5m above the roof surface. 3 temperature and humidity sensors (HOBO) 1.5m above the roof surface.
(4) C.Y Jim	Hong Kong, China	Winter	All orientations	Experimental	Continuous green facade	3-4ºC (East) 1-2ºC (West and North)	3 days between January and February	A stainless steel wire mesh with 7.5cm square aperture and at 10 cm away from the wall face.	Air temperature, relative humidity and radiometer for surface temperature at 3m height. Pyranometer at 6m and 3m height.
(5) C.Y Cheng., et al.	Hong Kong, China	Summer	Southwest	Experimental	Continuous green facade	14ºC	10 weeks	A prefabricated external cladding of 100 x 50 x 75 cm3 aluminium module with slabs of hydroponic medium.	Temperature sensor embedded 1cm beneath the exterior side of the wall; on grass surface; embedded in substrate; on the interior side of the wall. Air temperature and humidity sensors inside a radiation shield and inside substrate. Substrate moisture sensor inside substrate. Heat flux sensors on the interior side of wall.
Continental									
(6) I. Susorova., et al.	Chicago, USA	Summer	All orientations	Experimental	Continuous green facade	0.8ºC to 2.1ºC	8 days	*Not specified*	Air velocity 15cm from the facade. Outdoor air temperature "near the facade". Surface temperatures attached to the wall. Pyranometers attached to a bracket installed on the south facade only.
Mediterranean									
(7) Mostafa Razzaghmanesh., et al.	Adelaide, Australia	Summer and Winter	West	Experimental	Continuous green facade	*No reduction* 4.12ºC warmer (0.5m - warm days) 4.65ºC warmer (0.5m - cold days) From 1.80ºC to 4.8ºC warmer (1m - 2arm and cold days)	7 months	A wall 4m width x 7m length x. 28m2 in area. 12x12 rows and columns.	Thermal and relative humidity sensors were installed on the surface, and the control wall. In front of the LW and CW. Suspended at horizontal distances of 0.50m and 1m away from the wall. 30 min intervals.
(8) Marina Paschoalino de Jesus., et al.	Madrid, Spain	Summer and Autumn	Southeast and Northeast	Experimental	Continuous green facade	2.7ºC	3 days of September	A wall 24m width x 19m length	Distance between 50 and 100m for data collection from the urban environment. 8 points (4 in each wall) at distances of 0.5m (point 1) 1,5m (point 2), 3m (point 3), and 5m (point 4). Temperature and humidity measurements at the height of 1.5m and the wind speed at 1.7m. Pyranometers 1.5m height.
Oceanic									
(9) Ross W.F. Cameron., et al.	Reading, Berkshire, UK	Winter	North and south	Experimental	Continuous green facade	3ºC	1 month	*Experiment 1*: 21.5 x 10.3 x 6.5cm *Experiment 2: no information included* *Experiment 3:* 3 growth cabinets with 2 small brick walls (5.9 x 1.00 x 6.6cm)	*Not specified*
Semi arid									
(10) Elham Shafiee., et al.	Shiraz, Iran	Summer and Autumn	West	Experimental	Continuous green facade	8.7ºC	10 days	3 x 2.40 x 2m	*Not specified*

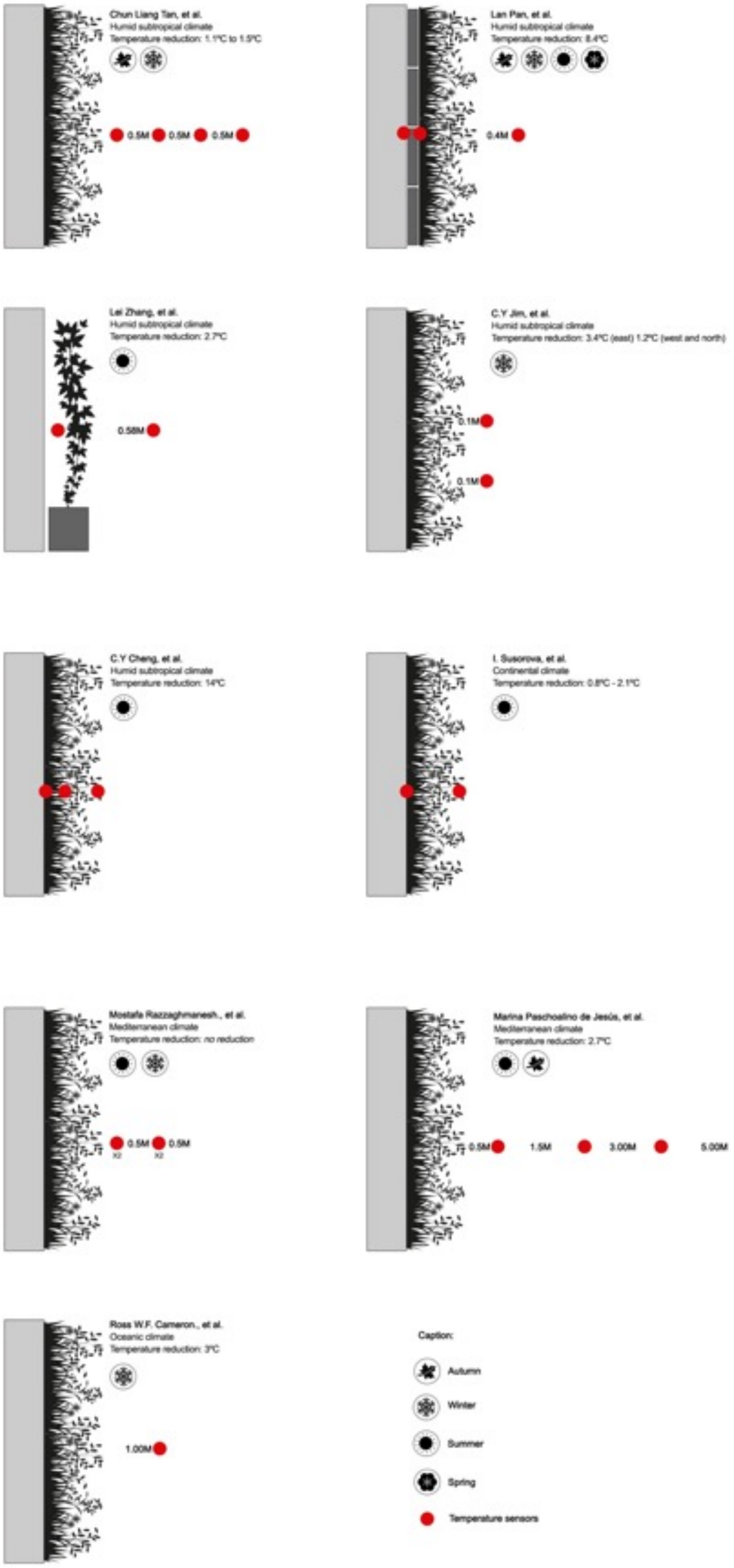

Figure 2: Green wall system configuration, sensor arrangement, and temperature reduction results in the air temperature correlation studies.

3.1.2 Non-vegetated wall correlation studies

Cities are experiencing a series of adverse effects resulting from the urbanization of the territory, combined with disruptive changes, such as social segregation and climate change. This accelerated urbanization leads to an increasing fragmentation of nature in both cities and peri-urban areas. These results in environmental impacts, such as the urban heat island effect, resulting, among other things, from the progressive loss of the benefits of plant shading and evapotranspiration, as well as impacts on society and the economy.

The demand for cooling of buildings is proportional to the increase in temperature in cities. The use of air conditioning is increasing. An Australian study (Australian Bureau of Statistics, 2011) states that air conditioning use in Australia has increased from 35% to 73% between 1999 and 2011. Such worldwide increases are leading to a rise in the average temperature of the earth, and hence the possibility of suffering the consequences of climate change.

Some nature-based climate change mitigation and adaptation strategies have the potential to cushion these impacts and improve people's quality of life. They are not only capable of regulating temperatures, improving air quality, or reducing sonic pollution, but they also offer economic benefits related to reducing energy consumption, which affects the balance of emissions locally and globally. These ecosystem services are increasingly recognised by building and environmental professionals.

Numerous studies have been carried out on energy efficiency in buildings, in which the use of nature-based solutions has been a tool. However, this review has identified a small consensus on the parameters that should be evaluated to determine how efficient these solutions are. In these studies, the predominant parameter is the surface temperature of the green wall. However, these results draw unspecific conclusions about the effects of a green wall on the energy consumption savings of a building, while the results become significantly clearer about the benefits of surface cooling and the consequent reduction in heat transmission to interior spaces.

Research on green walls shows that they are environmentally sustainable; however, no studies have been developed that categorise the behaviour of a green wall according to the season. (Hunter et al., 2014) state that valid comparisons of the thermal performance of green walls within certain climatic regions are still not possible, as the number of published studies is limited. Although it is not possible to give a precise estimate of the behaviour, the following studies show that, in certain regions, the reduction of surface temperature can have a certain tendency.

(Pan and Chu, 2015) and (Chen et al., 2013) have investigated how the orientation, humid subtropical climate, and the configuration of a modular green wall can influence the thermal performance of the building. The former obtained a maximum reduction in surface temperature of 6.1 °C and a maximum difference of 3.6 °C in indoor air temperature, compared to a wall without vegetation (Pan and Chu, 2015). The second obtained the same cooling effect through results showing a maximum reduction of 20.8 °C at the exterior surface temperature, 7.7 °C at the interior surface temperature, and 1.1 °C indoor (Chen et al., 2013).

Although the studies developed in the same climatic regions, the variable that influences the results has been the configuration of the green wall; the first has been installed directly on the wall, while the second has left an air cavity between the wall and the green wall of 600 mm, in addition to having vertical and horizontal shading devices. Despite this, in both cases, the reduction of a modular plant façade in a humid subtropical climate has yielded positive results that reaffirm the loss of heat from the surface due to the combined effect of heat exchange by convection and heat exchange by radiation.

On the other hand, (Castiglia Feitosa and Wilkinson, 2020, 2018) evaluated the effect of a modular green wall located in a humid subtropical climate on the attenuation of thermal stress (HI) (this value considers the combined effect of temperature with relative humidity on the human body's exposure to heat). Its results showed an attenuation of HI between 5 °C and 20 °C, with the majority of results (4.1%) between 5 °C and 10 °C. A comparison of the results of the prototypes with vegetation and without vegetation, considering the reduction range between 5 °C and 10 °C, confirmed a significant attenuation caused by heat exchange and the evapotranspiration process. In fact, vegetation provides shade and absorbs solar radiation, and soil absorbs and stores heat during the day and releases it at night, thus cushioning the heat transfer process.

Furthermore, (Kokogiannakis et al., 2019) analysed the surface temperatures behind four different types of green walls with a vegetated surface of 0.95 m^2. Reductions were found between 1.4 °C and 3.8 °C compared to the reference wall. In addition, the green wall system had the lowest maximum surface temperatures in contrast to the reference wall (6.2 ºC to 13.4 ºC). The analysis of these results does not consider the incident solar radiation flux, which shows that, as in the case of the previous studies, in a humid subtropical climate, this type of facade can avoid heat gain in summer.

In the case of semi-arid climates, the behaviour of the green walls may be slightly different. (Sánchez-Reséndiz et al., 2018) carried out a study that demonstrates the behaviour of a modular green wall system in semiarid climates in Mexico, giving results of a reduction in surface temperature compared to the reference wall of 2.5 °C. The results show that this type of system contributes to improving the time and percentage of heat loss and gain, reflected in the achievement of an average comfort temperature of the space where the systems were installed of 21 °C. However, it is necessary to extend the work in a semi-arid climate, and at present the studies are limited, so it is not possible to reach concrete conclusions.

For the Mediterranean and continental Mediterranean climate, three studies have been analysed to assess the effect of a modular system of green walls, formed by plants and substrate, having the summer as a constant variable as the season in which measurements have been taken. The reduction in surface temperature obtained in the three studies is an average of between 12 °C and 25 °C compared to the reference wall.

Specifically, (Olivieri et al., 2014) showed in their conclusions that the effect of vegetation has been very positive (reduction of the average surface temperature of 25.1 ºC), particularly during the daytime quality hours, stating that green walls can be used as a passive cooling strategy, also reducing energy consumption for the conditioning of the interior space, and improving the thermal comfort of the users around the building. Consistent with these results, (Bianco et al., 2017) have shown that the presence of vegetation in a building can lead to a reduction in the external surface temperature of up to 23 °C. Likewise (Mazzali et al., 2013) demonstrated in their study carried out on a prototype with 18 plant modules, a reduction in the surface temperature of between 12 °C and 20 °C regarding the wall without vegetation; confirming the fact that under a Mediterranean climate this type of solution can be very favourable,

Most of the results obtained in the previously discussed studies are attributable to the presence of the substrate, mainly due to its thermal inertia. However, despite being the principal element in the thermal performance of these solutions, several studies carried out on continuous green walls with vertical and horizontal support and in the same climates described above have demonstrated positive results.

(Lee and Jim, 2017) investigated the behaviour of two continuous vegetal façades installed on a building of 19.5 m and 13.2 m height, respectively, under various climatic conditions in a humid subtropical climate. From their study, it can be concluded that the best thermal behaviour occurred during sunny summer days, with reductions in surface temperature between 0.52 ºC and 3.49 ºC in relation to the reference wall without vegetation. The study demonstrates the cooling benefits of this type of solution in subtropical summers.

(Yin et al., 2017) conducted a study with the same objective, this time using a new methodology to evaluate the cooling effect of the green wall through thermal infrared (TIR) data and three-dimensional point clouds (3DPC). Despite innovation in the type of measurement, an average of the previous study can be considered. Having reduced the average surface temperature by 4.67 °C, this study, in addition to demonstrating the cooling effect, establishes a correlation between the percentage of vegetation cover and the cooling effect, making it a significant factor to consider in this type of green wall.

This aspect has been studied in depth in some references. (Li et al., 2019a) analysed the thermal performance of a continuous green wall in a humid subtropical climate. Among the most relevant aspects of its results is that, despite having made measurements with the same orientation, climate type, time, and intensity of solar radiation, the results varied according to the plant species.

According to the author, the reason for this is the Leaf Area Index (LAI), the surface area of the leaves, and the thickness of the foliage. The solar radiation is reflected by the leaves, part of it penetrates into the gaps between the leaves and is absorbed by the supporting wall, and the rest is absorbed by the leaves. Based on the study carried out with vegetation thicknesses of 7.2 cm, 19.8 cm, and 30.5 cm, the best result was obtained with a leaf thickness of 19.8 cm, obtaining a reduction in surface temperature of 6.3 °C maximum and 0.1 °C minimum, compared to the reference wall without vegetation. These results are due to the higher convective heat transfer between the support structure and the leaves.

(Kontoleon and Eumorfopoulou, 2010), verified this hypothesis by analysing the influence of orientation and the coverage percentage of a green wall. His results show that the higher the coverage percentage, the higher the impact on temperature reduction. Values range from 1.62 °C to 19.1 °C within a coverage percentage between 0% and 100%. Furthermore, these results were favoured when the facade was facing east or west.

Such affirmations were verified through the study of (Jim, 2015a), who evaluated the winter thermal behaviour of a continuous vegetal façade with three different species of climbers: *Pyrogestia venusta, Bauhinia corymbosa and Ficus pumila*. Its results showed sequential variations in the reduction of surface temperature mainly due to the heat dissipation effect related to vegetation density and the percentage of relative humidity.

The density of the vegetation and its correlation with the reduction of temperature have to do, among other things, with the shading effect they have. In this regard, a study carried out by (G Pérez et al., 2018) shows how the growth of four types of climbing plants reduces surface temperatures. Its results were between 5.55 °C and 15.2 °C for the reference wall, creating a microclimate between the building wall and the plant façade characterized by lower temperatures with an average of 1.4 °C and higher relative humidity. These results demonstrate that this type of solution in continental Mediterranean climates can become a natural barrier against radiation and wind.

The studies presented in this section **(Table 3)** show how, depending on the configuration of the green wall, some components have more influence than others on the thermal behaviour. The substrates for modular facades are particularly notable and the density of vegetation for continuous façades. However, a transversal element in both of these is the effect of evapotranspiration, which (M.-T. Hoelscher et al., 2016) has called a lower proportion compared to the density of vegetation, emphasizing that this effect will depend on the plants being sufficiently watered with up to 2.5 l/m^2/day, thus introducing a prescriptive condition which, if fulfilled, can obtain surface reduction.

Table 3: Non-vegetated wall correlation studies

Bare wall correlation studies									
Author	***Location***	***Season***	***Orientation***	***Type of study***	***Type of system***	***Surface reduction***	***Duration***	***Sample size***	***Sensor distance***
Humid Subtropical									
(11) Lan Pan., et al.	Hong Kong, China	All seasons	North and West	Experimental	Modular green facade	6.1ºC	12 months	Two testing rooms (1,3x1,2x1,3m) as mockup. Green wall area of 1.3m2. 54 planting pots.	Indoor air temperature, wall surface temperature and air temperature at 40cm from the substrate surface. All sensors 60cm above ground level. 30 min intervals.
(12) Haiwei Yin., et al.	Nanjing, China	Summer	West	Experimental	Continuous green facade	4.67ºC	3 days in August	*Not specified*	Meteorological station 1m away from the building.
(13) Georgio Kokogiannakis., et al.	Nottingham, China	Summer	South	Experimental	Modular and continuous green facade	1.9ºC to 4.8ºC (continuous) 1.4ºC to 3.8ºC (modular boxes)	18 days in July	Green wall area of 0.95m2	21 locations around the test cells.
(14) Cuimin Li., et al.	Suzhou, China	Summer	South	Experimental	Continuous green facade	6.3ºC	11 days between July and August	The measurement was taken in a south oriented wall located on the second floor of the southeast corner with 11.5m long, 4.8m wide, and 3.9m in height.	Four measuring points each with area of 20x20cm at similar heights (15 sets of thermocouples). Three points covered with plants and with different foliage thicknesses. All the 4 measuring areas were 4.8m above the ground. Sensors of measuring points 5, 10 and 15 cm.
(15) Louis S.H. Lee., et al.	Hong Kong, China	Summer	Northeast and Northwest	Experimental	Continuous green facade	0.52ºC to 3.49ºC (High-block) 0.55ºC to 2.73ºC (Low-block)	June, July, August (3 months - 15 minutes sampling) 10 sunny, 4 cloudy and 12 rainy days.	Two blocks, namely high block and low block, which were respectively 19.5m and 13.2m above the road surface.	*High block*: The green wall was installed 1m away from the wall and the temperature and infrared sensor was placed 2.6cm away from the wall. *Low block:* The green wall was installed 0.30m away from the wall and the temperature and infrared sensor was placed 1.18m away from the wall.
(16) C.Y Jim	Hong Kong, China	Winter	North	Experimental	Continuous green facade	3-4ºC	3 days between January and February	A stainless steel wire mesh with 7.5cm square at 10 cm away from the wall face.	Air temperature and relative humidity at 3m height. Radiometer for surface temperature at 3m height. Pyranometer 6m and 3m height
(17) Qiuyu Chen., et al.	Wuhan, China	Summer	West	Experimental	Modular green facade	20.8ºC	2 months	25 vegetation boxes of 50cm in square and 1cm in depth, arrayed and hung on the steel structure to cover the whole west wall area. Installed on two thermal identical labs.	6 different sensors to collect surface temperature data. 2 dataloggers in the center of the room to monitor the indoor air. 2 dataloggers in the air layer to monitor the air layer condition. A weather station located 10m away. 30min intervals.
(18) Renato Castiglia F., et al.	Rio de Janeiro, Brazil Sidney, Australia	Summer	*Not specified*	Experimental	Modular green facade	5ºC to 10ºC	The Rio de Janeiro records comprise a 161-day period from October 31st 2016 to February 8th 2017, and the Sydney tests were performed over 300 days, from January 19th 2016 to November 20th 2016.	All prototypes are devoid of insulation and have identical dimensions: 120 cm width; 150cm length; 100 cm front height; 120 cm back height.	The dataloggers were placed about 700mm above the floor of the structures, which corresponds, in real scale dwellings, to a level equivalent to the average height of people.
(19) Renato Castiglia F., et al.	Sidney, Australia	Summer and Winter	*Not specified*	Experimental	Modular green facade	8.3ºC (summer) 8.7ºC (winter)	61 days in Summer, 92 days in autumns, 92 days in winter and 55 days in spring.	Timber-framed prototype structures of 1.5m length; 1.2m width; 1.00m front height; 1.2m rear height.	The measurements were taken every 30 min and totalled, 14,415 data points for each prototype. The individual data loggers were placed approximately 700 mm above the floor level of each prototype and could be accessed through a 100 mm diameter circular opening in the real facade.
Continental									
(20) Lorenza Bianco., et al.	Turin, Italy	Summer and Winter	South	Experimental	Modular green facade	23ºC (summer) 8ºC (winter)	*Not specified*	Panels of 40x50cm and 4.00cm depth. Test cells (2.00m x 1.8m x 1.8 m)	*Not specified*
(21) F. Olivieri., et al.	Colmenar Viejo, Madrid	Summer	South	Experimental	Modular green facade	Between 15.1ºC and 31.9ºC. An average of 25.1ºC	3 months	The building has a rectangular floor plan and three storeys. The first two are equal in size, (13.8m x 40m), whereas the top floor (13.8m x 28.9m) shows a terrace facing south where the experimental prototype built-in in the façade is installed.	3 surface thromboresistance's in both façades were installed: between the sheet metal layer and the panel's felt layer; between the panel and the extruded polystyrene; and in the interior surface of the extruded polystyrene, inside the module. PT100 thromboresistance's (6.3 x 0.8 x 0.2cm) in three threads were used to obtain the surface temperature of each component of the enclosure. 2 ambient temperature sensors were installed in the interior of the modules, located in the central zone, one near the floor.
Arid									
(22) J.A. Sánchez-Reséndiz., et al.	Queretaro, Mexico	All seasons	South	Experimental	Modular green facade	2.5ºC	4 months	Two experimental huts. Both huts have identical dimensions (interior of 2.50m length × 3.20m width and 2.30m height) and same orientation N43 °W, with 15.00 m of separation in between. 5.46m2 of living wall (76.57%). Modules of 53 x 24 x 5.00cm. 30 plants on each module.	Temperature sensors were placed in the insulation layer and on the interior face of the wall.
Mediterranean									
(23) Ugo Mazzali., et al.	Lonigo, Venice and Pisa, Italy	Summer	Southwest	Experimental	Modular green facade	12ºC to 20ºC	2 months	3.00 x 3.00m prototype installed in Lonigo and Venice. A wall, 10.80m long and 2.80m height and made up of 126 recycled polypropylene of 60cm long x 40cm height installed in 7 lines of 18 panels.	The 6 surface temperature sensors were placed on the wall behind the vertical garden, on the supporting structure, behind the vegetation and embedded in the vegetation, as well as on the inner and outer face of the bare wall.
(24) K.J Kontoleon., et al.	Thessaloniki, Greece	Summer	All orientations	Experimental	Continuous green facade	1.62ºC to 19.1ºC	3 months	A vacant square space 10 x 10 x 3.00m. Zone volume area of 300m2 and floor area of 100m2.	*Not specified*
(25) G. Pérez., et al.	Lleida, Spain	All seasons	Southeast, Southwest and Northwest	Experimental	Continuous green facade	5.55ºC to 15.2ºC	1 year	4 modular trellises prepared to accommodate a container garden at the bottom.	*Not specified*
Oceanic									
(26) Marie Therese Hoelscher., et al.	Berlin, Germany	Summer	Southwest, East and West	Experimental	Continuous green facade	15.5ºC	Experiment 1: from 19th July to 16th August Experiment 2: from 1st August to 6th August Experiment 3: from 16th to 20th September.	3 building facades that were greened on one half, while the other half was bare.	Meteorological measuring stations were installed 0.4m in front of the bare wall and the green wall at approximately 2.8m above the ground. Air temperature, reaching the facade were measured in 5 min intervals.
Tropical rainforest									
(27) R.U. Galagoda., et al.	Colombo, Sri Lanka	Autumn	All orientations	Experimental and simulations	Continuous and modular green facades	Living Wall - 0.28ºC - 8ºC Indirect green facade - 1.33ºC - 7.86ºC Direct green facade - 1.34ºC - 6.64ºC	2 days	9 different facades	At 1m in front of the green wall, 0.1m in front of the green wall, inside foliage, in the air gap and exterior wall surface for each green wall.

