Universitat de Lleida

Greenery systems for climate change mitigation: field analysis in buildings and in the urban context

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http://hdl.handle.net/10803/673822

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TESI DOCTORAL

Greenery systems for climate change mitigation: field analysis in buildings and in the urban context

Marta Chàfer Nicolás

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida

Programa de Doctorat: Enginyeria i Tecnologies de la Informació

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2021

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Departament d'Informàtica i Enginyeria Industrial
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Memòria presentada per optar al grau de Doctor per la Universitat de Lleida redactada segons els criteris establerts en l'Acord núm. 67/2014 de la Junta de Govern del 10 d'abril de 2014 per la presentació de la tesis doctoral en format d'articles.

Programa de doctorat: Enginyeria i Tecnologies de la Informació
Directors de la Tesis: Dra. Luisa F. Cabeza, Dr. Gabriel Pérez, Dr. Anna Laura Pisello i Dr. Franco Cotana

La Dra. Luisa F. Cabeza, Catedràtica de l'Escola Politècnica Superior de la Universitat de Lleida, el Dr. Gabriel Pérez, professor agregat de l'Escola Politècnica Superior de la Universitat de Lleida, la Dra. Anna Laura Pisello, professora a temps complet de la Universitat de Perugia i Dr. Franco Cotana, catèdratic a la Universitat de Perugia.

CERTIFIQUEN:

Que la memòria *Greenery systems for climate change mitigation: field analysis in buildings and in the urban context* presentada per Marta Chàfer Nicolás optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, Juliol 2021

Acknowledgements

It is with some sadness, as well as satisfaction, that I finish my doctoral studies, having enjoyed both the process of writing it and the accompanying period of my life. The PhD has given me a unique space to indulge my curiosity and explore a range of topics that are of professional interest and personal importance. In doing so, I have also been lucky to have received support from a range of people whom I would like to thank.

First of all, I would like to thank my PhD thesis supervisors, Prof. Luisa F. Cabeza and Dr. Gabriel Perez from the University of Lleida, not only for granting me the opportunity to dive deep into the research world but also for their guidance and wisdom that I got along the challenging path of a PhD student. Moreover, for supporting my unusual ideas and challenging topic. I also want to thank my supervisor Dr. Anna Laura Pisello, from the University of Perugia, for the contagious passion that she transmitted to me.

I would like to thank all the funding received to carry out this PhD thesis. To the Spanish government (ENE2015-64117-C5-1-R (MINECO/FEDER)), the Ministerio de Ciencia, Innovación y Universidades de España (RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE) and the Agencia Estatal de Investigación (AEI), of the Ministerio de Ciencia, Innovación y Universidades (RED2018-102431-T). To the Catalan Government for the quality accreditation given to the research (2017 SGR 1537), as well as the certification for GREiA as certified agent TECNIO in the category of technology developers from the Government of Catalonia.

I would also like to wish my gratitude to the supervisors of my research stay abroad: first in the CIRIAF research centre of the University of Perugia, Dr. Anna Laura and Prof. Franco Cotana, where I have done my cotutelle PhD thesis, and second, in the National University of Singapore, with Dr. Tan Chun Lian and Prof. Nyuk Hien Wong. I was warmly welcomed in both Universities.

Special mention must be given to my colleagues from GREiA Research Group for going along the research sinuous path with me and sharing their knowledge. Especially to those who were more than colleagues.

Special mention to my friends and my beloved ones, who stand by me all this period. They have been the ones who have pushed me to write the thesis, also on my weekends, being habitual my absences with them, and always encouraging me to finish this long path.

Finally, and foremost my heartfelt gratitude goes to my parents. I would not be writing these lines if it had not been for their unconditional support.

My sincere apologies if this note has unintentionally missed acknowledging any person.

Dedication

This dissertation is dedicated to my beloved father, Josep Chàfer, who inspired me and helped me to start every day full of energy. He encouraged me to pursue my dreams and to finish my dissertation. Moreover, he taught me the value of hard work, being curious, and constantly asking everything I see around me.

"The only way forward, if we are going to improve the quality of the environment, is to get everybody involved."

Richard Rogers

Summary

One of the great challenges of the 21st century is the fight against climate change, as it represents a major threat to health and sustainable development. The world recently recognised the importance of these issues with the approval of the 2030 Agenda for Sustainable Development, with which governments pledged to ensure progress on 17 Sustainable Development Goals (SDGs). Green spaces (green roofs and green facades,, urban parks, etc.) offer solutions to the impact of rapid and unsustainable urbanisation on the health and well-being of citizens. These spaces are of crucial importance and should be studied in the context of global issues such as climate change and other priorities set out in the SDGs. Increasing the number and quality of green spaces can help mitigate climate change and the urban heat island effect, contributing notably to 7 million premature deaths in the year related to air pollution. Therefore, this thesis is framed in the study of greenery systems as a tool for mitigating climate change and energy saving in buildings. The thesis is framed in two scales, at the building level and the urban level. The thesis begins by looking at worldwide research trends and the main shortcomings of the literature. To carry out the experimental part of the thesis, a pilot plant located in Puigverd de Lleida, Spain, was used. Different vertical greenery systems were analysed, and therefore their environmental impact throughout their life cycle was also studied. Likewise, a system of green pergolas in the same pilot plant was also studied to experimentally see the potential of the green system in reducing temperatures in the local micro-climate. Finally, it was extrapolated to urban scale, in this case, how urban parks could reduce temperatures in the tropical climate in large cities such as Singapore. The results showed that, in both Mediterranean continental and tropical climates, green systems reduce the local temperatures and their immediate surroundings. This thesis can be a support for future policies regarding strategies to mitigate climate change through green spaces in cities.