3.2 Impact of green walls on outdoor noise reduction

Environmental noise has become an aspect of great relevance to public health, as it has several negative impacts on human health and well-being. This reality has raised awareness among researchers, planners, and governments, resulting in decisions and guidelines that help to control it (Héroux et al., 2020). According to the World Health Organisation (WHO), noise is the second most important cause of health problems due to environmental factors after air quality. The adverse effects caused by noise will depend on its intensity and exposure. Following the WHO, 0 dB is considered the hearing threshold at which it is possible to hear a signal, 50 dB level of acoustic comfort, 65 dB desirable limit, 85 dB damage to the ear, and 120 dB pain threshold. In terms of frequency, values from 20 Hz to 20 kHz were usually taken for signals that can be perceived by the human ear (Van Den Berg, 2007).

Studies by the United Nations show that the world population will increase by two billion people in the next 30 years, from 7.7 billion today to 9.7 billion in 2050 (Nations, 2015b). If we also consider that road traffic is one of the main contributors to noise pollution in the urban environment, we face the growing need to mitigate the impacts to reduce the detrimental effects they may have on urban areas.

In this context, the use of vegetation as a solution for noise reduction arises. Several studies have demonstrated the ability of tree belts to reduce road traffic noise in cities, showing decreases between 5 and 10 dB (Van Renterghem et al., 2015, 2013). However, trees and shrubs are such deficient barriers to sound. Only if the vegetation is thick enough to prevent seeing through it and intercepting the noise waves can it be considered an attenuation. Moreover, this effect will depend on the location of the receiver and the source.

When sound propagates through an urban area, buildings act as noise barriers, and this effect depends on the propagation of waves between buildings and the reflection between their surfaces. The combined effect of the shielding and surface reflection is a measure of noise attenuation (César Díaz Sanchidrían, 2002). Therefore, the effect that a green façade can produce is considered shielding. The placement of a screen between the emitter and the receiver causes a decrease in the sound pressure level in the area of the receiver, thus producing physical phenomena of reflection, absorption, transmission, and diffraction. While reflecting in buildings causes an amplification of noise, absorption by plants, covering a facade prevents such amplification (Van Renterghem et al., 2015).

The following sections analyse the most relevant results found in the literature on the acoustic absorption produced by green walls in controlled environments and in natural environments, as well as those relating to some components of this type of system. In addition, the characteristics and conditions that, according to each type of study, provide a higher absorption capacity are highlighted. In this case, the distance variable in the measurements analysed has not been a determining factor, as the studies do not highlight it as influencing the results, while other variables such as frequency (Hz), type of experiment, substrate and thickness, and type of vegetation are.

3.2.1 Studies conducted under controlled conditions

Several studies have been conducted to determine the sound absorption coefficient of a green wall under controlled conditions **(Table 4).** The results obtained have shown the capacity of absorption, diffraction, and reflection of sound by plants, indicating that vegetation can improve human perception of well-being in space by reducing noise, if a series of characteristics are met. The ability of a modular green wall system to reduce noise was studied using a series of 10 m^2 modules (Azkorra et al., 2015a). Their results show that the introduction of a modular green wall system in a reverberation chamber implied a reduction in reverberation time from 4.2 to 5.9, demonstrating a higher absorption coefficient at low frequencies that attributes it better properties compared to other building materials (Tang and Yan, 2017). One of the most important findings of his study was precisely to confirm that green walls offer higher performance at low frequencies. If we take into account that the frequency of the human voice is 60 dB, this corresponds perfectly to the frequency at which a green wall module is most efficient, which indicates that they can be ideally used in public spaces and people's transition spaces.

Although some results show a better performance of green walls compared to porous materials (Azkorra et al., 2015a). (Davis et al., 2017) demonstrate through their study that the noise absorption in a green wall comes from the substrate. The statement states that the substrate behaves like any other porous building material in which absorption is proportional to frequency. However, the most notable effect was the increase in the absorption of noise caused by vegetation at frequencies above 400 Hz, demonstrating that in addition to the substrate, if there is dense vegetation, the absorption coefficient can increase by between 0.2 and 0.3. However, some studies claim that it is the substrate that provides significant sound absorption, while vegetation only acts as a layer that reduces the returned sound power (Attal et al., 2021b).

The proportionality between the absorption coefficient to sound frequency and vegetation density has also been demonstrated by (Nyuk Hien Wong et al., 2010a). In contrast to the studies previously analysed, their results confirm that there is a performance framework for each of the components of the plant façade. On the one hand, it was observed that the substrate absorbs a higher amount of acoustic energy at low frequencies (100 – 250 Hz), which results in a reduction of the reverberation time, and, on the other hand, the vegetation offers better results at medium frequencies (400 – 1250 Hz) with an absorption coefficient between 0.30 and 0.57 and high frequencies (1600 – 5000 Hz) between 0.48 and 0.57.

These results show that as the frequency increases, the differences between the absorption coefficients for vegetation density between 43% and 100% increases. Unlike the substrate, in the case of vegetation, the reduction in reverberation time increases when the density of plants decreases. The main reason for this is that the effect of vegetation on absorption is to disperse noise.

Table 4: Studies conducted under controlled conditions in a reverberation chamber

Controlled conditions										
Author	***Location***	***Type of study***	***Type of system***	***Sample size***	***Frequency (Hz)***	***Vegetation species***	***Vegetation dimension and thickness (cm)***	***Substrate mix***	***Substrate thickness (cm)***	***Sound absorption coefficient (α)***	
(28) M.J.M Davis et al.	Delft, Netherlands	Reverberation chamber *(indoor)*	Modular system	10m2 made up from 50 modules	Low frequency (100 - 315) Mid frequency (400 - 1250) High frequency (1600 - 5000)	*Nephrolepsis Exaltata (Boston fern)*	16 medium sized *Boston Ferns* per module	Potting soil (50%), coco chips (33%) and sphagnum moss (17%)	10	**Solely with susbtrate at low, mid and high frequency:** Connected - on floor 0.76, 1.00, 0.94. Connected - 5cm air gap 0.82, 1.00, 0.98 Connected - 10cm air gap 0.80, 1.00, 0.99 Dispersed - on floor 0.73, 1.00, 0.95 Dispersed - 5cm air gap 0.74, 1.00, 0.95 Dispersed - 10cm air gap 0.73, 1.00, 0.93	**Densely planted:** Connected - on floor 0.64, 1.00, 1.00 Connected - 10cm air gap 0.80, 1.00, 1.00 Dispersed - on floor 0.59, 1.00, 1.00 Dispersed - 10cm air gap 0.69, 1.00, 1.00
(29) Z. Azkorra, et al.	Spain	Reverberation chamber *(indoor)*	Modular system	42 modular cultivation units given a total area of 10.08m2	100 - 5000	*Helichrysum Thianschanicum*	24 pre-cultivated plants per module with 4cm thickness	Coconut fibre	8	0.40	
(30) Nyuk Hien Wong, et al.	Singapur	Reverberation chamber *(indoor)*	Eight different types of green facade: mesh systems and iving wall systems	Two wooden frames given a total area of 10.08m2	50 - 50.000	*Nephrolepsis Exaltata (Boston fern)*	140 pots of plants are defined as covering 100% of the wall with plants. Each pot is 0.2m diameter and height of 0.14m. (S1) 0.100m (S2) 0.100m (S3) 0.120m (S4) 0.120m (S5) 0.110m (S6) 0.055m (S7) 0.120m (S8) 0.200m	*Not specified*	(S1) 0.250m (S2) 0.080m (S3) 0.230m (S4) 0.080m (S5) 0.070m (S6) 0.065m (S7) 0.060m (S8) 0.280m	**Greenery coverage (43% - 71% - 100%)** 100 Hz - 0.06 - 0.04 - 0.04 125 Hz - 0.12 - 0.10 - 0.09 160 Hz - 0.10 - 0.11 - 0.14 200 Hz - 0.17 - 0.18 - 0.18 250 Hz - 0.25 - 0.28 - 0.23 315 Hz - 0.31 - 0.30 - 0.29 400 Hz - 0.32 - 0.30 - 0.32 500 Hz - 0.51 - 0.47 - 0.49 630 Hz - 0.57 - 0.55 - 0.47 800 Hz - 0.50 - 0.44 - 0.41 1000 Hz - 0.61 - 0.54 - 0.48 1250 Hz - 0.54 - 0.57 - 0.49 1600 Hz - 0.65 - 0.57 - 0.51 2000 Hz - 0.66 - 0.56 - 0.49 2500 Hz - 0.64 - 0.57 - 0.50 3150 Hz - 0.62 - 0.56 - 0.49 4000 Hz - 0.57 - 0.51 - 0.47 5000 Hz - 0.58 - 0.54 - 0.48	

3.2.2 Studies conducted in outdoor conditions

Noise pollution in urban environments is one of the causes of urban discomfort. It can potentially affect speech interference, hearing discomfort, sleep disturbance, reduced productivity, etc. Although there are many sources of noise related to the activities of people, traffic is the most important urban noise. How much external noise reaches a receiver depends on the type and speed of the sound, the distance between the source and the receiver, the obstacles between them, and the characteristics of the environment. Today, most of the measures that are usually necessary to control noise in cities, such as high noise barriers, cannot be used in dense urban environments due to lack of space, safety, or visual impact (Lacasta et al., 2018).

Does the question arise as to what a space that provides acoustic comfort should be? What decisions must be made to configure the ideal public space? Studies have shown that the level of noise and the perception of noise in a given place are often independent of each other (Brambilla et al., 2013). Answering these questions will be easier if we can compare, for example, the conditions of the space before and after inserting a new element, taking into account that the result goes beyond what the metrics say.

An example could be the work of (Lacasta et al., 2016). In this study, the potential of a green wall to isolate road noise was analysed through a comparison between a green wall and a traditional wall. An absorption coefficient of 0.7 and a reduction of 4 dB due to the vegetated barriers demonstrate two relevant aspects. The first establishes that the development of vegetation is an influential factor in the absorption coefficient of this type of solution, and the second that the multiple reflections between the different barriers are effectively minimised by the absorption of the vegetation.

These aspects have also been confirmed by the work carried out by (Romanova et al., 2019). In their results, it is confirmed that the presence of plants with a high area density, such as *Bergenia cassifolia* (layer thickness = 0.18 m) significantly improves the absorption properties of a green wall (α = 1.00) as opposed to other species (α = 0.9), in particular under medium and high frequencies (below 1000 Hz). Another relevant aspect has been the verification that the configuration of modules in a green wall affects the reduction of the acoustic resonances, which are attenuated or disappear.

The noise absorption capacity of vegetation at low and medium frequencies has also been verified (Nyuk Hien Wong et al., 2010a). In which eight types of green wall systems were analysed, and this effect was attributed to the presence of substrate. From the results, it is worth noting that of the eight systems analysed, those with a greater thickness of the substrate (between 0.060 m and 0.080 cm) had a reduction of 5-10 dB, while those with a lesser thickness (between 0.0230 cm and 0.080 cm) obtained a reduction between 2 dB and 3.9 dB.

In addition to the density of vegetation and the thickness of the substrate, the configuration of the system also influences the acoustic absorption capacity of this type of solution. Studies demonstrated the absorption potential of an indirect green wall over a direct one (Gabriel Pérez et al., 2016b). The façade installed indirectly on the wall was able to provide an increase in sound insulation of 2 dB over the direct façade. These results were attributed to the thickness and composition of the substrate, the vegetation layers, the impedance of the sealing joints between the modules, and the insulation of the supporting structure.

However, it is not only the characteristics of the elements in the urban space that can influence the perception of noise, but also their position. Evaluations of the attenuation of noise produced by a vegetal façade as a function of the distance to the source of the noise it was located have shown that they are more effective at large distances from the source location (Ismail, 2013). This makes it an optimal solution to attenuate noise at a distance from urban activity.

Table 5: Studies conducted in outdoor conditions

Outdoor conditions										
Author	***Location***	***Type of study***	***Type of system***	***Sample size***	***Frequency (Hz)***	***Vegetation species***	***Vegetation dimension and thickness (cm)***	***Substrate mix***	***Substrate thickness (cm)***	***Sound absorption coefficient (α) / Sound insulation (dB)***
(31) A.M Lacasta	Spain	In situ measurements *(outdoor)*	Modular system	2.62 x 2.42 x 0.20m	250 - 4000	*Helichrysum Thianschanicum*	24 pre-cultivated plants per module	50/50 vol/vol mix of compost and coconut fibers	15	0.7
(32) Anna Romanova, et al.	UK	In situ measurements *(outdoor)*	Modular system	1m2	1000 - 100.000	*Hedera Helix and Bergenia Cordifolia*	8 modules and 96 plants	*Not specified*	10	Soil: 0.5 - 1.00 Soil (impedace tube): 0.2 - 0.9 Hedera Helix: 0.45 - 0.95 Bergenia cassifolia: 0.25 - 1.00 Bergenia cassifolia model: 0.20 - 1.00
(33) Nyuk Hien Wong, et al.	Singapur	In situ measurements *(outdoor)*	Eight different types of green facade: mesh systems and living wall systems	9 walls of 4 x 8 x 0.3m	630 - 10.000	*Not specified*	(S1) 0.100m (S2) 0.100m (S3) 0.120m (S4) 0.120m (S5) 0.110m (S6) 0.055m (S7) 0.120m (S8) 0.200m	*Not specified*	(S1) 0.250m (S2) 0.080m (S3) 0.230m (S4) 0.080m (S5) 0.070m (S6) 0.065m (S7) 0.060m (S8) 0.280m	**Frequency 125 - 1250 Hz:** (S1): -2.5 - 5.6dB (S2): -1.1 - 9.9dB (S3): -4.5 - 2.2dB (S4): -1.5 - 4.0dB (S5): -3.3 - 7.0dB (S6): -2.4 - 5.4dB (S7): 0.3 - 8.4dB (S8): -0.6 - 3.1dB **Frequency 40 - 10.000 Hz:** (S1): -0.6 - 3.1dB (S2): 2.2 - 3.8dB (S3): -4.0 - 3.2dB (S4): -2.5 - 2.0dB (S5): 0.3 - 2.8dB (S6): -1.6 - 3.2dB (S7): 0.0 - 3.9dB (S8): 2.6 - 8.8dB
(34) Gabriel Pérez, et al.	Lleida, Spain	In situ measurements *(outdoor)*	Modular system and double-skin green facade (wire mesh)	Two cubicles of 3 x 3 x 3m	20 - 10.000	Green wall: *Rosmarinus Officinalis* and *Helichrysum Thianschanicum* Double skin: *Boston Ivy*	24 small shrubs	Coconut fiber	*Not specified*	1dB for a layer of vegetation of 20-30cm (traffic noise) 2 - 3dB for a layer of vegetation (pink noise)

3.2.3 Studies on system components

Previous studies have shown how acoustic performance can be affected during plant growth or by substrate thickness. Therefore, these are the main elements to consider when introducing a solution that aims to isolate or reduce the sound. It has become apparent that it will be necessary to use species that have a good development of biomass and are adapted to local climate conditions, but what other determining factors should be considered?

The studies analysed in this section aim to look at the characteristics of the components of the green wall, which individually influence the overall acoustic performance **(Table 6).**

Asdrubali et al. showed that plants could absorb a significant amount of acoustic energy, especially in the presence of substrate (Asdrubali et al., 2014). It is highlighted that the substrate can absorb up to 80% of the incident energy at frequencies above 1000 Hz. In particular, the combination of plants such as Baby Tears and substrate gave results of between 0.75 and 0.9 absorption coefficients, tested at frequencies between 300 Hz and 1600 Hz. Simulations of the sound absorption capacity of substrates have shown that moisture tends to reduce the absorption coefficient, depending on the composition of the substrate. (Attal et al., 2021a).

These statements have been confirmed by (Ding et al., 2013), who added characteristics: substrate porosity. They show that when a leaf is placed in front of a porous or low-permeability substrate, its absorption characteristics change considerably. The increase in absorption caused by leaves is in the frequency range of road traffic in a city, while the losses in vegetation capacity are achieved at frequencies that are too high to be relevant in the analysis of urban acoustic comfort.

To a greater or lesser extent, all species can absorb a proportion of the incident energy. A study developed by D’Alessandro et al. states that the main absorption layer of a green wall system is the substrate, which absorbs 80% of the energy. This percentage can be improved by between 10% and 20% when vegetation is added. There are species such as Ferns that can increase substrate absorption by 25% (D’Alessandro et al., 2015).

Without a doubt, if the species and substrate are chosen with the appropriate porosity and resistivity, they are capable of providing an efficient screen effect for noise absorption. As previously demonstrated, the substrate plays a very significant role, but plants complement it and, in some cases, improve it significantly (Horoshenkov et al., 2013).

Simulations of the sound absorption capacity of substrates have shown that moisture tends to reduce the absorption coefficient, depending on the composition of the substrate. (Attal et al., 2021a).

Table 6: Studies on system components

Partial or components									
Author	***Location***	***Type of study***	***Sample size***	***Frequency (Hz)***	***Vegetation species***	***Vegetation dimension and thickness (cm)***	***Substrate mix***	***Substrate thickness (cm)***	***Sound absorption coefficient (α)***
(35) Mostafa Refat Ismail	Cairo, Egypt	Computer model	410 x 410m urban area with six lateral and six perpendicular streets. Building density of 73%.	*Not specified*	*Not specified*	*Not specified*	*Not specified*	*Not specified*	0.41 (4m building height) 0.48 (8m building height) 0.54 and 0.85 (12m building height)
(36) Francesco D'Alessandro., et al.	Perugia, Italy	Experimental	Impedance tube of 28mm	50 - 1600	*Boston Fern* and *Helxine (Baby tears)*	The Fern produces large fronds 50-250 cm long and 6-15 cm wide. The Helxine grows naturally close to the ground in mats, reaching up to 10-15 cm in height.	70% coconut fibers and 30% expanded perlite	10	**Boston Fern and substrate** 0.75 at 300Hz 0.9 at 1600Hz **Helxine and substrate** 0.75 at 300Hz 0.95 at 1600Hz
(37) Francesco Asdrubali., et al.	*Not specified*	Experimental	Impedance tube of 29mm	50 – 1600	*Boston Fern*, *Baby Tears, Begonia, Maidenhair Fern and Green Ivy.*	*Not specified*	Coconut and perlite soil for hydroponics	*Not specified*	**Boston Fern and substrate** 0.8 - 1 **Baby Tears and substrate** 0.6 - 0.9 **Begonia and substrate** 0.8 - 0.9 **Maidenhair Fern and substrate** 0.7 - 0.9 **Green Ivy and substrate** 0.6 - 0.8
(38) H. Benkreira., et al.	*Not specified*	Experimental	Impedance tube of 29mm	50 - 1600	*Pieris Japonica, Green Ivy* and *Primrose*	Pieris Japonica (0.41mm) Green Ivy (0.23mm) Primrose (0.74mm)	Mix of perlite, coconut fibres and polymer gel	*Not specified*	**Pieris Japonica and substrate** 0.2 - 0.6 **Green Ivy and substrate** 0.5 - 0.9 **Primrose and substrate** 0.4 - 1
(39) Emmanuel Attal., et al.	*Not specified*	Experimental	Impedance tube	180 - 1000	*Euonymus japonicus*	5cm long and 3cm wide	Coir dust and perlite	8	**Transmission losses** ***Perlite layer without vegetation*** 8dB - 15dB ***Coir dust layer without vegetation*** 10dB - 35dB ***Perlite layer with vegetation*** 14dB ***Coir dust with vegetation*** 12 dB - 15 dB
(40) Emmanuel Attal., et al.	*Not specified*	Experimental	Impedance tube of 192mm (diameter)	100 - 1000	*Euonymus japonicus*	5cm long and 3cm wide	Coir dust and perlite	8	**Composite sample with dry perlite** 0.95 **Composite sample with dry coir dust** 0.8

4. Results and discussion

4.1 Reduction of temperature through green walls in urban environments

In the field of temperature reduction, several studies have been developed with the aim of studying the effect of vegetated facades on the temperature of the immediate environment (Tan et al., 2014); identifying the aspects that contribute to the cooling effect (Koyama et al., 2013); investigating thermal performance (Daemei et al., 2019); studying the effect of orientation in a given climate type (Pan and Chu, 2015); and even the correlation between thermal performance and photosynthesis and evapotranspiration processes (Zhang et al., 2019).

A large part of the developed studies present experimental approaches, with data collection on prototypes (Castiglia Feitosa and Wilkinson, 2020; Djedjig et al., 2017; Olivieri et al., 2014; Serra et al., 2017). It is also common to see modelling studies that seek to characterise the thermal behaviour of green walls under prespecified climatic and urban conditions (Herath et al., 2018; Tan et al., 2015; Wai et al., 2020). Few cases have studied the external temperature reduction capacity of façades installed on real buildings at street level (de Jesus et al., 2017; Sendra-Arranz et al., 2020).

In the analysed literature, aspects such as the characteristics of the substrate and the plant species used; the distance of the measurement points; the orientation according to the location; the duration of data collection; the type of façade; among others, have been studied separately, providing results of great interest that can be enhanced if they are analysed as a whole. However, these methodological approaches leave aside the characterisation of the thermal behaviour of a green wall according to the climate in which it is located or the radius of impact on the reduction of air temperature at street level. Both tools are necessary for their implementation in cities.

In the review of the literature, a distinction was made between studies that related their results to air temperature (9 studies) and those that did so to a reference surface temperature (16 studies).

There are four aspects that, according to all experimental studies assessed, are essential characteristics for the thermal performance and microclimatic benefit of these systems:

- The thermal regulating effect of green walls is mainly due to photosynthesis and evapotranspiration of plant leaves, which is called the thermal equilibrium of vegetation. The results show reductions of up to 2.7 °C compared to air temperature due to the absorption of solar radiation and convective heat transfer (Zhang et al., 2019).

- The effect of the combination of shade and evapotranspiration leads to a reduction in air temperature between 1 °C and 3 °C, although this can vary depending on climate and substrate composition (Wong et al., 2016). Most of the results obtained are attributable to the presence of the substrate, mainly due to its thermal inertia (Abdo and Huynh, 2021; Dede et al., 2021). In cold climatic conditions, these effects are only enhanced if there is a minimum solar radiation of 500 W/m^2 (Jim, 2015a).

- The type of species, the Leaf Area Index (LAI), the area covered, and the thickness of the plant (Li et al., 2019b) significantly influence the performance of green walls. The higher the coverage, the higher the impact. One of the best performing species is *Prunus laurocerasus* (Cameron et al., 2014).

- Evapotranspiration has an important impact on temperature reduction as long as the vegetation is irrigated with more than 2.5 l/m^2/day (M. T. Hoelscher et al., 2016).

The results found according to the type of climate show that, in humid subtropical climates, continuous green walls can lead to temperature reductions between 1.1 °C and 14 °C, while modular green walls range from 6.1 °C to 20.8 °C. In continental climates, the values for continuous green walls range between 0.8 °C and 2.1 °C, while modular green walls range between 8 °C and 31 °C. In the Mediterranean climate, continuous green walls show reductions between 1.62 °C and 19.1 °C, while modular green walls vary between 12 °C and 20 °C. In oceanic climates, continuous green wall reductions are between 3 °C and 15.5 °C, while in semi-arid climates it is between 2.5 °C.

This study suggests two aspects that need an in-depth study to more concretely determine the impact of green walls on urban comfort. The reduction in outdoor temperature produced by a continuous green wall is between 0.8 °C and 19.1 °C, while that of a modular green wall reaches values between 6.1 °C and 31 °C. Although these values are in a constant range, they do not consider the measurement distance as a variable to determine the radius of action of a green wall in urban space. Furthermore, taking measurements of prototypes under urban conditions can influence the results. Both are aspects that are missing in the studies analysed.

4.2 Noise attenuation through green walls in urban environments

Most studies in the field of acoustic absorption have been developed under controlled conditions such as reverberation chambers or laboratories through impedance tubes, with the main objective of identifying the absorption capacity of various types of green walls taking into account the type of substrate and plants (D'Alessandro et al., 2015; Ding et al., 2013; Horoshenkov et al., 2013), façade configuration (Asdrubali et al., 2014; Davis et al., 2017) or the influence of distance from the emitter (Ismail, 2013). Despite this, the field of acoustic absorption in full-scale vegetated façades under real-use conditions remains an underexplored field of research.

Noise absorption and attenuation capacity were analyzed through a total of 11 studies, which were classified according to the type of experiment carried out: in controlled conditions such as reverberation chambers (3 studies), in outdoor settings (4 studies), and in specific components such as substrate or plants (4 studies).

The most relevant variable in this type of study has been the absorption coefficient, which demonstrates the capacity of these systems to absorb energy in the urban environment. However, the analysis of other variables such as distance from the emitter, sound frequency, substrate composition, and vegetation development have been a determinant.

Four aspects have been identified as relevant and indispensable for optimal acoustic performance, allowing for sensory and psych perceptual benefits in urban contexts:

- Green walls offer higher performance at mid to high frequencies. However, they can also do so at low frequencies, their properties being even better than those of other sound-absorbing materials. If we consider the frequency of the human voice 60 dB, it perfectly corresponds to the frequency at which the green wall is most efficient (below 400 Hz), so it could be used as an effective measure in public spaces. (Azkorra et al., 2015b; Davis et al., 2017).

- Noise absorption in green walls comes from the substrate - 80% of the received energy is absorbed by the substrate at frequencies above 1000 Hz - (D'Alessandro et al., 2015; Ding et al., 2013), which behaves like any other porous material in that its absorption is proportional to the frequency of the noise. Furthermore, the thickness of the substrate in modular systems influences the reduction. The thicker the substrate (0.060 m - 0.080 m), the greater the reduction (5-10 dB), and the thinner the substrate (0.0230 m - 0.080 m), the lower the reduction (2 dB - 3.9 dB) (N H Wong et al., 2010).

- Plants play a fundamental role in noise absorption. Density is the most relevant variable. As the frequency increases, the differences between the absorption coefficients for vegetation density between 43% and 100% increases. It is mainly due to the multiple reflections between the different barriers that are effectively minimized. If there is dense vegetation, the absorption coefficient can increase by 0.2 and 0.3. The best performing species was *Bergenia cassifolia* (layer thickness = 0.18 m) and absorption coefficient (α = 1.00) (Romanova et al., 2019).

- Unlike the thermal performance, the configuration of the system can influence the acoustic absorption capacity, mainly due to the thickness and composition of the substrate, the vegetation layers, the impedance of the sealing joints between the modules, and the insulation of the supporting structure (Sierra-Pérez et al., 2016).

It is not possible to make an average of sound absorption according to the type of system studied because many variables come into play. However, the results confirm the capacity of this type of system to absorb noise beyond its constructive typology.

Two aspects must be explored in greater depth to determine the impact of green walls on acoustic absorption. The results mention the substrate and its composition, porosity, and resistivity, as well as vegetation, LAI index, shape, and thickness, as indispensable variables to ensure absorption. However, no reference was made to other variables, such as the saturation of the substrate. Furthermore, as environmental noise is a subjective variable and is influenced by many other variables, it is relevant to study in-depth effects that green walls can have in open spaces where they are exposed to different sources of noise.

5 Conclusions

The selected studies on green walls and their impact on urban comfort have shown that significant developments have been made in this scientific field. It becomes evident in the diversity of experimental, modeling, and laboratory studies that assess the different variables of a vegetation system considering the influence of the construction system and its configuration on the installation, density and type of vegetation, stage of plant development, composition, porosity, and resistance of the substrate, materials used such as felt geotextiles or polymeric materials, and the type of climate on the ability to reduce temperatures or absorb noise. All of these approaches are valuable for disseminating the implementation of this technology as a mitigation measure of climate change.

The vast majority of studies carried out in the field of green walls and their ability to reduce temperature are experiments with prototypes developed for data collection and testing of surface temperature reduction or building façades under full-size conditions. However, the latter are very scarce. For sound absorption, it was identified that most studies are carried out in laboratories to test the characteristics of the substrate or vegetation in noise absorption or in reverberation chambers where experiments were carried out under controlled noise conditions. This study has identified the importance of deepening this scientific field, with the development of studies that evaluate the reduction of temperature and acoustic absorption of green walls in urban and pedestrian conditions to demonstrate the benefits that these solutions can have in the mitigation of climate change in cities.

Analysis of the results of the selected studies demonstrated three fundamental aspects: (i) the temperature reduction is mainly influenced by the shading capacity of the type of vegetation selected, the natural evapotranspiration process of the plants and the presence of substrate, (ii) the acoustic absorption capacity is influenced to a greater extent by the configuration of the system (direct or indirect wall), the characteristics of the substrate (porosity, composition, granulometry) and the density of the vegetation, and (iii) in both cases the environmental conditions in which they are located can vary the impact to a greater or lesser extent.

More research is needed on the capacity of green walls to improve air quality in cities. It would complete the framework of variables needed to assess the overall effect of green walls on outdoor comfort conditions. Furthermore, despite extensive research on reducing surface temperatures in the building area, more research is needed on the impact on hygrothermal comfort that façade can have if installed at street level.

Regarding urban noise reduction, it is necessary to study in-depth noise absorption capacity of these solutions in life size and under uncontrolled conditions, as most studies have been developed in laboratories or reverberation chambers that do not reflect the reality of a city's soundscape. These considerations are relevant for the implementation of green walls as a mitigation tool for climate change in cities and the development of new technology research approaches to complement those analysed in this review.

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Análisis de ciclo de vida de dos sistemas modulares de jardinería vertical

En la actualidad, el sector de la construcción en Europa representa el 40% de la energía primaria consumida a partir de recursos no renovables, de un total del 87% a nivel mundial (Izrael et al., 2007). Esto supone un gran reto para el sector en términos de uso de materias primas y sus implicaciones en el balance energético y de emisiones de las edificaciones. En España, la actividad constructora es la que más recursos naturales consume y es una de las más contaminantes, la construcción en general, no solo la edificación de viviendas es responsable de entre el 30% y 40% del total de emisiones de gases de efecto invernadero (GBCe, 2021).

El impacto de una edificación empieza con la extracción de recursos (áridos, metales, piedras, maderas, fibras, etc.) que son transportados y procesados antes de ser utilizados en la construcción. Durante la construcción, además de la emisión de contaminantes y el uso ingente de agua y electricidad, se generan residuos que deben ser transportados y tratados. La construcción de un edificio, desde la extracción de los materiales hasta la finalización, conlleva a la emisión de 6.809 toneladas de dióxido de carbono (GBCe, 2023).

Ante el compromiso de Europa de alcanzar la neutralidad climática en 2050, se hace evidente la necesidad de reducir al máximo las emisiones operativas y contabilizar el carbono embebido (en los materiales, generado en su transporte y en los procesos de construcción). Para ello, es fundamental regular la huella de carbono de todo el ciclo de vida de un edificio, y esto supone reducir el carbono que se emite durante la fabricación de materiales, el cual representa el 11% de las emisiones del sector de la construcción y supondrá más del 50% de las emisiones acumuladas durante los próximos 30 años (GBCe, 2023).

Existen muchos métodos para evaluar el impacto ambiental de los materiales y componentes en el sector de la construcción. El análisis de ciclo de vida (ACV) se ha utilizado en este sector desde 1990 (Fava, 2006), y su popularidad se debe a la recopilación de todos los datos relacionados con los materiales y su impacto medioambiental. La evaluación incluye todo el ciclo de vida de un producto, proceso o sistema, que abarca la extracción y el procesamiento de materias primas, la fabricación, el transporte y la distribución, el uso, la reutilización, el mantenimiento, el reciclaje y la eliminación final. Esta evaluación se estructura a partir de una metodología establecida por la norma ISO 14040 que consta de cuatro pasos: definir el objetivo y el alcance, crear el inventario del ciclo de vida, evaluar el impacto, y finalmente, interpretar los resultados (Khasreen et al., 2009).

En el caso de las edificaciones es posible analizar tanto el entero ciclo de vida del edificio como de un componente o material constructivo. Esto lo ha convertido en una herramienta para fomentar prácticas de diseño y construcción sostenible que, sin embargo, no ha sido desarrollada como en el sector de la ingeniería y las infraestructuras. Esto se debe fundamentalmente a dos aspectos que afectan este tipo de evaluación en la edificación, por un lado, los edificios tienen una larga vida útil, a menudo de más de 50 años, y es difícil predecir todo el ciclo de vida, por otro, durante la vida útil de un edificio, este puede sufrir muchos cambios en su forma y función, que pueden ser tan significativos como el producto original, además de que la mayoría de los impactos medioambientales del edificio se producen durante su uso. Esto se traduce en que no existe una normalización del diseño y uso de edificios que facilite la implementación de esta metodología.

Los efectos medioambientales relacionados con el uso de la vegetación en el diseño urbano, arquitectónico y de interiores son objetivo de estudio desde principios de los años 70. A las fachadas verdes se les atribuyen beneficios como la mitigación del efecto isla de calor, reducción de la contaminación acústica, reducción de la demanda de energía para calefacción y refrigeración, absorción de partículas de compuestos orgánicos volátiles (VOC), aumento de la biodiversidad (Weinmaster, 2009). Estos beneficios son decisivos en el diseño de una fachada, pero no suficientes. Una fachada vegetal para su construcción requiere de un gran número de materiales, componentes y sustancias, que según los requisitos del CEN/TC 350: "Sostenibilidad en la construcción", la planificación de la construcción es una etapa crucial para minimizar el impacto medioambiental y reducir la intensidad de materiales o la explotación de materias primas.

En los últimos años se han incorporado al mercado numerosas soluciones de jardinería vertical, entre las que destacan las modulares. Los estudios hasta ahora desarrollados sobre este tipo de soluciones no tienen en cuenta las emisiones y la energía embebida desde la fabricación hasta el desmontaje, lo que representa una oportunidad de investigación. Los resultados obtenidos a partir de este tipo de evaluación pueden ser una herramienta útil para diseñadores y constructores que decidan incorporar este tipo de tecnología como una estrategia de diseño sostenible.

En la línea del enfoque de ACV descrito, en el marco de esta tesis doctoral se ha desarrollado el artículo científico: Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García, Jacopo Bacenetti (2020). *An environmental Life Cycle Assessment of Living Walls Systems*. Journal of Environmental Management, 254, 109743. Q1 (JCR). DOI: 10.1016/j.jenvman.2019.109743. En el que se presenta el análisis de ciclo de vida (ACV) de dos sistemas modulares de jardinería vertical, en el que se evalúan los impactos de fabricación, construcción y mantenimiento, con la finalidad de seleccionar aquel con el menor impacto ambiental para el desarrollo del análisis experimental.

Para el desarrollo del estudio se seleccionaron dos prototipos que cumplían con los criterios de selección establecidos en la tesis: modularidad y uso de sustrato. Los sistemas seleccionados correspondían a sistemas modulares, uno en fieltro y otro en plástico reciclado, con sustrato hidropónico y orgánico respectivamente. El propósito es cuantificar los impactos y beneficios asociados a la fabricación, uso y mantenimiento de dos sistemas muy difundidos en el mercado actual, que cumplen la misma función, pero de materiales (plásticos y geotextiles), proceso de fabricación y montaje distinto.

Un ACV completo incluye cinco fases: fabricación, construcción, uso, mantenimiento y fin de vida útil. En este estudio se han considerado las siguientes fases:

- **la fabricación de los componentes,** centrada en analizar la energía y emisiones embebidas en los materiales y recursos utilizados para fabricar los sistemas;
- **la construcción,** en la que se analiza el montaje del sistema, el modo de transporte y la distancia recorrida, así como las emisiones de CO_2 derivadas del transporte de estos materiales;

- **y el mantenimiento**, en la que se evalúa fundamentalmente el consumo de agua, teniendo en cuenta las necesidades de riego del sistema.

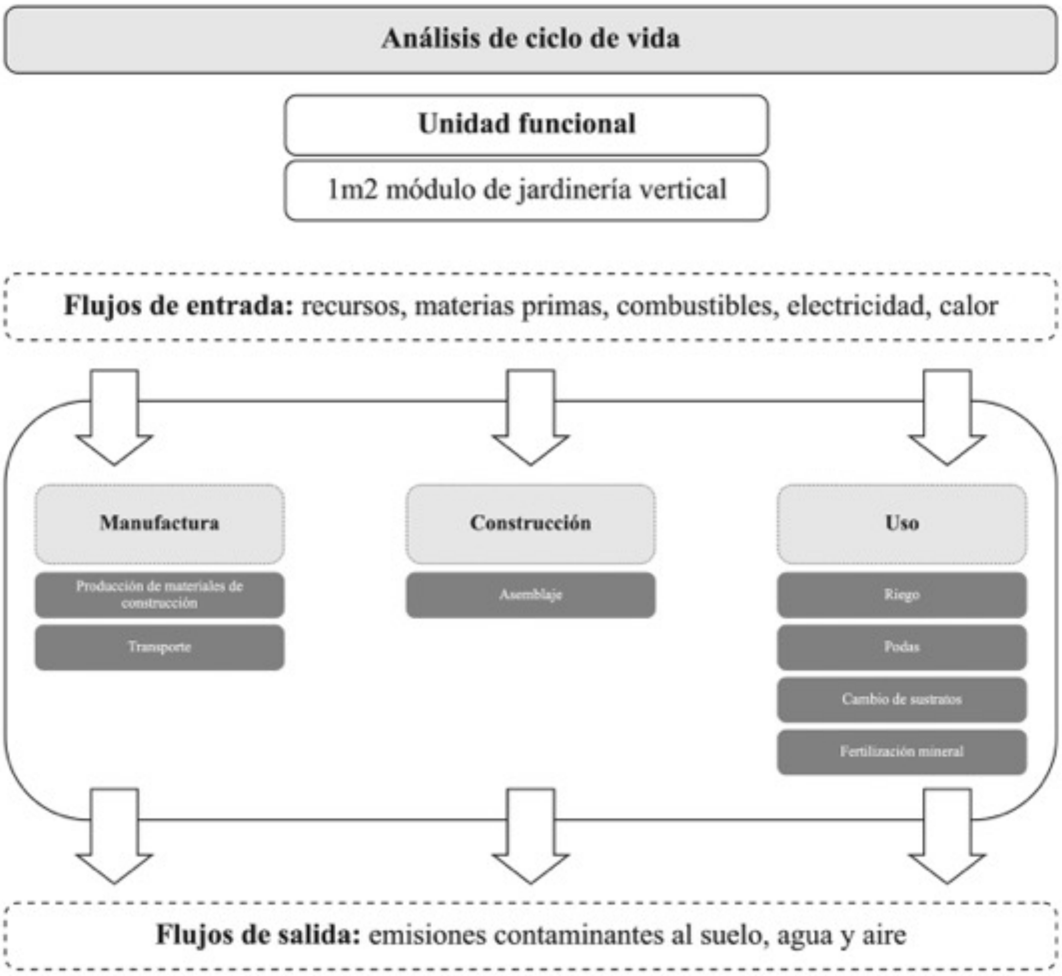
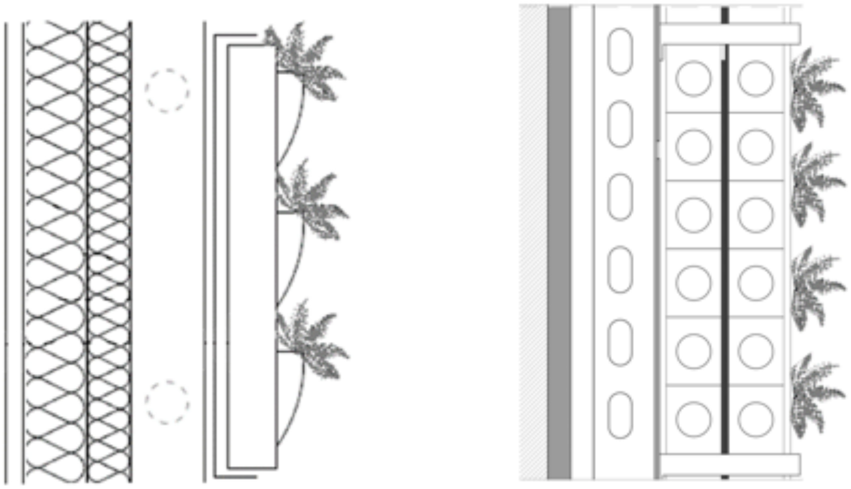


Figura 11: Fases incluidas en el análisis de ciclo de vida de los sistemas modulares de jardinería vertical

Los sistemas evaluados cuentan con las siguientes características:

- **Sistema modular en fieltro**, consta de una estructura de soporte de aluminio, una malla interna para el anclaje del sistema radicular y una serie de capas de fieltro de distintos materiales para cubrir el panel y alojar las plantas. El sustrato se compone de fibra de coco para sistemas hidropónicos, fieltro triturado procesado de residuos (con capacidad de retención de agua), micorrizas granulares con mezcla de colonia de hongos edomicorrícicos y elementos inertes como pizarra y arcilla expandida, y gránulos de abono. El consumo de agua del sistema es de 2 l/m^2 diarios y requiere de dos podas al año.

- **Sistema modular en plástico**, compuesto por una estructura tridimensional de polietileno reciclado con un diseño celular. La estructura se rellena de sustrato y plantas pre-cultivadas. La capa final del módulo está compuesta por un fieltro que cumple dos funciones: mantener la humedad del módulo y evitar el desprendimiento de la vegetación. Cada unidad de cultivo se rellena con sustrato orgánico compuesto por fibra de coco, turba y humus. Este sistema consume cerca de 8 l/m^2 al día y se basa en procesos naturales que mantienen un equilibrio en la nutrición y crecimiento de las plantas, por lo que no requiere fertilización y las podas son limitadas.



(a) (b)

Figura 12: Sistemas modulares de jardinería vertical utilizados para el desarrollo del acv: (a) módulo en fieltro; (b) módulo en cajas

Para el desarrollo del ACV se evaluaron todos los componentes y materiales de los dos sistemas seleccionados, información proporcionada por los fabricantes y proveedores en cada caso. Los datos sobre las materias primas, el uso de la energía en la fabricación y las emisiones asociadas a cada uno de estos materiales se obtuvieron a partir de la base de datos Ecoinvent® v 3.5.

Tabla 1: Componentes del sistema modular de jardinería vertical en fieltro

Componentes	**Material**	**Masa (kg)**	**Vida útil (años)**	**Distancia recorrida para su uso (km)**
Capa externa	Fibra de polipropileno y geotextil (fieltro)	0.53	10	80
Estructura de soporte	Aluminio	3.9	10	10
Capa hidrófila	Viscosa	1.15	10	50
Contenedor de sustrato	Monofilamento de polipropileno (fieltro)	2	10	50
Sustrato	50% tierra cruda; 30% SAP; 15% fibra de coco; 5% musgo	2.1	10	40
Capa de cierre	Policarbonato alveolar en resina	2	10	50
Vegetación	*Lonicera nitida*	1.66	10	40

Tabla 2: Componentes del sistema modular de jardinería vertical en cajas

Componentes	**Material**	**Masa (kg)**	**Vida útil (años)**	**Distancia recorrida para su uso (km)**
Capa externa	Poliéster	0.25	10	50
Estructura de soporte	Cajas de polipropileno	1.34	10	80
Capa hidrófila	Poliéster	0.25	10	50
Sustrato	Fibra de coco, turba y humus	4	10	40
Capa de cierre	Poliéster	0.25	10	50
Sistema de enganche	Aluminio	0.6	10	10
Vegetación	*Hedera hélix*	1.50	10	40

Para la realización del análisis se evaluaron las siguientes categorías de impacto:

- Cambio Climático (expresado en kg CO_2 eq);
- Disminución de la capa de ozono (expresado en kg CFC^{-11} eq.);
- Formación de material particulado (expresando en kg $PM_{2.5}$ eq.);
- Toxicidad en humanos sin efecto cancerígeno (expresado en CTUh);
- Toxicidad en humanos con efecto cancerígeno (expresando en CTUh);
- Formación fotoquímica de ozono (expresado en kg NMVOC eq.);
- Acidificación terrestre (expresado en molc Hfl eq.);
- Eutrofización terrestre (expresado en molc N eq.);
- Eutrofización del agua (expresado en kg P eq.);
- Eutrofización marina (expresado en kg N eq.);

- Ecotoxicidad del agua (expresado en CTUe);
- Uso de la tierra (expresando en kg C deficit);
- Agotamiento de los recursos hídricos (expresado en m^3 water eq.);
- Agotamiento de los recursos minerales y fósiles (expresado en kg Sb eq.)

La comparación de los resultados de ambos sistemas demostró el impacto de los materiales y sustancias utilizadas para la fabricación y mantenimiento de los módulos, que, en ambos casos, representan más del 80% del impacto ambiental en la mayoría de las categorías analizadas (Figura 13). De los dos casos, destaca el sistema modular en fieltro, que cuenta con una estructura de soporte en aluminio (40% del impacto total) y requiere del uso de fertilizantes durante la fase de mantenimiento del sistema (50% del impacto total).

El sistema modular en plástico arrojó mejores resultados durante las tres fases analizadas, principalmente por la cantidad y tipo de materiales empleados para su fabricación y el uso de sustrato orgánico no dependiente de fertilizantes para su mantenimiento. Los impactos identificados en este sistema podrían reducirse aún más sustituyendo materiales como el poliéster de los geotextiles y el aluminio de los anclajes por textiles y aluminio reciclado.

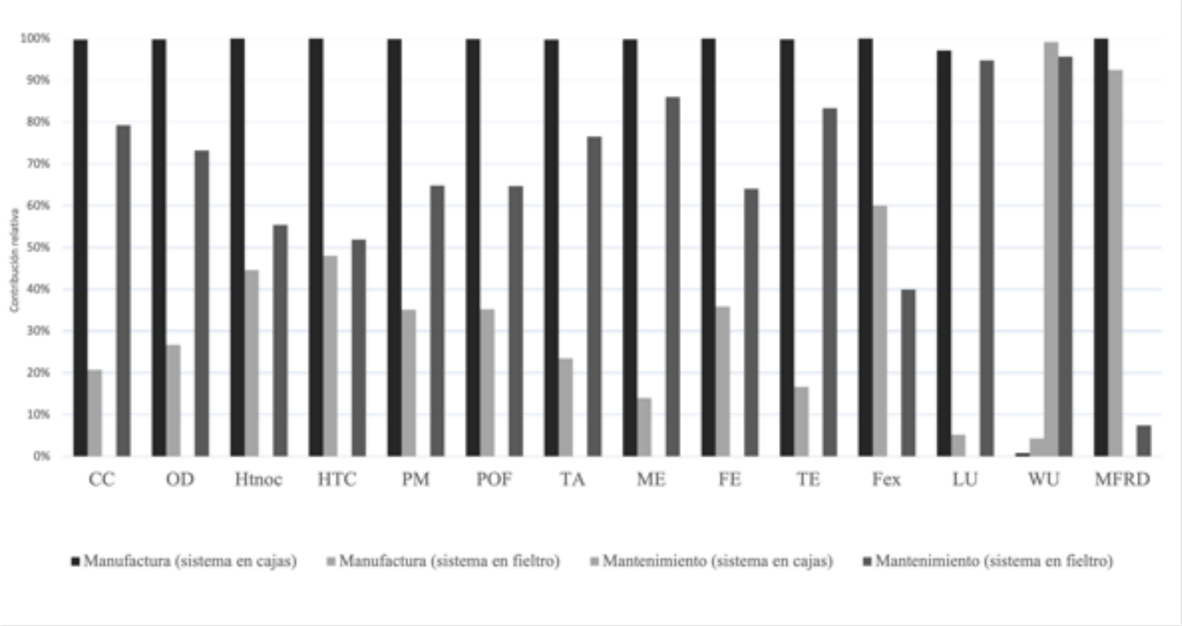


Figura 13: Comparación de los resultados de ambos módulos en todas las categorías de impacto estudiadas

Los resultados obtenidos en la realización de este estudio han demostrado la importancia de ir más allá de los beneficios intrínsecos de la tecnología. Los materiales utilizados para la fabricación tienen un impacto medioambiental durante su entero ciclo de vida, que, de no ser seleccionados con criterios sostenibles, afectaran el balance energético y de emisiones del edificio en el que sean instalados. El uso de materiales reciclados y de bajo impacto ambiental, así como de sustratos orgánicos y la estandarización del proceso constructivo para la reducción de materiales, forman parte de alguna de las directrices a tener en cuenta tanto para el diseño como para el uso de este tipo de soluciones tecnológicas.

Si bien son escasos los proyectos de desarrollo industrial de este tipo soluciones en los que se tienen en cuenta todos los impactos de la solución en las distintas fases de su ciclo de vida, la experiencia de este estudio muestra el potencial que tiene establecer un proceso de diseño de la construcción, producción y puesta en funcionamiento integral y alineada con la sostenibilidad. Además, se ha puesto de manifiesto que a través de metodologías como el ACV en todo el proceso de toma de decisión, desde la elección de los materiales hasta los métodos de montaje y de mantenimiento, puede mejorar el rendimiento medioambiental de este tipo de sistemas.

A partir de las conclusiones de este estudio, se seleccionó el sistema modular en plástico para el análisis experimental propuesto en esta tesis doctoral.

Figura 14: Proceso constructivo del sistema modular en plástico

Artículo 4

An environmental Life Cycle Assessment of Living Walls System.

Valentina Oquendo-Di Cosola, Francesca Olivieri, Luis Ruiz-García, Jacopo Bacenetti (2020).

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Q1 (JCR)

An Environmental Life Cycle Assessment of Living Wall Systems

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Abstract: The Life-Cycle Assessment (LCA) is a standard approach for evaluating the environmental impacts of products and processes. This paper presents the LCA of Living Wall Systems (LWS), a new technology for greening the building envelope and improve sustainability. Impacts of manufacture, operation, and use of the systems selected, were evaluated through an LCA. LWS are closely related to several environmental benefits, including improved air quality, increased biodiversity, mitigation of heat island effects, and reduced energy consumption due to savings in indoor cooling and heating. Two prototypes have been selected, taking into account the modularity and the use of organic substrate as selection criteria. The systems evaluated were a plastic-based modular system and a felt-based modular system. The inventory data was gathered through the manufacturers. The LCA approach has been used to assess the impact of these solutions by focusing on the construction phase and its contribution to both the energy balance and the entire life cycle of a building. This approach has never been done before for LWS. The study found that out of the two systems through the manufacturing, construction, and maintenance stage of the LCA, the felt-based LWS has an impact on almost 100% of the impact categories analyzed, while plastic-based LWS has the lowest influence on the total environmental impact.

Keywords: Living Wall Systems, Life Cycle Assessment, Sustainability, Green Walls

5. Introduction

Today, the European construction sector represents 40% of primary energy consumed from non-renewable resources, out of a total of 87% globally. In turn, the human ecological footprint has increased to 80% between 1960 and 2000 (Izrael et al., 2007). One of the most important challenges in construction is the use of raw materials, and the implications in terms of energy balance, consumption and the sustainability of the building during its useful life (Weißenberger et al., 2014). Thus, the reduction in energy consumption and its associated emissions is a main issue in architecture and engineering.

The duality of the life cycle concept and the construction sector can be summed up in concepts such as that of “low energy building” or “NZEB” (neat zero energy buildings), which aims to achieve the reduction of the impact on the environment during the building life cycle, the minimisation of the energy and resources consumption, as well as land use (Loga et al., 2017). An energy efficient building uses active and passive technologies to counteract transmission heat loss that affect energy consumption. The highest energy input in a building is found in the materials, known as embodied energy. Dixit et al. (Dixit et al., 2012) define the embodied energy like the energy sequestered in buildings and building materials during the entire life cycle. The construction sector has one of the most important environmental impacts on cities, and to face its consequences and reduce energy consumptions is necessary to promote solutions with an efficient performance during its entire lifecycle.

New technologies and building construction processes are being developed in order to improve the sustainability and efficiency of building envelops. Research has been carried out to develop new adaptable and intelligent facades that highlight their thermal behaviour and adaptability to different climatic contexts (Iommi, 2018), within these, the vegetable façades are particularly noteworthy.

Greening the building envelope provides benefits related to improved efficiency, a contribution to the immediate context through temperature regulation and reduced wind speed, as well as increased biodiversity in dense urban environments (Perini et al., 2011). Living wall systems (LWS) as part of vertical green solutions can improve the quality of urban living and reduce the global environmental impact caused by climate change (Dunnett, N., Kingsbury, 2008). The use of plants on buildings creating green facades have aesthetical and environmental benefits (Ottelé et al., 2011); improve the air quality by reducing the air pollution (Gourdji, 2018; Klingberg et al., 2017) reduce fine dust levels in the air (Perini et al., 2017); increase biodiversity (Perini et al., 2011); reduce the heat island effect in cities (Mariani et al., 2016; Sheweka and Magdy, 2011), and reduce the energy consumption for indoor cooling and heating (Pan and Chu, 2015; Perini and Rosasco, 2013a). Some of the aspects that influence the performance of a LWS are the density of the foliage, the humidity of the substrate and the air chamber between some layers, as well as the properties of the materials used (UK Green Wall Association, 2013).

The following studies investigated the ability of green facades and living wall systems to reduce energy consumptions by intercepting solar radiation. A study carried out by C.Y Jim. et al., [21] (Jim and He, 2011) studied the thermodynamic transmission process of the vertical vegetation ecosystem, monitoring solar radiation and climatic conditions, and simulating heat flow and temperature variations. Their results show that seasonal heat flows in the green wall will vary with fluctuating meteorological driving forces, protecting the vegetation efficiency of the green wall that absorbs radiant energy and prevents it from reaching the building surface. Coma J. et al. (Coma et al., 2014), studied the behaviour of vegetal facades in a Continental Mediterranean climate during the summer. The results show the capacity of vegetation to reduce the surface temperature of the exterior façade by up to 14 ºC, and the effect of shade on the reduction of the internal temperature by up to 1 ºC. Manso M. et al. (Manso and Castro-Gomes, 2016), studied a modular system of vegetal façade called Geogreen, through the analysis of local climatic conditions in three different periods. The experiment was carried out based on two measurements, one on a reference wall and one on a wall covered with vegetation modules. Results proved the capacity of vegetation to reduce maximum temperatures and increase minimum temperatures. Specifically, the studied system has demonstrated the ability to mitigate heat transfer up to a maximum of 75% input heat, and 60% quality heat, improving thermal insulation. Nadia S. et al., (Nadia et al., 2013) studied the influence of green walls on the thermal behaviour of buildings in semi-arid regions during the summer period. Outcomes showed that vegetation coverage optimises indoor temperature and reduces heat exchange through the wall structure, characterized by reduced temperature and increased relative humidity. Perez G. et al., (Pérez et al., 2011) through research determined that the surface temperature of a building wall in a shaded area was on average 5.5 ºC higher than in areas partially covered by vegetation. This difference was greatest during the summer, reaching an average temperature of 15.2 ºC on the southwest side in September. Olivieri F. et al., (Olivieri et al., 2014) carried out an evaluation of the thermal behaviour of a modular plant façade on drainage cells, and the results indicated that the performance of this pre-vegetated façade was better than a solar protection system, since it reduced overheating by 33% in the cooling system compared to other ventilated façade solutions. Mazzali U. et al., (Mazzali et al., 2013) tested three LWS to investigate the potential effects of energy behaviour on building envelopes under different climatic conditions in Mediterranean contexts. Their results showed similar behaviour in similar climatic conditions. During sunny days the differences in air temperature of the vegetal wall were from a minimum of 12 ºC to a maximum of 20 ºC, and during cloudy days the differences are reduced to 1 ºC - 2 ºC. From these studies, the capabilities of LWS as a technology to improve the performance and thermal insulation of buildings are evident. Therefore, it can be said that these systems have the capacity to limit the heat fluxes is the same in all the vertical greening systems. The differences on the performance might be by the presence of factors like the foliage index, the moisture content, vegetation type and materials involved.

Life Cycle Assessment (LCA) is one of many tools for assessing environmental issues. It is defined by ISO 14040 as: *"A technique for assessing the environmental aspects and potential impacts associated with a product, by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases"* (Fava, J.A.; Consoli, F.; Dension, R.; Dickson, K.; Mohin, T.; Vigon, 1993). The LCA approach has been used in the construction sector since the 1990s (Fava, 2006), and its popularity is due to the compilation of all material-related data and its environmental impact. It is a tool to promote sustainable design and construction. Jeswani et al. (Jeswani et al., 2010), identified LCA like a systematic and robust tool for quantifying potential environmental burdens and impacts of a process or product selection, and also for improving design and optimization. When a building LCA is carried out, only the building itself is studied, and the outcome is an assessment of the entire building process. In case the

LCA concerns a part of the building, such as a component or building material, the results might be called *"building material and component combination"* (BMCC) (Khasreen et al., 2009).

According to the ISO standards, 14040/44 (ISO, 2006) ((ISO), n.d.) “a Life Cycle Assessment is carried out in four distinct and interdependent phases:

- Goal and scope include functional unit selection and system boundary definition;
- Life cycle inventory involves the definition of energy and material flows between the systems and the environment and through the different subsystems and operations of the evaluated systems;
- Impact assessment, during which the inventory data are converted into environmental indicators, discussion and interpretation of the results, the results from the inventory analysis and impact assessment are summarized, sensitivity and uncertainty analysis are carried out and recommendations are given”.

Many researchers have made LCA studies calculating the environmental impacts of some construction materials to determine guidelines for the improvement of the building's performance. Asif et al. (Asif et al., 2007), carried out a study of CO_2 emissions from eight different building materials, including wood, concrete, aluminium, slate, glass, ceramics, and plasterboard. From the study, it was concluded that the material with the highest emissions and energy incorporated was concrete with 61%; Broun et al. (Broun and Menzies, 2011), studied three types of partition walls from a life-cycle approach: clay bricks, hollow concrete blocks, and a traditional wooden structure. The results showed that the most relevant material is brick both in terms of energy consumption and environmental impacts related to the life cycle. Kosareo et al. (Kosareo and Ries, 2007), conducted a LCA of intensive and extensive green roofs through a comparison with conventional solutions. The results obtained demonstrated the energy benefits provided by vegetation due to the lower thermal conductivity of the substrate. Altan et al. (Altan et al., n.d.), conducted the LCA of five different types of green wall systems in the UK, researching the environmental impacts and benefits associated with all phases of the life cycle. The results evidenced the lower impact of continuous unsupported solutions due to the lower maintenance and reuse of their components.

Faced with this series of studies and proven benefits, in recent years numerous LWS solutions have been launched on the market, among which the modular ones stand out. However, most of the studies developed have to do with the performance during the use phase, without taking into account the emissions and energy incorporated from manufacturing to disassembly. This is the approach of the present study.

Living Wall Systems should be assessed through LCA to study environmental impacts related to the entire lifecycle. This is a research gap that should be closed. These results could be a useful support tool for researchers and manufacturers in sustainable design (Ingrao et al., 2015). Particularly, the building sector, LCA helps to evaluate the important aspects related to embodied energy, embodied carbon and consumption energy of the materials and greenhouse gases emissions (Malmqvist et al., 2011).

6. Objectives

The aim of this study is to evaluate the energy and environmental life cycle of two living wall systems using different materials, types of assembly, and components. The purpose is to quantify the impacts and benefits associated with the manufacture, construction, and maintenance of a plastic and a geotextile based LWS. This has never been done before.

A comparison of the results was carried out to obtain guidelines that will lead to improving the environmental sustainability of the systems during their useful life. With the final purpose in mind of achieving designs with less environmental impact and more environmentally sustainable constructions. This study will help architects, ecologists, and engineers to find new nature-based solutions to address the consequences of climate change from the construction sector.

7. Materials and methods

3.1 Functional unit

According to ISO 14040 ((ISO), n.d.), the functional unit is the measurement value for quantifying the results in an LCA. In this study, emissions, energy consumption, and materials are based on 1 m^2 of LWS. The results of this analysis are calculated as the total environmental impact over the lifetime, excluding the decommissioning phase. With this data, we can choose between options and select the one that is compatible with the environment. The results show the total environmental impact throughout the useful life of each system. Also, these results allow the identification of improvements compatible with the concept of sustainability and environmental awareness.

3.2 System boundaries

The system boundary comprises the manufacture of the system components, construction and maintenance (fig.2). Manufacturing and construction cover the resources and process for producing the materials for the system components. The construction phase comprises all electricity consumption per square meter of LWS. The maintenance phase comprises the water consumption of the two LWSs, based on both system requirements and fertilization. Finally, all activities related to the use and disposal phases are excluded.

The study of the aspects that potentially affect the environment has been based on 10 years of useful life. The data that has been supplied by the manufacturers. It is assumed that the useful life of both LWS is 10 years, as well as that of all materials. The replacement frequencies of plants for the LWS made in plastic are 10% replacement per year, and 20% replacement per year for the system made with felt layers. The LWS need a nutrient solution if has a non-organic substrate, which is considered only for the system made with felt layers. The water consumption for the plastic-based LWS is assumed to be 8 l/day and for the felt-based LWS on 2 l/day. Irrigation systems are not considered.

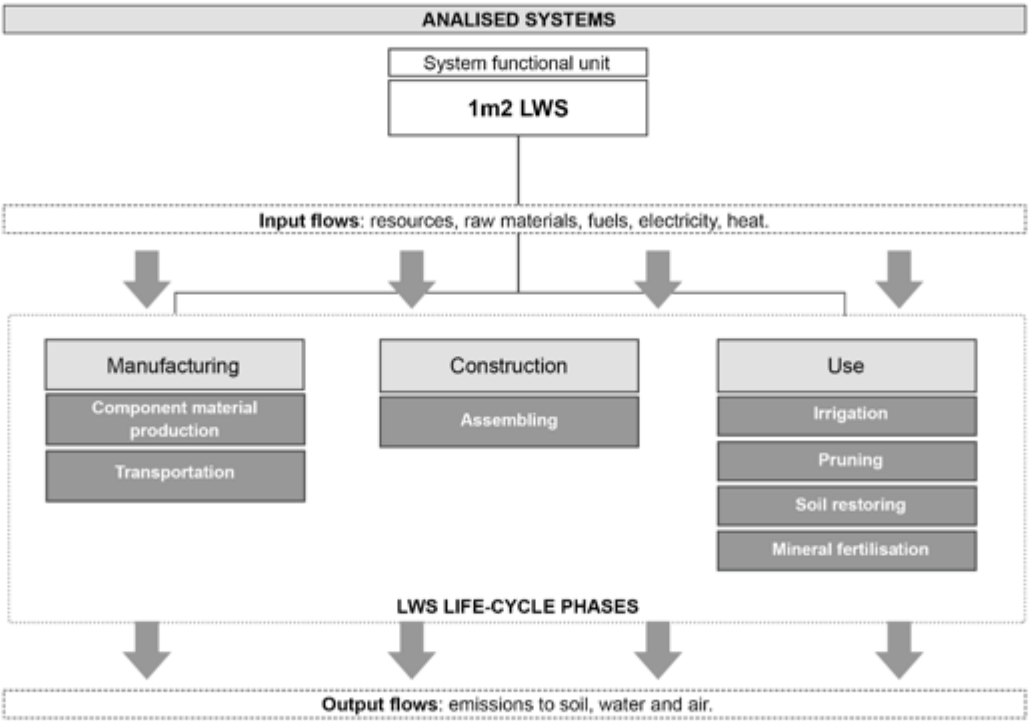


Figure 1: Boundaries of the analyzed systems

3.2.1 Manufacturing stage

The production phase focuses on analyzing the materials used to manufacture each of the systems. This helps to understand the energy content of the materials and the carbon emissions of the materials itself. The data was collected from the Ecoinvent® Database v.3.5 (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2016).

During manufacturing, two methods were considered for the construction of the systems. In the case of the LWS made with felt layers it is built by hand, which may require 1 to 2 people to assembly. Thus, it is not necessary to use heavy machinery to assemble these systems. In the case of LWS made of plastic, specialized machinery is required for their assembly, and it has an electrical energy consumption of 0.044 kWh for the production of panels and 0.8 kWh for the production of anchoring systems.

3.2.2 Construction stage

In this phase, the assembly of each system and its materials, the mode of transport and the distance traveled are analyzed, as well as the CO_2 emissions resulting from the transport of these materials. These factors have been important in obtaining the total environmental impact of each material during its life cycle. Each phase is calculated using SimaPro 8.5.

3.2.3 Maintenance stage

The maintenance phase studies the life cycle burden of the two systems attributed to water consumption, considering the number of times the systems need to be irrigated. This phase helps to obtain data on the system with the greatest impact due to resource consumption. Water consumption is an important factor that should be considered as it provides important insights into the water input needed to keep systems operating throughout the useful life. In this case, the plastic-based LWS has the highest water consumption (8 l/m^2 per day), while the one in the felt-based LWS is lower (2 l/m^2 per day).

3.3 System description and inventory data collection

3.3.1 Description of the studied LWS

Living Wall Systems (LWS), are often built from modular panels, in which the substrate can be organic, from natural compounds such as hummus, or hydroponics, with an artificial culture media such as foam, felt, perlite or mineral wool, i.e., that uses nutrient solutions for fertilizing the plants (Altan et al., n.d.). Figure 1 shows the difference between a LWS made with felt layers (a), and LWS made with planter boxes (b).

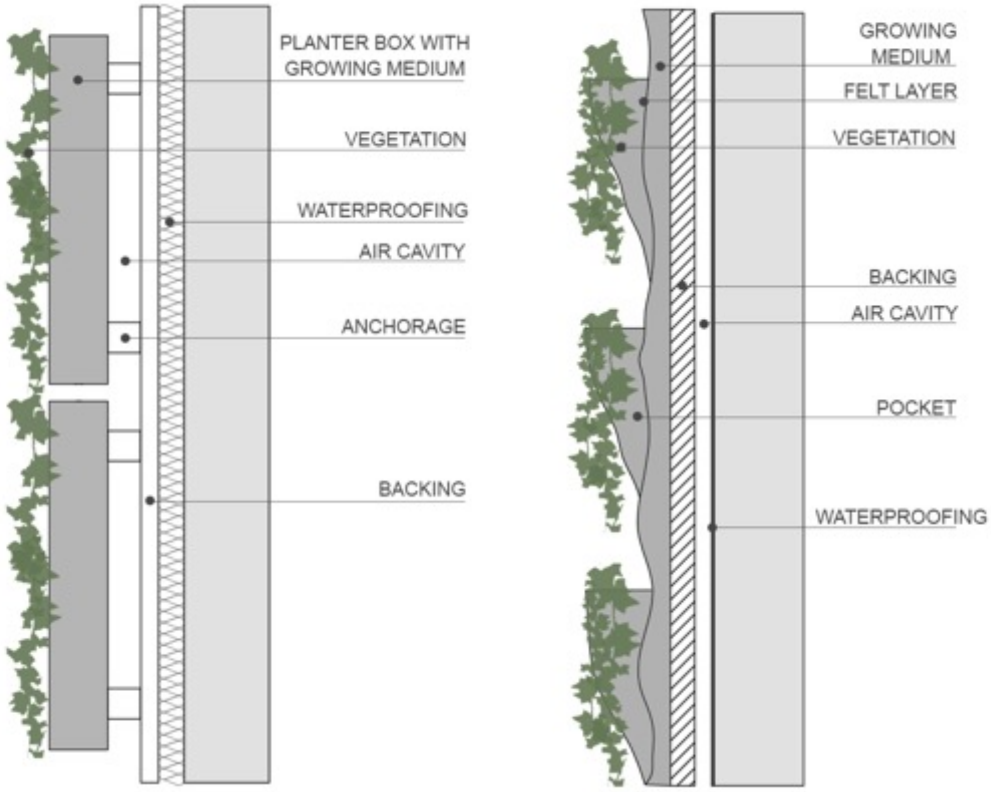


Figure 2: (a) Living wall system based on planter boxes; (b) Living wall system made with felt layers.

The characteristics of the two types of living wall systems used in this study are:

- The felt modular system, a type of modular system that uses plants, which can be pre-grown and inserted into gaps. The system was produced by a Spanish company, whose objective is to design and manufacture sustainable solutions to create horizontal and vertical green spaces in urban environments. Its design was developed in the field of air purification, to allow the growth of roots in contact with the air, favoring biofiltration. Thus, the main objective is to decontaminate the air through the rhizosphere of plants.
- The modular system in boxes is a vertical system formed by plastic modules. These panels provide the rigidity and impermeability of the entire system. Vegetation can be inserted before or after installation. This system requires an irrigation system and can be automated.

> This project has been carried out by a multidisciplinary group of Italian researchers in collaboration with small companies with experience in prefabricated modular construction, waste recycling, and textiles. The modules were designed, prototyped, and implemented through an environmental approach based on the use of recycled materials, high environmental performance, thermal, acoustic, and agronomic.

Through an inventory analysis, the two LWSs have been analysed. The data about the materials used in each system were collected from manufacturers and suppliers. A complete LCA includes five different stages: manufacturing, construction, use, maintenance, and end of life. In this study, only three phases have been considered: manufacturing, construction, and maintenance.

The use phase has been excluded. It is assumed that the capacities of these systems in terms of thermal insulation and temperature reduction are the same in all systems in which plants and substrates are present, with some differences that are not relevant. This statement is supported by Nyuk Hien Wong et al. (N. C. N. H. Wong et al., 2010), who studied 8 different vertical vegetation systems to evaluate their thermal impacts on system performance. Their results demonstrated the same thermal benefits in all system. These benefits minimize the demand for cooling and heating, and energy costs in buildings.

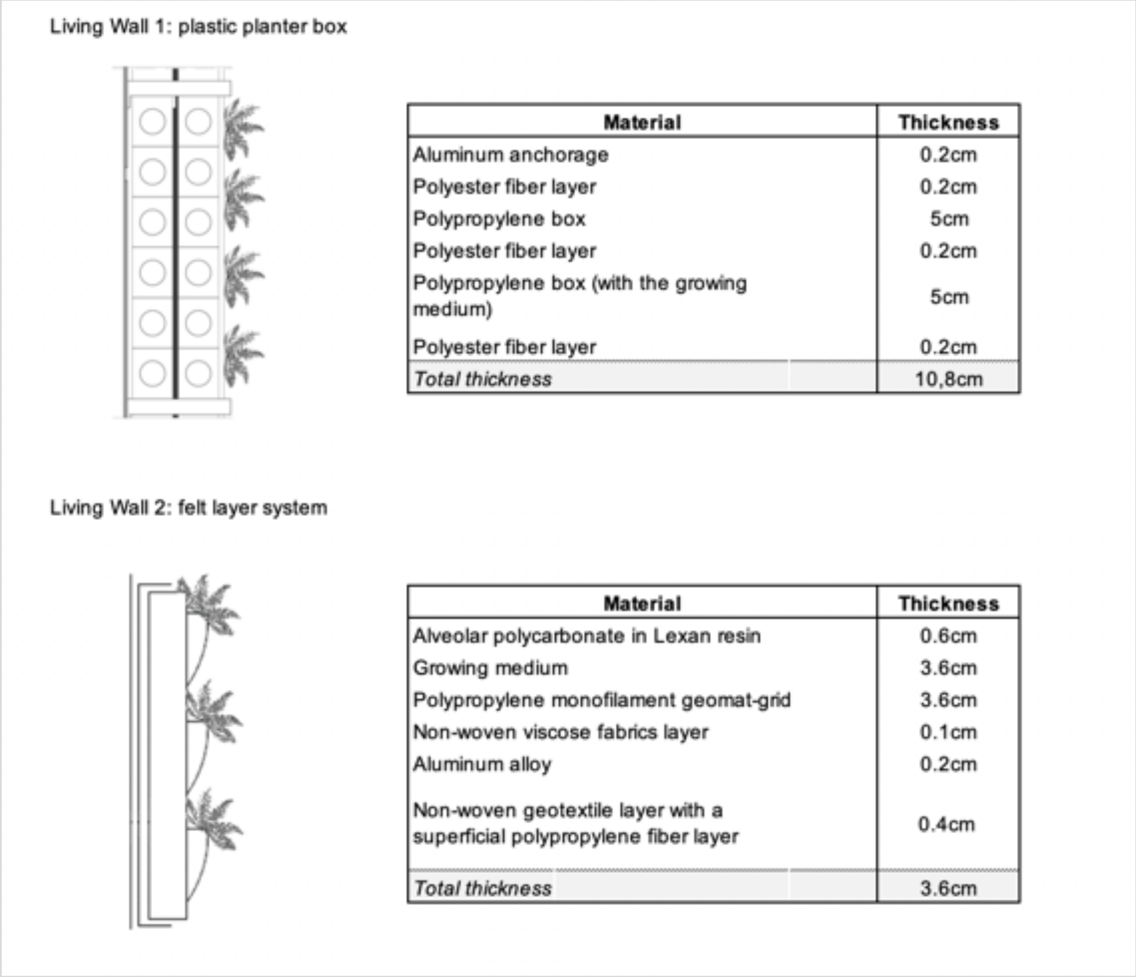
3.3.1 Inventory data collection

The data and details of each system were gathered by the use of Ecoinvent® Database v 3.5 (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2016), and also provided by the manufacturers. For this LCA, all the components of the two living wall systems selected were examined. The differences between the two systems came from the materials used and the way they are assembled. In the case of the LWS made of plastic, the system has only one three-dimensional structure for the plants and another that serves as an air chamber. The second LWS is made with felts, which involve several layers to root, waterproof, and support.

The data used for this inventory was collected from material data sheets and information obtained directly from manufacturers. All elaboration phases play important roles in LCA studies but, the inventory analysis is considered the most important (Ingrao et al., 2015). The final product has been studied to calculate the impacts related to its materials and processes. In this work, an inventory analysis was carried out by obtaining information on the production, construction and maintenance of the systems.

LWS is used as an external surface of buildings that provides a thermal insulation benefit that impacts on interior well-being. Modular LWSs are often made using a frame and a series of layers that act as a climatic barrier to insulate the interior and exterior of the building. The difference between the proportions of materials that impact the environmental load of the two systems comes from the layers involved (Fig.3).

In the case of the plastic modular system, the layers consist of a box made of that material which can be HDPE (High-Density Polyethylene), polypropylene and other recycled plastics, filled with potting soil. In the case of the modular felt system, it has several layers to root, waterproof, and support the substrate and plants.



Living Wall 1: plastic planter box

Material	Thickness
Aluminum anchorage	0.2cm
Polyester fiber layer	0.2cm
Polypropylene box	5cm
Polyester fiber layer	0.2cm
Polypropylene box (with the growing medium)	5cm
Polyester fiber layer	0.2cm
Total thickness	10,8cm

Living Wall 2: felt layer system

Material	Thickness
Alveolar polycarbonate in Lexan resin	0.6cm
Growing medium	3.6cm
Polypropylene monofilament geomat-grid	3.6cm
Non-woven viscose fabrics layer	0.1cm
Aluminum alloy	0.2cm
Non-woven geotextile layer with a superficial polypropylene fiber layer	0.4cm
Total thickness	3.6cm

Figure 3: Main components and thickness of the living wall systems studied

All the transportation distances used are to and from Madrid. For the LWS the majority of the materials are local; plants and substrate come from an area 40 km away from Madrid. The materials used in the LWS studied are an aluminum alloy, polypropylene monofilament, polypropylene fiber, growing medium, vegetal species biomass, felts and polyester. As for fertilizers, the following have been considered in the analysis 0.73 kg Nitrogen (N), 0.73 diphosphorus pentoxide (P_2O_5), and 0.73 potassium oxide K_2O.

The materials analyzed in each LWS are shown in tables 1 and 2. The raw materials, manufacturing energy use, and emissions associated with each of these materials were obtained from processes in the Ecoinvent® Database v 3.5 (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2016)

Table 1**:** Analysis of the components of the Living Wall System made with plastic planter boxes

Components	Material	Mass (kg)	Distances (Km)	Service life (years)
External finishing layer	Polyester	0.25	50	10
Bearing structure	Polypropylene boxes	1.34	80	10
Hydrophilic layer	Polyester	0.25	50	10
Growing medium	Coconut fibre, turf and hummus	4	40	10
Closing layer	Polyester	0.25	50	10
Hooking system	Aluminium	0.6	10	10
Vegetation layer	*Hedera spp* stems biomass	1.50	40	10

Table 2: Analysis of the components of the Living Wall System made with felt layers mass

Components	Material	Mass (kg)	Distance (km)	Service life (years)
External finishing layer	Polypropylene fibre and non-woven geotextile	0.53	80	10
Bearing structure	Aluminium alloy	3.9	10	10
Hydrophilic layer	Non-woven viscose fabrics	1.15	50	10
Growing medium containment layer	Polypropylene monofilament geomat-grid	2	50	10
Growing medium	50% of raw soil; 30% of SAP; 15% of coco-coir; 5% of peat moss.	2.1	40	10
Closing layer	Alveolar polycarbonate in Lexan resin	2	50	10
Vegetation layer	Lonicera n. stems biomass	1.66	40	10

3.4 Life Cycle Impact Assessment

The following impact categories were evaluated using the ILCD (International Reference Life Cycle Data System) midpoint method (European Commission, 2011), the LCIA method endorsed by the European Commission:

- Climate Change (CC, expressed as kg CO_2 eq.);
- Ozone Depletion (OD, expressed as kg CFC-11 eq.);
- Particulate Matter Formation (PM, expressed as kg $PM_{2.5}$ eq.);
- Human Toxicity-No Cancer Effect (HTnoc, expressed as CTUh);

- Human Toxicity-Cancer Effect (HTC, expressed as CTUh);
- Photochemical Ozone Formation (POF, expressed as kg NMVOC eq.);
- Terrestrial Acidification (TA, expressed as molc H+ eq.);
- Terrestrial Eutrophication (TE, expressed as molc N eq.);
- Freshwater Eutrophication (FE, expressed as kg P eq.);
- Marine Eutrophication (ME, expressed as kg N eq.);
- Freshwater Ecotoxicity (FEx, expressed as CTUe);
- Land Use (LU, expressed as kg C deficit);
- Water resource depletion (WU, expressed as m^3 water eq.);
- Mineral and Fossil Resource Depletion (MFRD, expressed as kg Sb eq.)

8. Results and discussion

a. Environmental impact of the LWS

The results show that in every impact category evaluated, the plastic based LWS is the one with the lowest environmental impact. The results show the highest impact of the systems in the manufacturing phase (Tables 4 and 5), and the use phase is the second with the highest impact. Table 3 shows the environmental impacts for the LWS made with plastic. The results compare each phase studied concerning the impact categories, and agree with the previous works [37], where the LWS based on plastic boxes has no major environmental impact. The phase that affects in a non-proportional way in the impact categories is the manufacturing phase.

In the manufacturing phase all impact categories influence in almost the same way, excluding water resource depletion, which represents only 0.80% while the rest of the categories influence 99% during the manufacturing process. The construction phase has a low influence during the study, with an average of 0.2% in all categories. The primary impact category for the use phase is water resource depletion, which represents 99.17% of the total, while the other categories have not an impact. The phase with the highest impact is the manufacturing phase, which is focused on analyzing the materials used for making the system. This explains the environmental impact contribution of the used materials.

Table 3: Environmental impacts for 1m^2 of the plastic based LWS

Impact category	Unit of measure	Manufacturing	Construction	Maintenance
Climate change	kg CO_2 eq	99.73%	0.26%	0.00%
Ozone depletion	kg CFC-11 eq	99.83%	0.16%	0.00%
Human toxicity, non-cancer effects	CTUh	99.99%	0.01%	0.00%
Human toxicity, cancer effects	CTUh	99.99%	0.01%	0.00%
Particulate matter	kg PM2.5 eq	99.87%	0.13%	0.00%
Photochemical ozone formation	kg NMVOC eq	99.86%	0.13%	0.00%
Acidification	molc H+ eq	99.76%	0.24%	0.00%
Terrestrial eutrophication	molc N eq	99.81%	0.19%	0.00%
Freshwater eutrophication	kg P eq	99.99%	0.00%	0.00%
Marine eutrophication	kg N eq	99.83%	0.17%	0.00%
Freshwater ecotoxicity	CTUe	99.99%	0.06%	0.00%
Land use	kg C deficit	97.13%	0.09%	0.00%
Water resource depletion	m3 water eq	0.80%	0.03%	99.17%
Mineral, fossil & ren resource depletion	kg Sb eq	99.99%	0.01%	0.00%

Table 4 shows the environmental impacts for the system based on felts for the three phases considered. It is important to denote that the results, in this case, do not include any data related to the use of electrical energy for the construction of the system since it is done manually. The results are particularly higher to the system made in plastic. The impact generated by the system is concentrated in the manufacturing and use phase, in which it varies considerably according to the impact category.

Table 4: Environmental impacts for a 1m^2 of the felt-based LWS

Impact category	Unit of measure	Manufacturing	Construction	Maintenance
Climate change	kg CO_2 eq	20.74%	0.00%	79.26%
Ozone depletion	kg CFC-11 eq	26.73%	0.00%	73.26%
Human toxicity, non-cancer effects	CTUh	44.60%	0.00%	55.40%
Human toxicity, cancer effects	CTUh	48.06%	0.00%	51.94%
Particulate matter	kg PM2.5 eq	35.14%	0.00%	64.86%
Photochemical ozone formation	kg NMVOC eq	35.27%	0.00%	64.72%
Acidification	molc H+ eq	23.46%	0.00%	76.53%
Terrestrial eutrophication	molc N eq	13.99%	0.00%	86.00%
Freshwater eutrophication	kg P eq	35.90%	0.00%	64.09%
Marine eutrophication	kg N eq	16.68%	0.00%	83.32%
Freshwater ecotoxicity	CTUe	60.04%	0.00%	39.95%
Land use	kg C deficit	5.20%	0.00%	94.79%
Water resource depletion	m3 water eq	4.31%	0.00%	95.69%
Mineral, fossil & ren resource depletion	kg Sb eq	92.52%	0.00%	7.48%

During the production phase, related to the use of materials, the greatest impact is given by mineral, fossil and renewable resource depletion with 92.52%, followed by freshwater ecotoxicity 60.04% and human toxicity cancer effects 48.06%. On the contrary, during the use phase, the categories with greater impact were water resource depletion 95.69%, land use 94.79% and Ionizing radiation 90.33%. The rest of categories have an impact proportional to the previously mentioned. These results reveal the environmental impact that this system has related to the materials used and during the useful life considered as 10 years.

For both systems, the LCA shows that the highest environmental impacts are associated with the manufacturing and use phase, that accounts for more than 80% of the total environmental impact in almost all the categories analysed. It is particularly elevated for water resource depletion, land use, and mineral, fossil, and renewable resource depletion. For these categories, the manufacturing phase accounts for 90-95% of the total environmental impacts.

The main difference between the two LWS is mainly due to the materials involved in the anchorage and supporting systems. Figure 4 and 5 show the influence of the materials for the anchorage and supporting systems on the evaluated impact categories. Because of this, the LWS plastic-based has the lowest environmental impact. In the case of the living wall system made with felt layers, the fertilization has an impact of 99.17% on water resource depletion, due to the necessity of doing annual chemical fertilizing.

For the impact categories related to toxicity and depletion of water resources, the plastic-based early warning system has a double impact than the felt-based early warning system (Fig.4). The results showed the environmental impact of two materials, mainly polypropylene and aluminium layers. In this case, a solution could be to avoid the use of aluminum or to use recycled aluminum, since the environmental impact can be reduced.

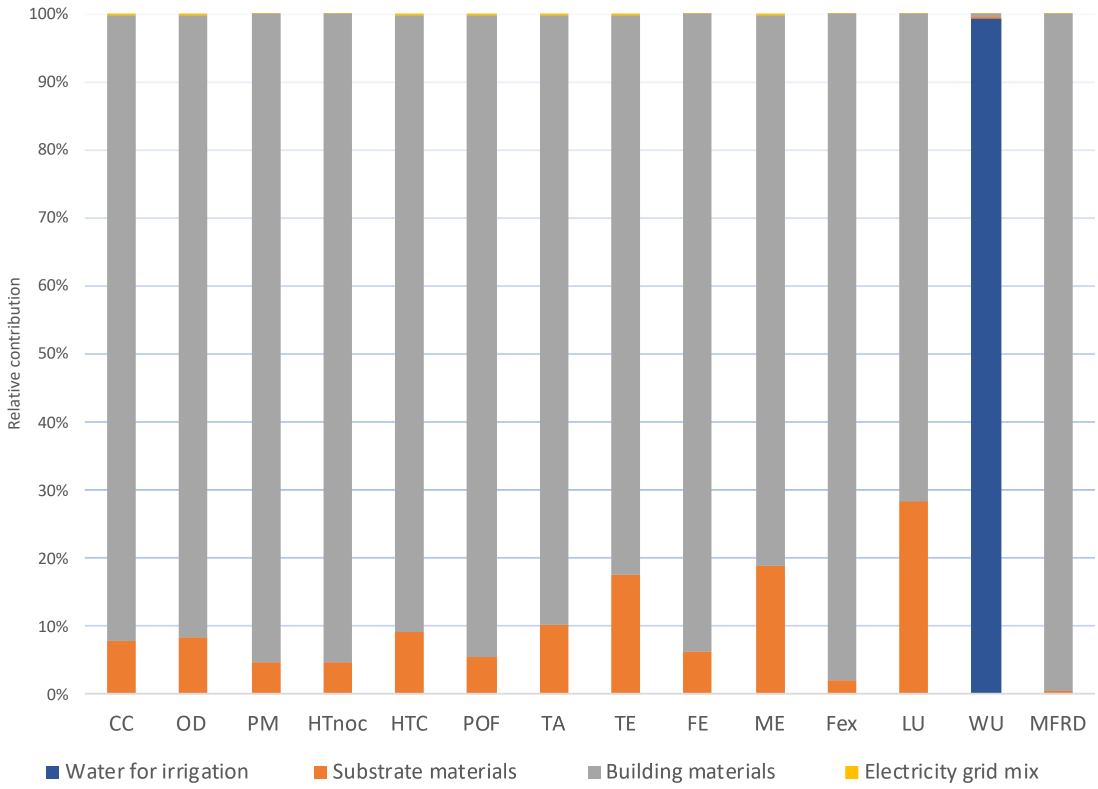


Figure 4: Environmental hotspots for the plastic-based LWS

The peat mixture used in the substrate has an impact on the category of water resource depletion, this is because peat is the result of the accumulation of dead organic matter from leaves, stems, and roots partially decomposed from different mosses and plants that have been concentrated in a water-saturated environment in the absence of oxygen. The plastic-based LWS is a lightweight one due to the reduced number of materials, which means less energy consumption and less environmental impact. Thus, it could be used as a building element in buildings, in order to reduce energy consumption and energy incorporation.

Unlike this, the living wall system made with felt layers have the highest environmental impact in almost all the categories. This is due to the environmental impact coming from the use of aluminium for supporting the system and the use of fertilizers during the use phase of the system. Ottelé et al., (Ottelé et al., 2011) have investigated the environmental impact of four materials commonly used for the vertical support of living walls systems. Results show that aluminium can be up to 10 times more polluting than other materials such as plastics, wood, and coated steel.

Both materials mentioned lead to increment the environmental burden profile. Furthermore, from figure 5, it can be seen that the LWS felt-based is the one without impacts in the construction phase because there are not electric energy consumptions associated. In this case, the highest environmental impacts in the use phase are due to the use of nitrogen fertilizer.

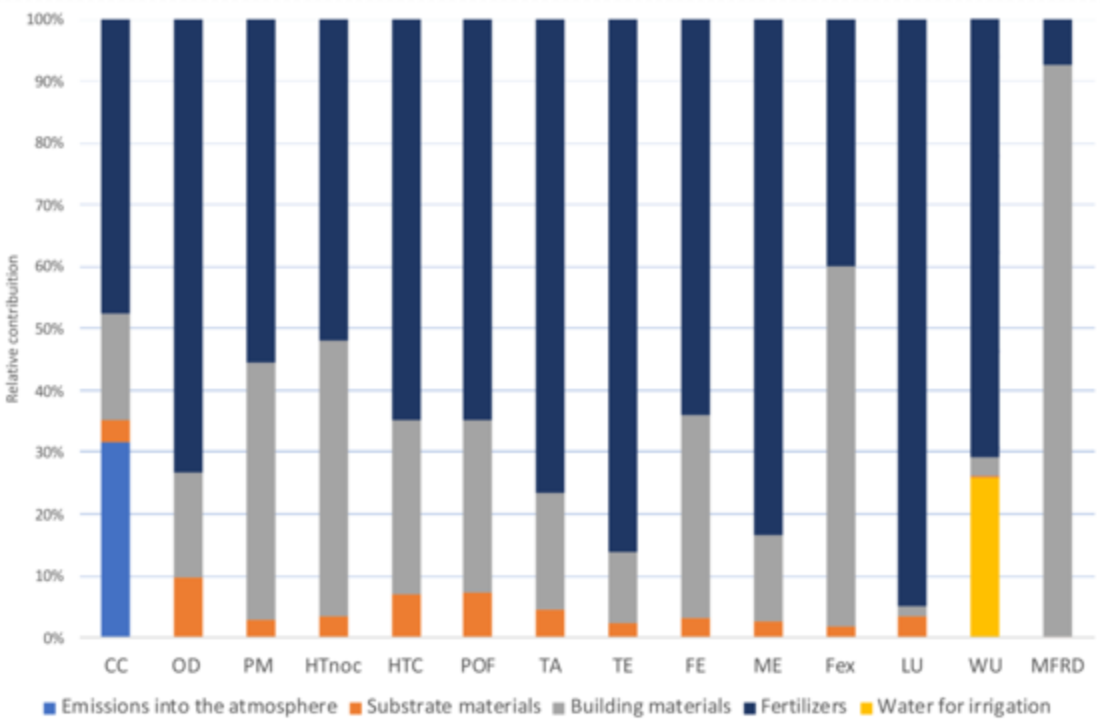


Figure 5: Environmental hotspots for the felt-based LWS

The results obtained show the impact of the systems due to the materials used. This impact could be reduced by a sustainable choice of materials. Specifically, the profile with the highest impact is the LWS made with felt layers, due to the support system around 40% and the fertilizers around 50% of the total impact.

In general, both systems can reduce impact by selecting a more sustainable material for the support structure and other components such as the type of substrate and fertilization. In both cases, reductions can be achieved with small changes. The impact categories analysed show similar results, with some notable differences due mainly to the use of materials such as aluminium and fertilization. For instance, for felt-based LWS, the most impactful categories are freshwater eco-toxicity, land use and climate change, as the substrate needs to be fertilized ten times in a 10-year lifespan. For the mineral, fossil and renewable resource depletion, both LWS have a high impact. The same trend is perceptible for the freshwater eco-toxicity.

The relative comparison between the two systems studied is reported in **Fig.6.** For each evaluated impact category, the LWS with the greatest impact is set equal to 100% while the second one is proportionally called. LWS made with felt layers demonstrates the greatest environmental burden for all impact categories assessed, except for the depletion of water resources. This is consistent with the study of Ottelè et al., (Ottelé et al., 2011), which conducted a life cycle analysis comparing conventional brick solutions with continuous and modular plant facades, including systems made of plastic and felt. Great differences were found in the impact categories studied for each alternative plant façade. In that case, the results were influenced by the type of material used for each system.

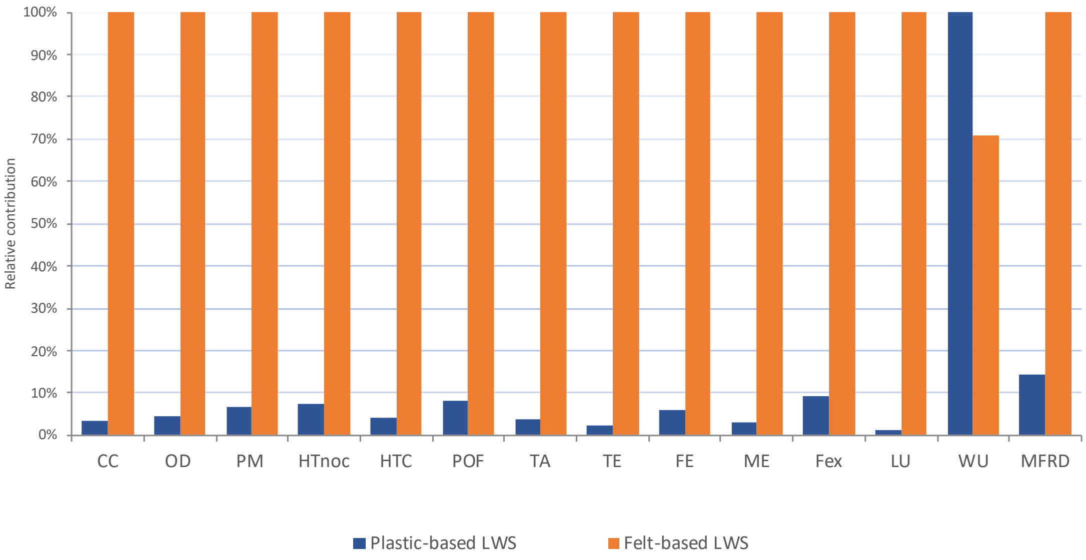


Figure 6: Comparison between the two LWS

Among the evaluated impact categories, water resource depletion is the only one for which the LWS made by plastic shows a higher impact, this is linked to the irrigation needs of the system. For the other categories, it is clear that the LWS based on felts is the one with the highest environmental impact due to the composition of the materials used and the fertilization. However, despite their environmental impact, the two LWS can counteract them through its reduction in energy consumption and temperatures.

Other authors (Altan et al., n.d.; Manso et al., 2018; Ottelé et al., 2011) have reached similar results considering the entire life cycle of the systems and studying vegetable façade systems different from ours. It has been demonstrated that, even if we do not consider the whole life cycle and exclude some phases, the results agree that the performance of the systems is the same whenever there is the presence of substrate and vegetation. Thus, the environmental impact will depend on the materials used for construction, and the substances used during maintenance according to the type of substrate. Besides, they argue that from the results of the LCA, it is possible to make improvements in the systems, which in some cases mean that the benefit is twice as great as the impact they can generate. This benefit is related to the temperature reduction potential.

4.2 Life Cycle Impact Assessment

This section aims to weight the results of the entire analysis. The most impacting phases are shown for each category in Figure 7. The data represents the impact caused for 1m^2 of LWS.

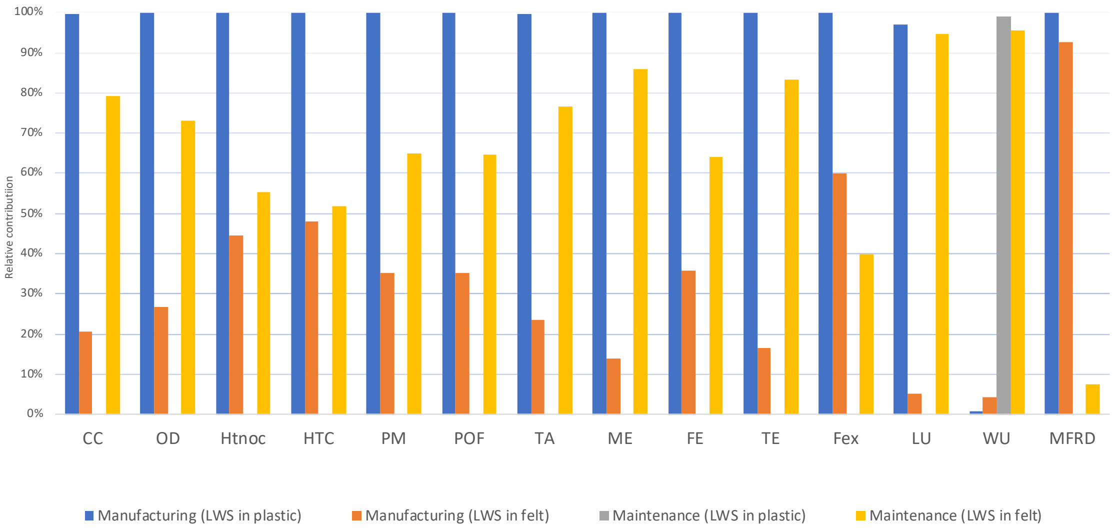


Figure 7: Impact categories per LWS studied. A comparison based upon LCA results.

The phase with the greatest weight in the process is the manufacturing phase, linked to the materials and assembly processes. The results were analyzed by comparing the systems. The impact of LWS made of plastic during manufacturing is notable due to the electricity consumption and the use of aluminum for the anchoring system. In the case of the climate change impact category, the difference is almost 80%. While the felt-based LWS has its 100% during the maintenance phase, due to the fertilizers used during its life cycle.

4.3 Limitations and future perspectives

In this study, it is assumed that the two living wall systems have the same thermal and environmental performances and the behavior of a plant façades during their life cycle is out of the system boundaries of this LCA study. On the one hand, as there are no monitoring data for the systems studied, there is no possibility of verifying their performance. In the same line of ideas, today there are no tools in which it is possible to simulate the reduction of energy consumption and temperatures to obtain a value. Also, the benefits of plant façades go far beyond the effect of thermal insulation; fundamental effects such as evapotranspiration, shade, acoustic insulation and the fixation of dust particles would be out of the study.

This study analyzed the living wall life cycle impact only in the phase of manufacturing, construction, and maintenance, to identify how the selection of materials affects, which is associated with an important series of environmental benefits. Unlike other studies (Altan et al., n.d.; Ingrao et al., 2016; Kosareo and Ries, 2007; Ottelé et al., 2011) in which these technologies and their materials are studied to identify how they affect their energy performance. These parameters should be explored in future comprehensive studies. However, even if the use phase is not included in the system boundary the achieved results can be useful. In fact, the study, quantifying the environmental impact and identifying the environmental hotspots (i.e., the process mainly responsible of the environmental impact) of the two LWS, is the starting point for a subsequent optimization.

9. Conclusions

This study helps designers and technology developers to understand the potential and the environmental concerns associated to LWS. Also, it is a starting point for identifying the best option on the market by understanding the impacts of the various lifecycle phases through the LCA approach.

The materials used to build an LWS have a significant environmental impact when installed in a building. From the incorporated and operational energy of a building, the role of the materials is fundamental, as it can be reduced depending on the proper selection of the materials.
Life cycle analysis of living wall systems considers several aspects, including integration into the building envelope, the selection of materials with low environmental impact and the consideration of other impacts, which can contribute to the correct decision when incorporating it as a sustainable technical solution.

The results of the LCA performed highlight the environmental impact of two LWS: a modular system made with solid plastic boxes and pre-cultivated vegetation inserted in cavities, and a system based on layers of felt with pre-cultivated vegetation inserted in pockets, both with aluminium anchoring system.

From the research during the three selected phases, it is clear that each LWS has strengths and weaknesses:

- plastic based LWS shows lower impact during the manufacturing, construction, and maintenance phases.
- The environmental impact of plastic-based LWS shows a lower impact respect to the felt-based LWS due to the low mass of materials used. This impact could be reduced further reduced by replacing materials like polyester with other recycled textiles and recycled aluminium for the system anchors.
- The felt-based LWS has an aluminium support that deeply affects the environmental load. With this regard, to improve the system towards a more environmentally sustainable one the design and research activities should focus on the identification of less impacting materials. Besides this, the use of fertilizers during the life cycle involves a significant impact, a less impacting option would be the use of an organic fertilisers or leguminous crops.

Greening the building envelope with LWS taking into account the materials involved is a key step in selecting a solution that leads to an environmentally friendly performance. This study highlighted that the use of recycled materials, organic substrates, and low environmental impact materials are part of the sustainable strategies for the design of these systems. These should be considered as key strategies for the environment, sustainability, and low energy consumption of LWS, throughout their life cycles.

Acknowledgments

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Análisis del impacto de los sistemas modulares de jardinería vertical en la reducción de temperaturas

El efecto isla de calor urbana es una de las consecuencias del cambio climático más evidente en los contextos urbanos, ya que contribuye al aumento de las temperaturas del aire y de las superficies de las ciudades. Dicho aumento depende fundamentalmente de la configuración del espacio (Choi et al., 2016), los materiales (Fahed et al., 2020), y las condiciones climáticas locales (Morris et al., 2017), lo que afecta proporcionalmente al consumo de energía en los edificios (Zhang et al., 2019), intensifica la concentración de contaminantes (Charoenkit and Yiemwattana, 2016b), y reduce el confort térmico en los espacios públicos (Taleghani, 2018a).

Este fenómeno ha despertado mucho interés en el estudio del confort térmico en el espacio urbano, principalmente debido a los riesgos para la salud. La correlación entre el confort térmico y las tasas de mortalidad en una ciudad ha sido demostrada en múltiples estudios (e.g. Price et al., 2015; Shafiee et al., 2020; Zhang et al., 2010). Un ejemplo claro han sido las olas de calor sufridas durante el verano de 2022, en las que, según la Organización Mundial de la Salud (OMS), dejaron 4000 muertos en España y 15.000 en el conjunto de Europa.

El aumento de las temperaturas superficiales ocurre a lo largo del año de diferentes maneras y a diferentes niveles. Esto se debe principalmente al estrés térmico, la formación de ozono, y el aumento del consumo de energía de los edificios por el aire acondicionado (Chun and Guldmann, 2018). Por ejemplo, se ha demostrado que los espacios verdes, en particular, los árboles, disminuyen las temperaturas en verano, reduciendo así el gasto en refrigeración en los edificios, al mismo tiempo que, durante el invierno, protegen del aire frío y el viento, aumentando así la temperatura ambiente y, por tanto, reduciendo el gasto en calefacción (Klemm et al., 2015). Sin embargo, este efecto depende de la interacción de diversas variables relacionadas sobre todo con la percepción humana.

Si consideramos que el confort térmico puede definirse desde el aspecto psicológico (expresión mental de satisfacción con las condiciones térmicas del entorno); el aspecto termofisiológico (contribución de las reacciones biológicas y los receptores térmicos de la piel al entorno); y el aspecto energético (flujo de luz hacia y desde el cuerpo humano), sabremos reconocer que la percepción de confort podrá cambiar según los materiales y superficies que conformen el espacio urbano.

Figura 15: Interacción del cuerpo humano y el espacio urbano

Fuente: Reelaboración a partir de (Cherunova et al., 2020; Fan et al., 2021)

La contribución de la vegetación al balance térmico de los espacios públicos ha sido estudiado en parques urbanos, jardines, techos verdes y jardines verticales (Leuzinger et al., 2010; Taleghani, 2018a; Vuckovic et al., 2017; Xing et al., 2017). En el caso de los jardines verticales, este efecto termorregulador se debe principalmente a dos mecanismos: el sombreado producido por la vegetación, que reduce la radiación solar incidente sobre el edificio; y el efecto refrigerante asociado al calor absorbido por las plantas y el sustrato que se disipa a través de la pérdida de agua por transpiración y evaporación (Charoenkit and Yiemwattana, 2017).

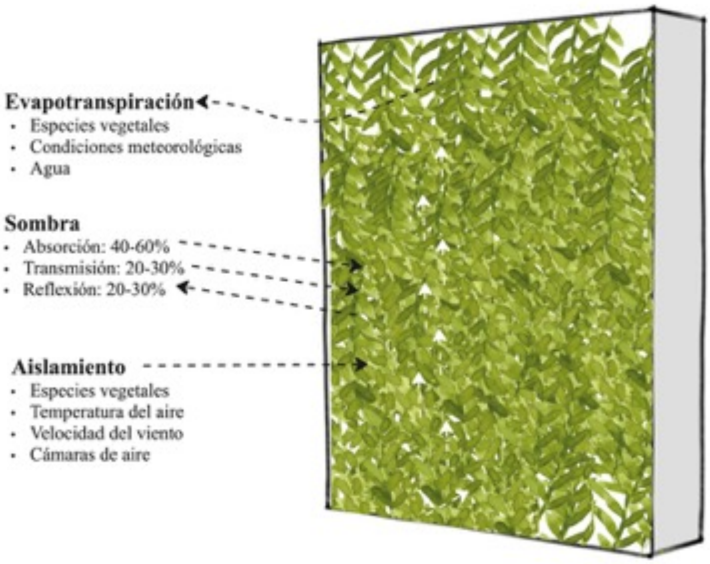


Figura 16: Interacción de un jardín vertical con el espacio urbano

Fuente: Reelaboración a partir de (Koch et al., 2020)

El efecto combinado de la sombra y la evapotranspiración -efecto termorregulador- puede reducir la temperatura del aire entre 1 y 3 ºC, según las condiciones climáticas (Wong et al., 2016). Este efecto ha sido estudiado para estimar el efecto global en ambientes interiores y exteriores en climas subtropicales húmedos, y los resultados demuestran la capacidad de reducir hasta 2.7 ºC la temperatura del aire en verano, debido a (i) la absorción de la radiación solar, (ii) la transferencia de calor por convección entre las hojas de las plantas y el aire, (iii) la transpiración de las hojas de las plantas; (iv) y los efectos térmicos de la fotosíntesis (Tan et al., 2014b).

Este mismo tipo de estudio ha sido realizado en invierno (Castiglia Feitosa and Wilkinson, 2018; Jim, 2015a), y los resultados muestran una variación de la temperatura del aire principalmente en días soleados de entre 3 y 4 ºC en jardines orientados al este, y entre 1 y 2 ºC en aquellos orientados al norte y oeste. Las conclusiones demuestran la influencia de la orientación en el invierno, la cual se ve principalmente afectada por la irradiancia, que debe ser mayor a 500 W/m^2 para lograr un calentamiento notable de la superficie y conseguir aumentar la temperatura. Además del clima húmedo subtropical, también se han desarrollado algunos estudios en clima continental, demostrando reducciones de entre 2 y 5 ºC (de Jesus et al., 2017; Susorova et al., 2014); y en clima oceánico, demostrando reducciones de hasta 3 ºC (Cameron et al., 2014).

Los resultados expuestos hasta ahora han sido realizados sobre jardines verticales construidos a partir de plantas trepadoras o sistemas continuos. Cuando se analizan los resultados de estudios realizados sobre sistemas modulares de jardinería vertical -tipología utilizada para el desarrollo de esta tesis doctoral-, los efectos de reducción de temperaturas son sustancialmente mayores, alcanzando desde 10.1 ºC (Pan and Chu, 2015) hasta 14 ºC (Cheng et al., 2010) en climas húmedos subtropicales. El estudio de la influencia de la vegetación en el microclima adyacente, requiere atender a la orientación, al tipo de sistema, y a la distancia a la que se recogen los datos (Razzaghmanesh and Razzaghmanesh, 2017a).

Los resultados comentados en este apartado han sido identificados en la revisión bibliográfica de esta tesis doctoral. Entre las conclusiones alcanzadas se encuentran dos especialmente relevantes: (i) la mayoría de los estudios analizan la reducción de temperaturas superficiales gracias a la vegetación y su impacto en el interior del edificio; (ii) la mayoría de los estudios realizados para evaluar el impacto de la vegetación en la reducción de la temperatura del aire, han sido desarrollados sobre prototipos y no a escala real; (iii) son muy escasos los estudios realizados en clima mediterráneo.

Estos aspectos dieron lugar a la investigación publicada bajo el artículo científico: Valentina Oquendo-Di Cosola, Francesca Olivieri, Lorenzo Olivieri, Luis Ruiz-García. *Assessment of the impact of green walls on urban thermal comfort in a Mediterranean climate*. Enviado a la revista Energy and Buildings Q1 (JCR), en la que se planteó estudiar la distancia como variable determinante para evaluar el impacto de la vegetación en la reducción de temperaturas y el comportamiento a escala real a través de las siguientes preguntas:

- ¿Puede un jardín vertical mejorar el microclima urbano a nivel peatonal en clima mediterráneo?
- ¿Es la distancia una variable que afecta el impacto en la reducción de temperaturas a nivel peatonal?

El análisis se realizó a partir de datos reales obtenidos monitorizando las fachadas sur y oeste del Centro de Innovación en Tecnología para el Desarrollo Humano (itdUPM), descritas en apartados anteriores. Los resultados pretenden cuantificar el impacto del jardín vertical en el microclima urbano y, en concreto, la variación de temperaturas y humedad relativa a nivel peatonal.

Figura 17: Fachadas monitorizadas en el edificio itdUPM

Para analizar el comportamiento de las fachadas, se instaló un sistema de monitorización distribuido en tiempo real. Dicho sistema se basa en un conjunto de ocho registradores de datos HOBO MX2301 con sondas internas de temperatura y humedad relativa, con una precisión de temperatura de ±0,25 °C de -40 a 0 °C; ±0.2 °C de 0 a 70 °C; y ±0.25 °C de 70 a 100 °C, y una precisión de humedad relativa de ±2.5% de 10% a 90% (típica) hasta un máximo de ±3.5% incluyendo histéresis a 25 °C; por debajo de 10% HR y por encima de 90% HR ±5%.

Además, se instalaron dos piranómetros, series SP-100 y SP-200 de Sensovat, en ambas fachadas, con el objetivo de medir la radiación solar incidente en el plano vertical. Por último, se instaló una estación meteorológica en las proximidades de la fachada para recoger los parámetros climáticos del lugar (HR%, temperatura del aire, irradiancia, velocidad y dirección del viento, y precipitaciones).

La base de datos utilizada para el desarrollo del estudio va desde diciembre 2020 hasta agosto 2021. El conjunto de datos comprende más de 50.000 muestras con un período de muestreo de 10 minutos. Las mediciones de la temperatura del aire y la humedad relativa adyacente al jardín vertical se tomaron en cuatro puntos situados a intervalos de 0.25 m hasta 1.00m del jardín vertical (i.e. a 0.25, 0.5, 0.75 y 1m, tal y como se muestra en la Figura 18).

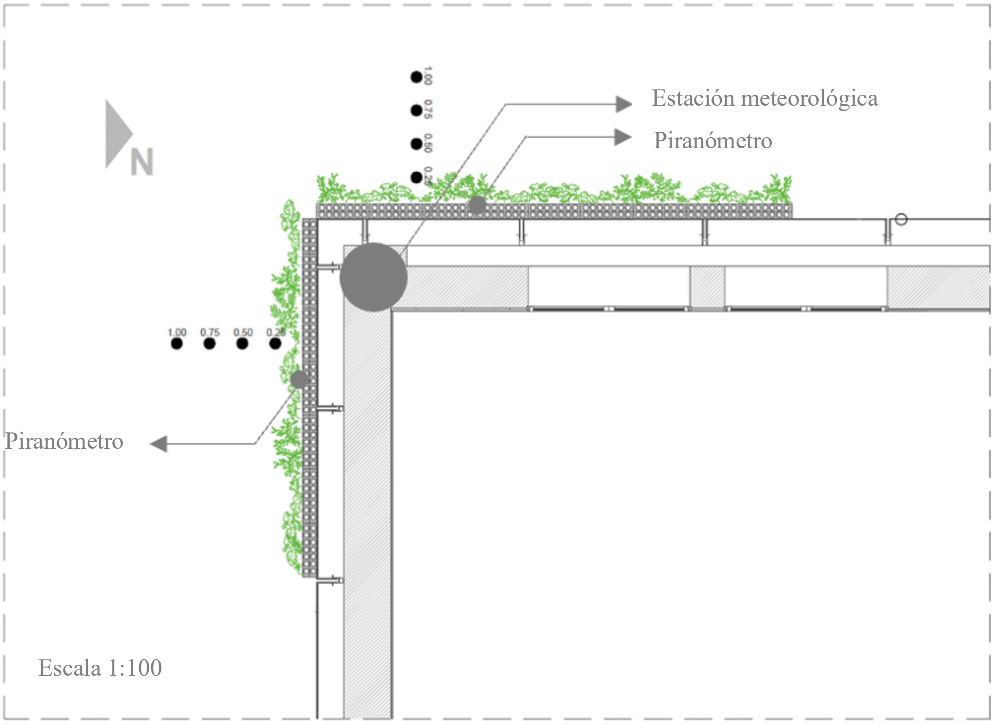


Figura 18: Posición de los sensores en las fachadas monitorizadas

Para el desarrollo del estudio se realizó un análisis estadístico de la base de datos a partir de cuatro pasos:

- ***Análisis estadístico descriptivo***

  Con la finalidad de caracterizar el entorno inmediato del jardín vertical e identificar anomalías en el registro, se realizó un análisis estadístico de la base de datos. Dicha base de datos está compuesta por información sobre la temperatura del aire y la humedad relativa registradas a las distintas distancias en las que se encuentran los sensores (0.25, 0.50, 0.75 y 1.00m); y la irradiancia en el plano vertical registrada por los piranómetros instalados en cada fachada. En la base de datos se distinguen dos series según la estación: invierno (89 días de toma de datos, entre el 1 de diciembre de 2020 y el 28 de febrero de 2021); y verano (91 días entre el 1 de junio de 2021 y el 31 de agosto de 2021).

  El análisis de la base de datos se realizó según las variables mencionadas:

- *Datos de temperatura*: el estudio cuenta con una base de 40.641 datos para la fachada sur y 54.216 datos para la fachada oeste. La diferencia de datos en la fachada sur tiene que ver con un error de registro en el sensor instalado a 0.75m de la fachada. En ambos casos la temperatura mínima es de -12 ºC, la máxima de 46 ºC, con una media de 20 – 21 ºC. Estos datos cuentan con un coeficiente de variación del 58%, lo que demuestra que ambas fachadas tienen un patrón de registro de temperaturas similar a pesar de la orientación.

En invierno, ambas fachadas registraron una media de 9 ºC, mientras que en verano la distribución de la temperatura muestra una combinación de dos distribuciones normales, con medias de 20 ºC y 35 ºC para la orientada al oeste, y 20 ºC y 36 ºC para la orientada al sur.

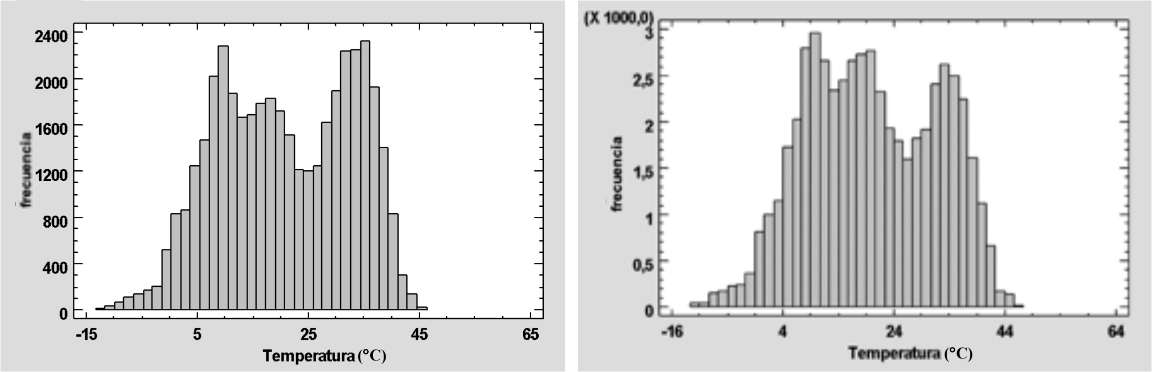


Figura 19: Histograma de temperatura de la fachada sur (a) y oeste (b)

- *Datos de humedad relativa*: el conjunto de datos de humedad relativa cuenta con una base de 46.143 datos para la fachada sur y 54.216 datos para la fachada oeste. Al igual que en el caso de los datos de temperatura, el número de datos de la fachada sur se ve afectado por un error de funcionamiento del sensor. En ambas fachadas la media de humedad relativa se sitúa entre 54 – 55%, con un coeficiente de variación de en torno al 43%. Durante el verano se registraron valores mínimos de 8% y durante el invierno máximas de 100%.

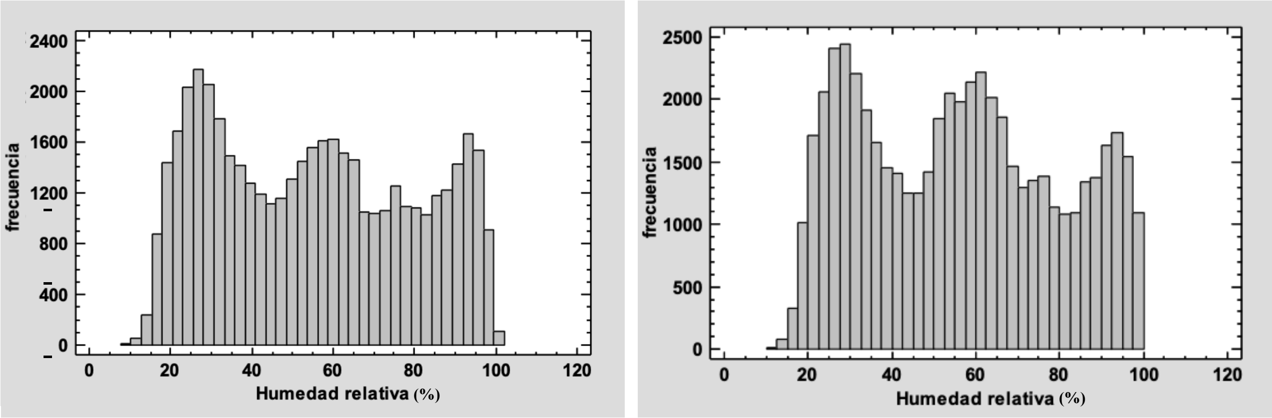
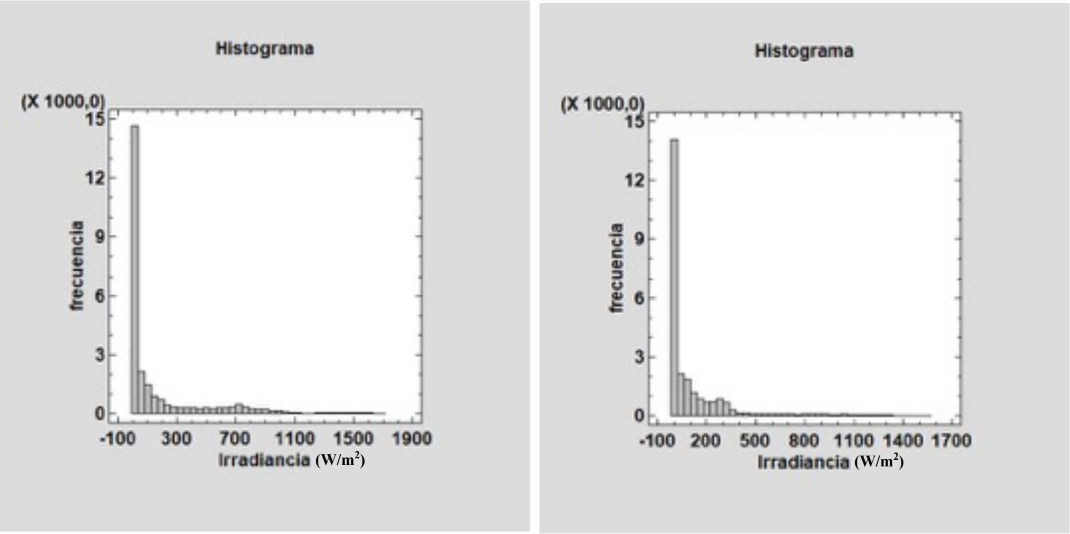


Figura 20: Histograma de humedad relativa de la fachada sur (a) y oeste (b)

- *Datos de irradiancia*: el estudio cuenta con una base de datos de irradiancia durante invierno y verano de 25.967 datos para la fachada sur y 25.967 datos para la fachada oeste. La irradiancia media oscila entre 179 – 339 W/m^2, con un coeficiente de variación entre 180 – 194%. La variación de los datos es mucho mayor que en el caso de la temperatura y la humedad relativa. Existe una diferencia significativa en los valores de irradiancia media y máxima entre las dos fachadas debido a la orientación, ya que la fachada sur recibe más radiación directa del sol, por lo que muestra una máxima y medias mayores.



(a) (b)

Figura 21: Histograma de irradiancia de la fachada sur (a) y oeste (b)

Las conclusiones de este primer análisis apuntan a que los jardines verticales estudiados se encuentran bajo condiciones climáticas normales de un clima mediterráneo continentalizado (Csa) (Kottek et al., 2006), con temperaturas medias en verano de 29 ºC e invierno de 8 ºC. En algunos casos la base de datos utilizada en este estudio alcanza valores inusualmente bajos debido a la presencia de la borrasca Filomena que afectó a España entre el 6 y 11 de enero de 2021.

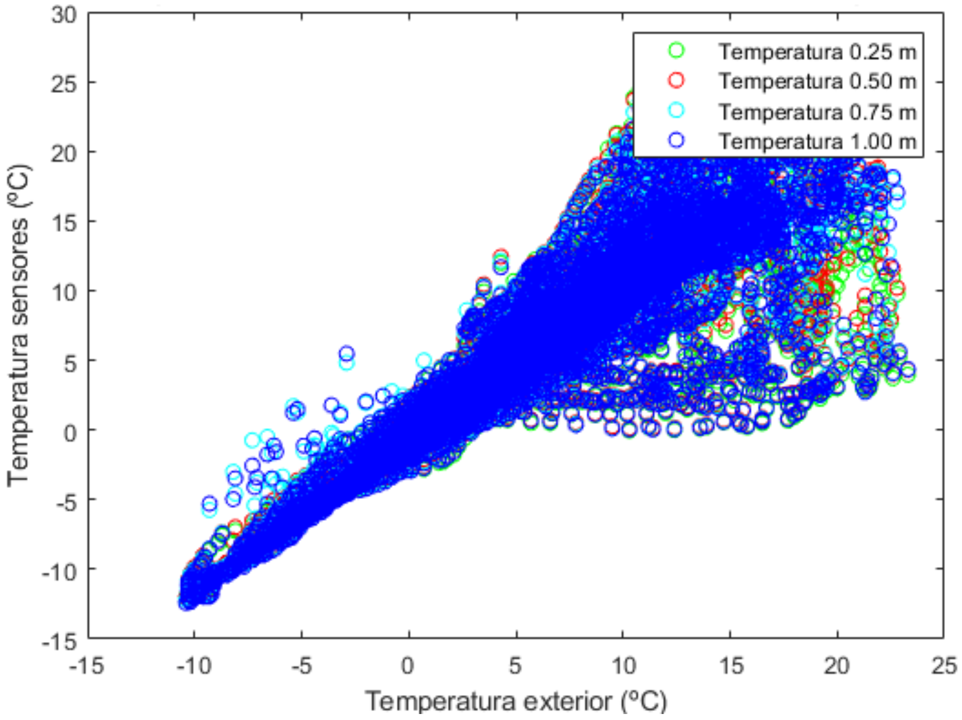
- ***Correlaciones entre las temperaturas de los sensores y otras variables***

  El segundo paso del análisis ha sido estudiar el grado de relación entre la temperatura registrada por los cuatro sensores (a distancias de 0.25, 0.5, 0.75 y 1.00 m) y otras variables ambientales como la temperatura del aire registrada por la estación meteorológica, la humedad relativa y la irradiancia, durante las estaciones de invierno y verano. El objetivo es identificar si estas variables están relacionadas linealmente, es decir, si cambian juntas a un ritmo constante, o si lo hacen mediante cualquier otra función matemática.

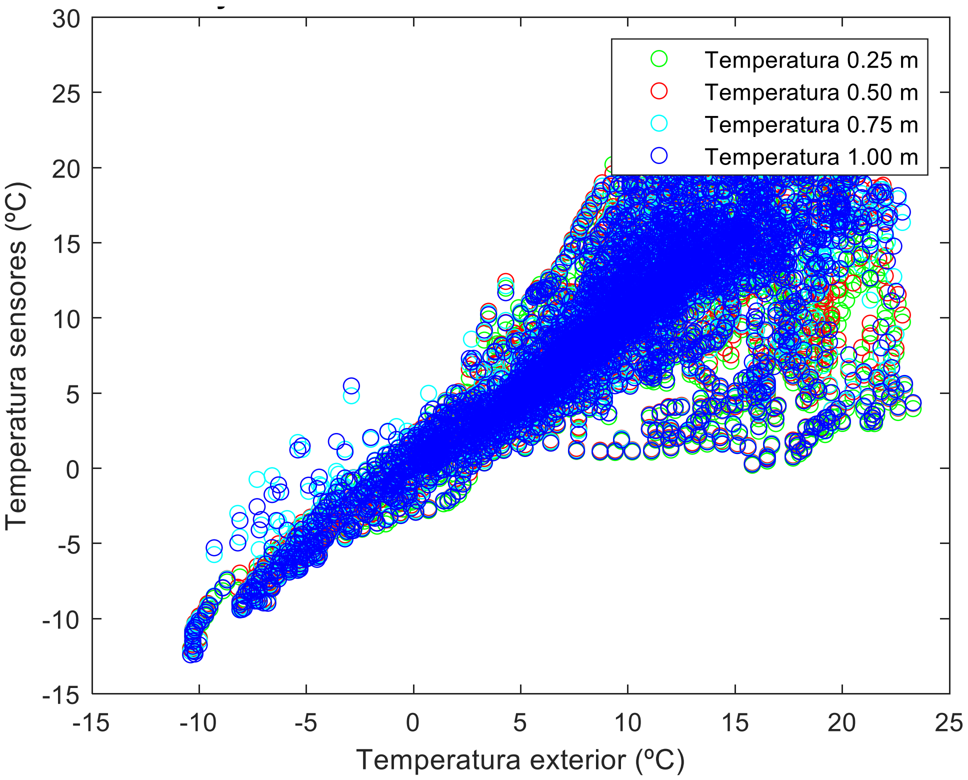
La muestra ha sido analizada a partir de dos series de datos: una que considera todos los datos registrados (día y noche), y otra que toma en cuenta sólo los datos registrados cuando la irradiancia supera los 0 W/m^2 (es decir, durante el día). La finalidad de esta distinción es estudiar la variabilidad de la temperatura y la humedad relativa según la irradiancia.

Esta es una metodología utilizada para describir relaciones sencillas sin hacer afirmaciones sobre causa y efecto. El coeficiente de correlación (R^2), cuantifica la relación entre ambas variables, siendo 1 el valor máximo que comprueba la significación estadística de la correlación. A continuación, se explican las correlaciones realizadas y sus principales conclusiones:

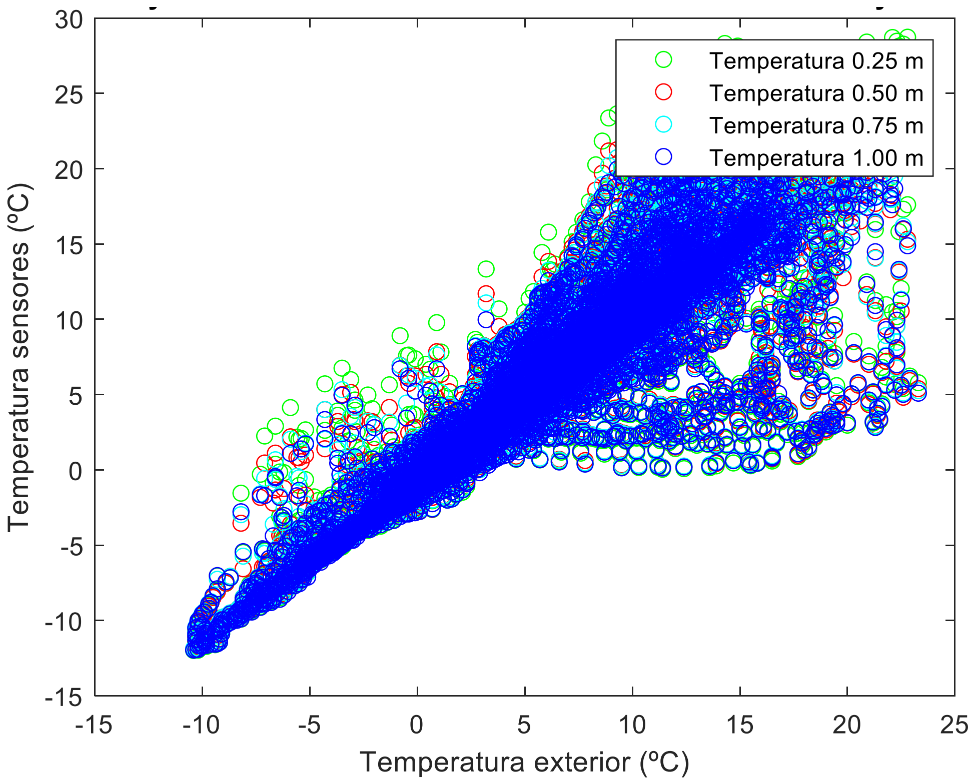
- *Correlación entre la temperatura del aire y la temperatura de los sensores:* los resultados mostraron una correlación positiva entre la temperatura del aire y la temperatura del sensor a todas las distancias, demostrado por el valor de R^2 superior a 0.88 en todos los casos, y en muchos de ellos con R^2 superiores 0.99 (tabla 3 – 6). Analizando los datos del verano, principalmente en los datos diurnos (figura 23), se observa un incremento en la correlación a medida que aumenta la distancia, lo cual puede deberse a la evapotranspiración de las plantas sobre el espacio que le circunda.



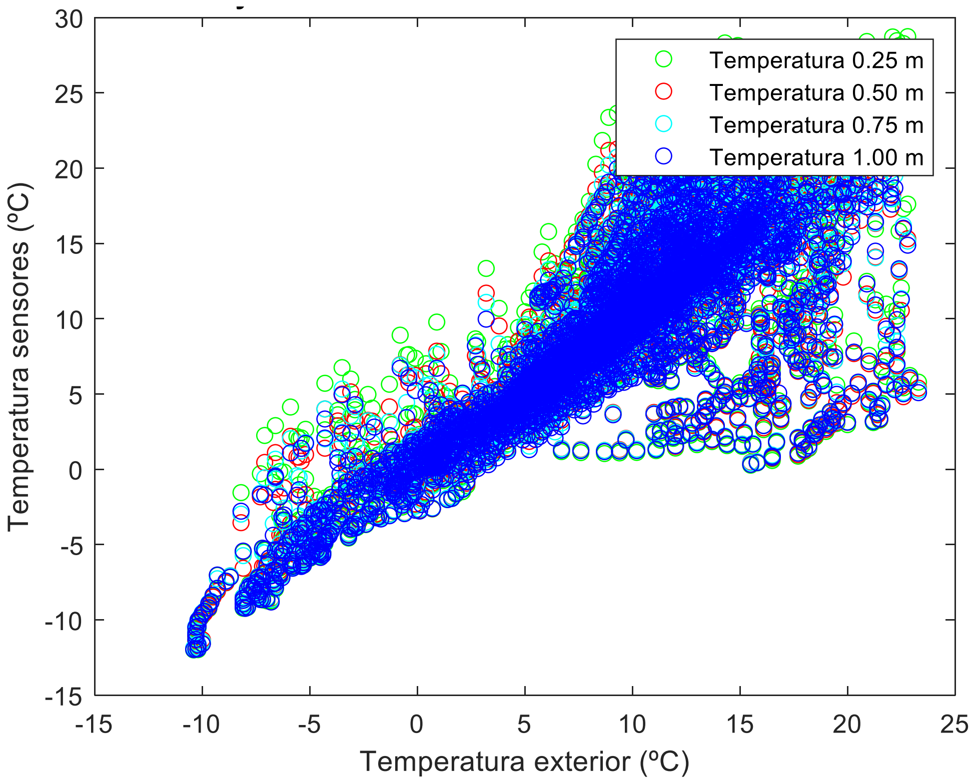
O-T: Fachada oeste base de datos de temperatura diurnos y nocturnos



O-D: Fachada oeste base de datos de temperatura diurnos (irradiancia > 0)



S-T: Fachada sur base de datos de temperatura diurnos y nocturnos



S-D: Fachada sur base de datos de temperatura diurnos (irradiancia > 0)

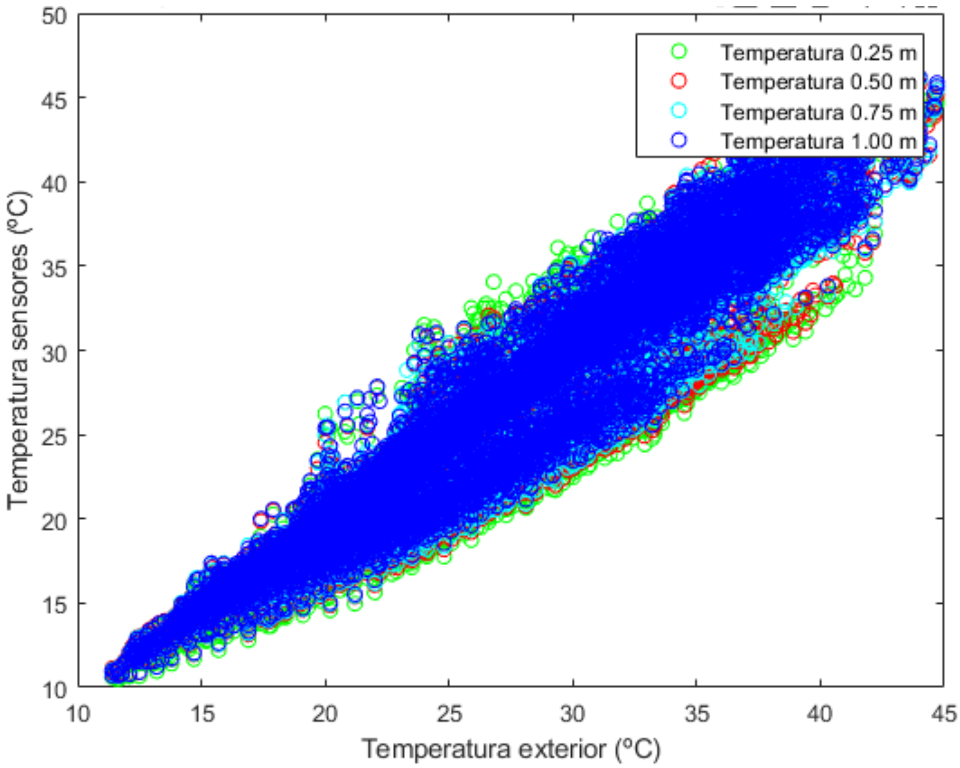
Figura 22: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el invierno

Tabla 3: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el invierno. Datos diurnos y nocturnos.

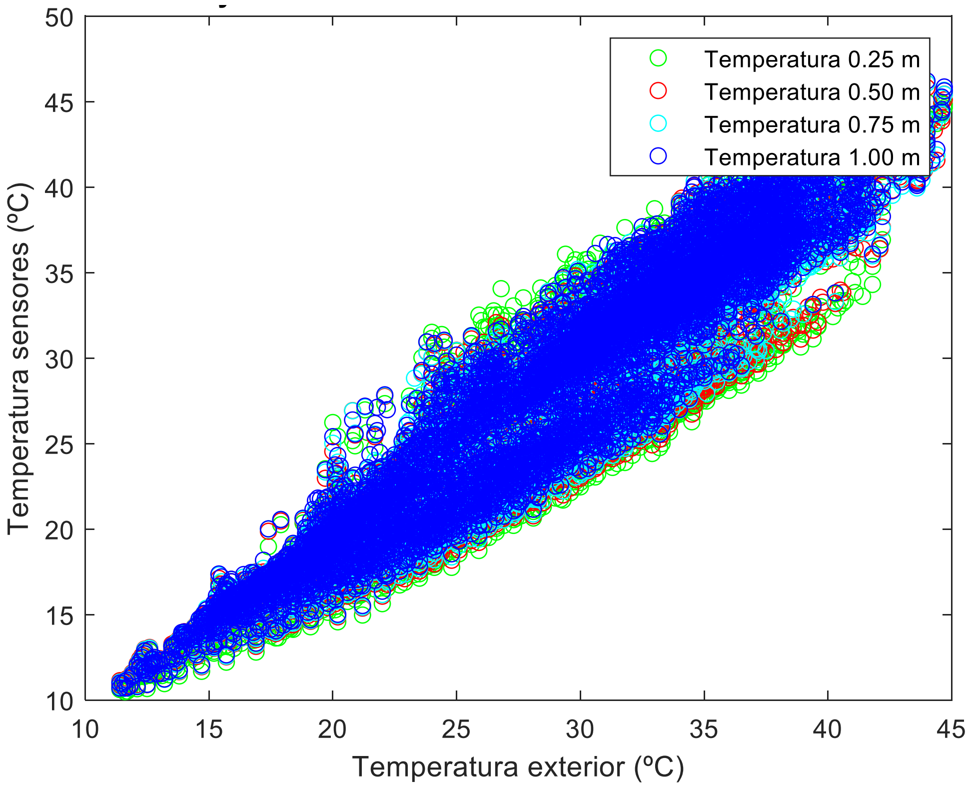
	x	**f(x)**	**Función**	**Coeficientes**	**R^2**
Fachada Oeste - Invierno	T aire	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.005054 p2 = 1.094 p3 = -0.5064	0.9940
	T aire	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.005429 p2 = 1.094 p3 = -0.3711	0.9972
	T aire	T 0.75 m	f(x) = p1*x + p2	p1 = 1.057 p2 = -0.4865	0.9958
	T aire	T 1.00 m	f(x) = p1*x + p2	p1 = 1.067 p2 = -0.5786	0.9776
Fachada Sur - Invierno	T aire	T 0.25 m	f(x) = p1*x + p2	p1 = 1.062 p2 = -0.5565	0.9817
	T aire	T 0.50 m	f(x) = p1*x + p2	p1 = 1.051 p2 = -0.4238	0.9863
	T aire	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.003677 p2 = 1.081 p3 = -0.3649	0.9934
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.004242 p2 = 1.088 p3 = -0.4406	0.9842

Tabla 4: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el invierno. Datos diurnos.

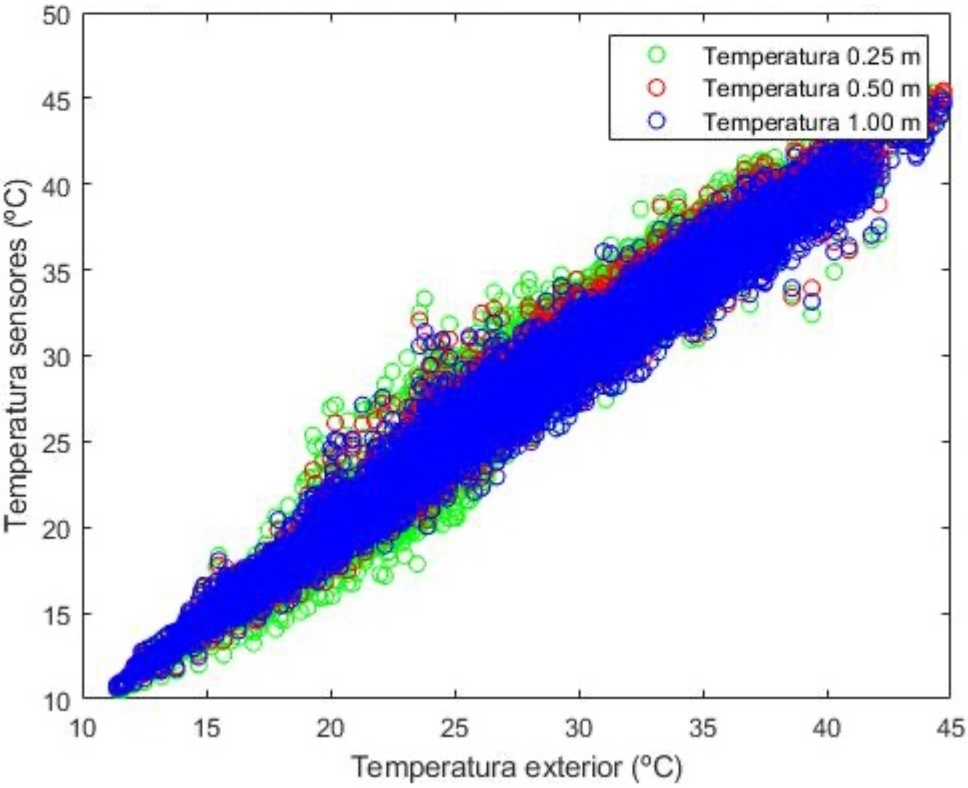
	x	**f(x)**	**Función**	**Coeficientes**	**R^2**
Fachada Oeste - Invierno	T aire	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.006522 p2 = 1.078 p3 = -0.01522	0.9895
	T aire	T 0.50 m	f(x) = p1*x + p2	p1 = 1.005 p2 = 0.1506	0.9951
	T aire	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.007507 p2 = 1.082 p3 = 0.1769	0.9954
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.007578 p2 = 1.085 p3 = 0.1304	0.9953
Fachada Sur - Invierno	T aire	T 0.25 m	f(x) = p1*x + p2	p1 = 1.044 p2 = -0.0188	0.9828
	T aire	T 0.50 m	f(x) = p1*x + p2	p1 = 1.02 p2 = 0.1021	0.9950
	T aire	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.002249 p2 = 1.041 p3 = 0.1314	0.9928
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.003068 p2 = 1.049 p3 = 0.08344	0.9895



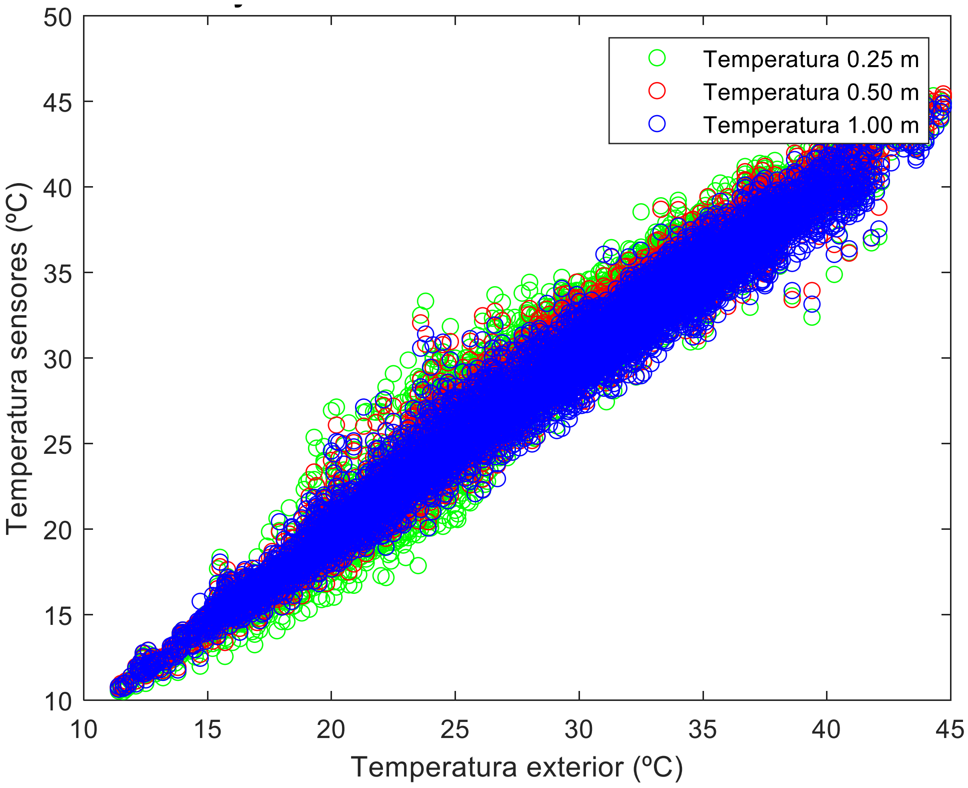
O-T: Fachada oeste base de datos de temperatura diurnos y nocturnos



O-D: Fachada oeste base de datos de temperatura diurnos (irradiancia > 0)



S-T: Fachada sur base de datos de temperatura diurnos y nocturnos



S-D: Fachada sur base de datos de temperatura diurnos (irradiancia > 0)

Figura 23: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el verano

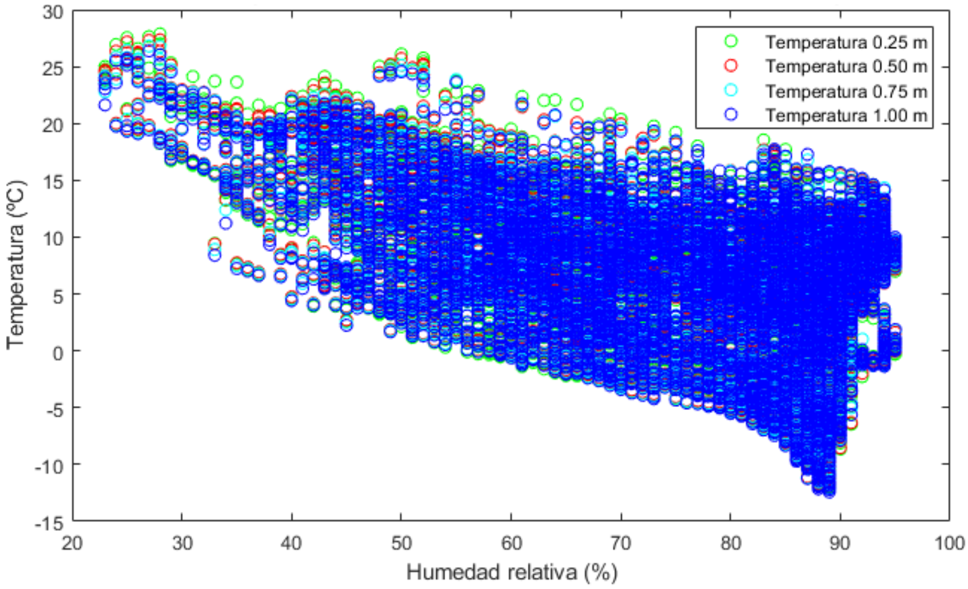
Tabla 5: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el verano. Datos diurnos y nocturnos.

	x	**f(x)**	**Función**	**Coeficientes**	**R^2**
Fachada Oeste - Verano	T aire	T 0.25 m	f(x) = p1*x + p2	p1 = 1.042 p2 = -1.565	0.9913
	T aire	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.0004976 p2 = 0.9768 p3 = -0.09448	0.9910
	T aire	T 0.75 m	f(x) = p1*x + p2	p1 = 1.025 p2 = -0.8109	0.9713
	T aire	T 1.00 m	f(x) = p1*x + p2	p1 = 1.019 p2 = -0.6639	0.9924
Fachada Sur - Verano	T aire	T 0.25 m	f(x) = p1*x + p2	p1 = 1.08 p2 = -1.985	0.9792
	T aire	T 0.50 m	f(x) = p1*x + p2	p1 = 1.05 p2 = -1.3	0.9945
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = -2.898e-05 p2 = 1.023 p3 = -0.7866	0.9971

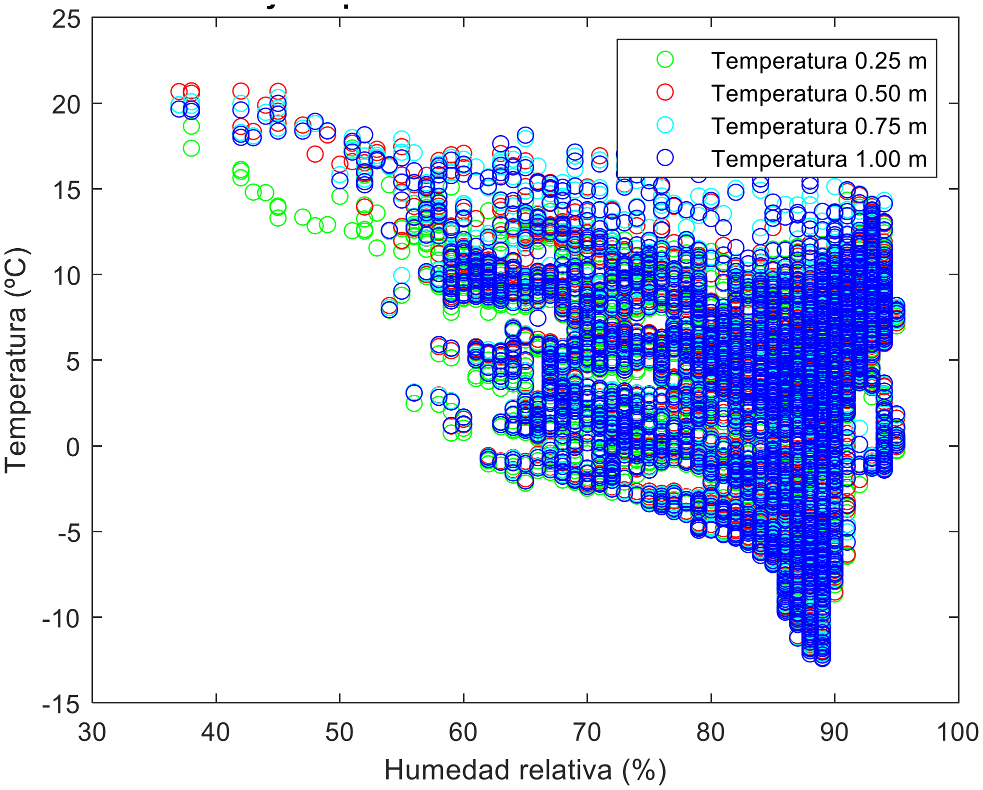
Tabla 6: Correlaciones entre la temperatura del aire y la temperatura de los sensores durante el verano. Datos diurnos.

	x	**f(x)**	**Función**	**Coeficientes**	**R^2**
Fachada Oeste - Verano	T aire	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.009491 p2 = 0.5329 p3 = 4.039	0.8832
	T aire	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.006945 p2 = 0.6303 p3 = 3.421	0.9016
	T aire	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.00491 p2 = 0.7582 p3 = 1.828	0.9119
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.002924 p2 = 0.8832 p3 = 0.2841	0.9185
Fachada Sur - Verano	T aire	T 0.25 m	f(x) = p1*x + p2	p1 = 1.086 p2 = -1.965	0.9910
	T aire	T 0.50 m	f(x) = p1*x + p2	p1 = 1.055 p2 = -1.286	0.9956
	T aire	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = -0.002149 p2 = 1.141 p3 = -2.245	0.9958

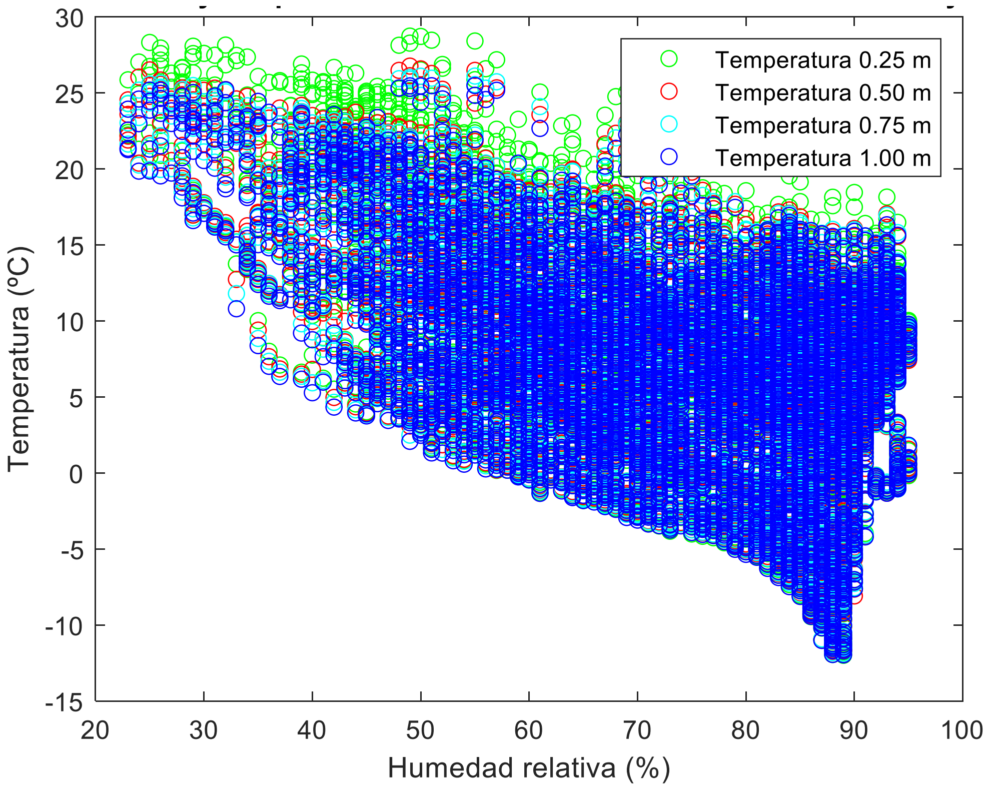
- *Correlación entre la humedad relativa y la temperatura de los sensores:* en el caso de la humedad relativa, en los datos de invierno solo existe una correlación relevante con los datos diurnos de la fachada oeste (figura 24). Sin embargo, en los resultados correspondiente a datos del verano, encontramos en muchos casos R^2 superiores a 0.7 (tabla 7 – 10). Estos resultados indican el efecto del aumento de la temperatura del aire en la reducción de la humedad relativa en verano, y, en particular, durante las horas de mayor irradiancia.



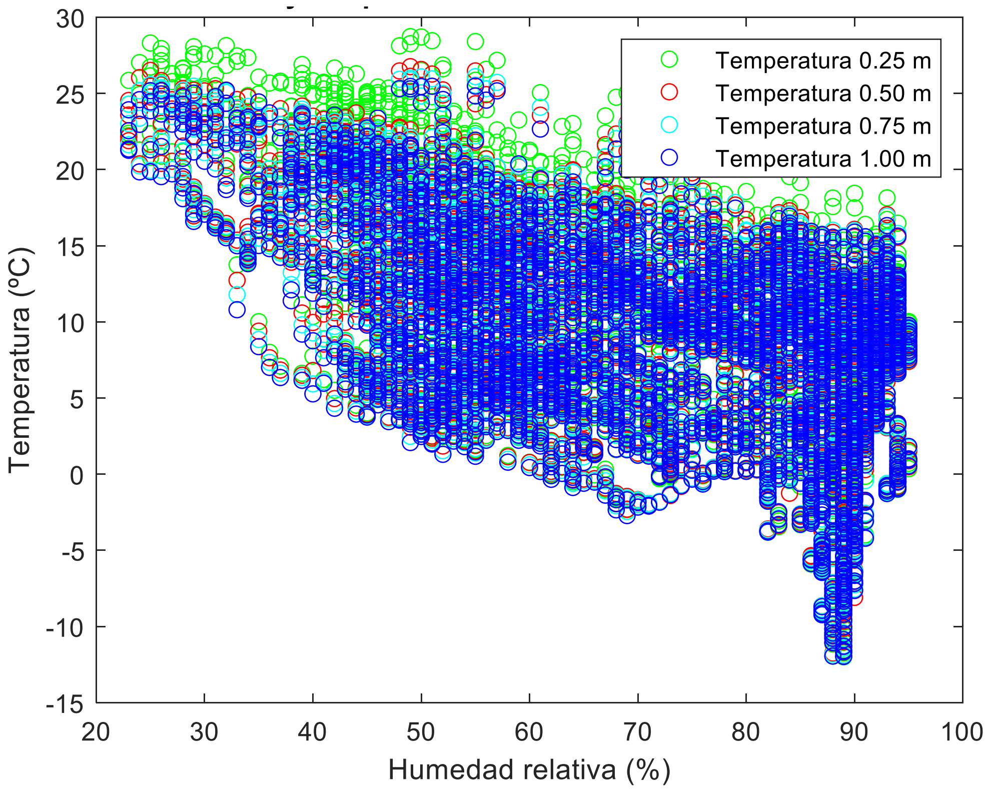
O-T: Fachada oeste base de datos de temperatura diurnos y nocturnos



O-D: Fachada oeste base de datos de temperatura diurnos (irradiancia > 0)



S-T: Fachada sur base de datos de temperatura diurnos y nocturnos



S-D: Fachada sur base de datos de temperatura diurnos (irradiancia > 0)

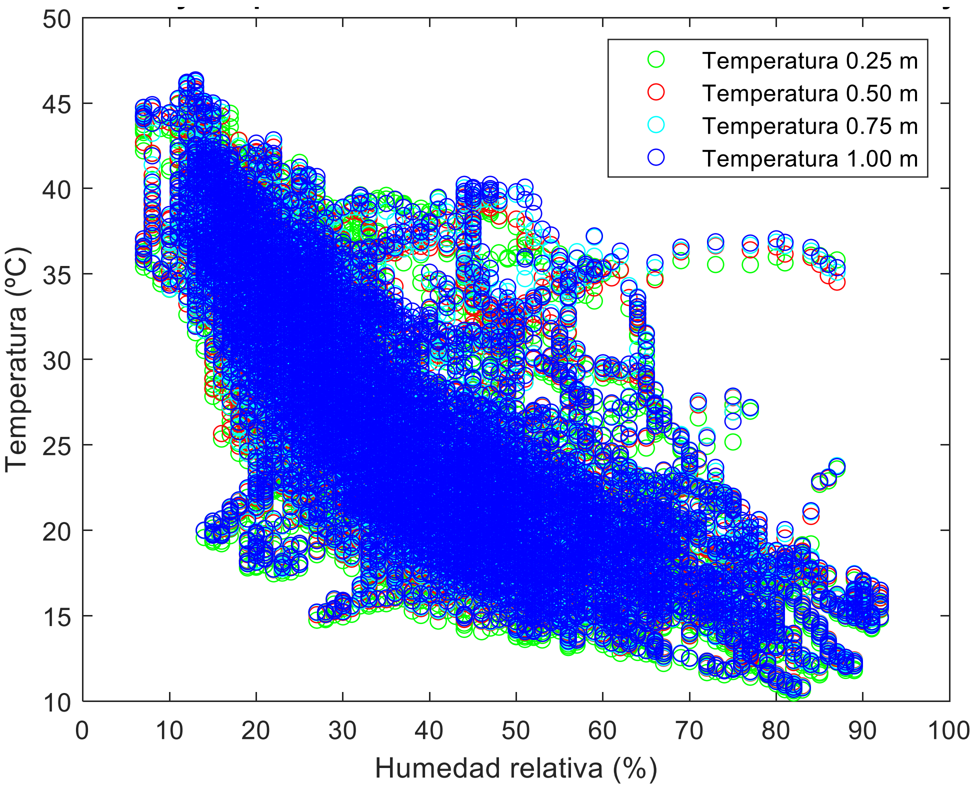
Figura 24: Correlaciones entre la humedad relativa y la temperatura de los sensores durante el invierno

Tabla 7: Correlaciones entre la humedad relativa y la temperatura de los sensores durante el invierno. Datos diurnos y nocturnos

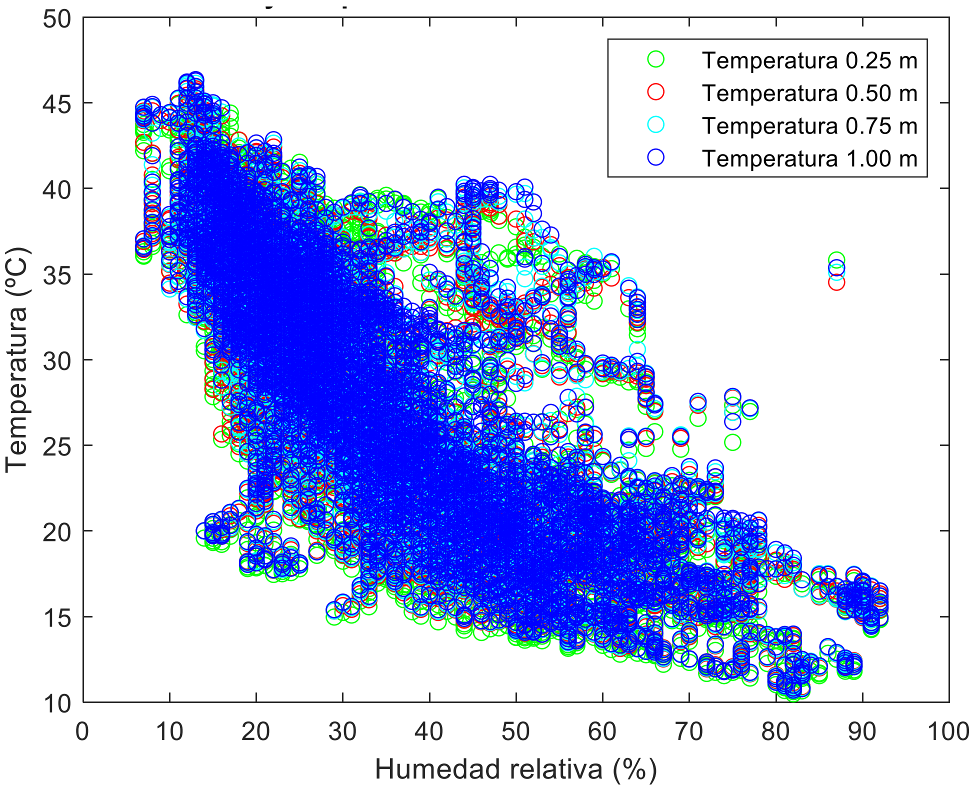
	x	f(x)	Función	Coeficientes	R^2
Fachada Sur - Invierno	HR	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.008862 p2 = -1.445 p3 = 63.83	0.3649
	HR	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.008415 p2 = -1.37 p3 = 60.68	0.3503
	HR	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.008274 p2 = -1.344 p3 = 59.58	0.3402
	HR	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.00681 p2 = -1.109 p3 = 50.13	0.2144
Fachada Oeste-Invierno	HR	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.008182 p2 = -1.327 p3 = 58.48	0.3367
	HR	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.007946 p2 = -1.295 p3 = 57.66	0.3349
	HR	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.007975 p2 = -1.298 p3 = 57.71	0.3298
	HR	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.00802 p2 = -1.303 p3 = 57.77	0.3258

Tabla 8: Correlaciones entre la humedad relativa y la temperatura de los sensores durante el invierno. Datos diurnos.

	x	f(x)	Función	Coeficientes	R^2
Fachada Sur - Invierno (solo día)	HR	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.004159 p2 = -0.7607 p3 = 41.51	0.2916
	HR	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.003757 p2 = -0.6886 p3 = 38.18	0.2763
	HR	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.003663 p2 = -0.6696 p3 = 37.27	0.2641
	HR	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.003566 p2 = -0.6511 p3 = 36.35	0.2538
Fachada Oeste-Invierno (solo día)	HR	T 0.25 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.01817 p2 = -2.885 p3 = 116.6	0.1332
	HR	T 0.50 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.02227 p2 = -3.493 p3 = 139.7	0.8409
	HR	T 0.75 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.0225 p2 = -3.529 p3 = 141.1	0.9387
	HR	T 1.00 m	f(x) = p1*x^2 + p2*x + p3	p1 = 0.02269 p2 = -3.555 p3 = 142	0.7563



O-T: Fachada oeste base de datos de temperatura diurnos y nocturnos



O-D: Fachada oeste base de datos de temperatura diurnos (irradiancia > 0)