Resumen

Uno de los grandes desafíos del siglo XXI es la lucha contra el cambio climático ya que representa una importante amenaza para la salud y el desarrollo sostenible. El mundo reconoció recientemente la importancia de estas cuestiones con la aprobación de la Agenda 2030 para el Desarrollo Sostenible, con la cual los Gobiernos se comprometieron a garantizar un progreso respecto de 17 Objetivos de Desarrollo Sostenible (ODS). Los espacios verdes (cubiertas y fachadas verdes, parques urbanos, etc.) ofrecen soluciones a la repercusión de la rápida urbanización y poco sostenible en la salud y el bienestar de los ciudadanos. Estos espacios son de una importancia crucial, y tienen que estudiarse en el contexto de cuestiones de interés mundial como el cambio climático y otras prioridades establecidas en los ODS. Aumentar el número y la calidad de los espacios verdes puede ayudar a mitigar el cambio climático y en la isla de calor urbano, los cuales contribuyen notablemente además de 7 millones de muertes prematuras en el año relacionadas con la contaminación atmosférica. Es por todo esto, que esta tesis está enmarcada en el estudio de los sistemas verdes como herramienta de mitigación del cambio climático y ahorro energético en edificios. La tesis abarca dos escalas de estudio, tanto a nivel de edificio como nivel urbano. La tesis inicia de una forma teórica revisando las tendencias mundiales de investigación y las principales carencias que podemos encontrar a la literatura. Para llevar a cabo la parte experimental de la tesis, se utilizó una planta piloto localizada en Puigverd de Lleida, España, donde se analizaron diferentes soluciones de fachadas verdes, de las cuales también se estudió su impacto ambiental a lo largo de su vida. También, se estudió en la misma planta piloto un sistema de pérgolas verdes para ver experimentalmente, qué potencial tenía un sistema verde en la reducción de las temperaturas en el micro-clima local, y finalmente, se extrapoló a escala urbana, los sistemas verdes, en este caso los parques urbanos podían influir en la reducción de temperaturas en las grandes ciudades como Singapur. Los resultados han demostrado que, tanto en nuestro clima mediterráneo continental como en el tropical, los sistemas verdes favorecen una reducción de las temperaturas locales y su entorno más próximo. Esta tesis puede ser un apoyo para las políticas de futuro en cuanto a las estrategias de mitigar el cambio climático a través de espacios verdes en las ciudades.

Resum

Un dels grans desafiaments del segle XXI és la lluita contra el canvi climàtic ja que representa una important amenaça per a la salut i el desenvolupament sostenible. El món va reconèixer recentment la importància d'aquestes qüestions amb l'aprovació de l'Agenda 2030 per al Desenvolupament Sostenible, amb la qual els Governs es van comprometre a garantir un progrés respecte de 17 Objectius de Desenvolupament Sostenible (ODS). Els espais verds (cobertes i façanes verdes, parcs urbans, etc) ofereixen solucions a la repercussió de la urbanització ràpida i poc sostenible en la salut i el benestar dels ciutadans. Aquests espais són d’una importància crucial, i han d'estudiar-se en el context de qüestions d'interès mundial com el canvi climàtic i d'altres prioritats establertes en els ODS. Augmentar el número i la qualitat dels espais verds pot ajudar a mitigar el canvi climàtic i a l'illa de calor urbana, els quals contribueixen notablement a més de 7 milions de morts prematures a l'any relacionades amb la contaminació atmosfèrica. És per tot això, que aquesta tesi està emmarcada en l’estudi dels sistemes verds com a eina de mitigació del canvi climàtic i estalvi energètic en edificis, la tesi compren dues escales d’estudi; tan a nivell d’edifici com a nivell urbà. La tesi inicia d’una forma teòrica veient les tendències mundials de recerca i les principals mancances que podem trobar a la literatura. Per dur a terme la part experimental de la tesi, es va utilitzar una planta pilot que tenim a Puigverd de Lleida, Espanya, on es van analitzar diferents solucions de façanes verdes, de les quals també es va estudiar el seu impacte ambiental al llarg de la seva vida. També, es va estudiar en la mateixa planta pilot un sistema de pèrgoles verdes per veure experimentalment, quin potencial tenia un sistema verd en la reducció de les temperatures en el micro-clima local, i finalment, es va extrapolar l’estudi d’escala d’edifici a escala urbana per veure com els sistemes verds, en aquest cas els parcs urbans podien influir en la reducció de temperatures en les grans ciutats com Singapur. Els resultats han demostrat que, tant en el clima mediterrani continental com en el tropical, els sistemes verds afavoreixen una reducció de les temperatures locals i el seu entorn més pròxim. Aquesta tesi pot ser un suport per a les polítiques de futur en quant a les estratègies de mitigar el canvi climàtic a través d'espais verds a les ciutats.

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Chapter 1

Introduction and objectives

"Everything we do during and after this crisis [COVID-19] must be with a strong focus on building more equal, inclusive and sustainable economies and societies that are more resilient in the face of pandemics, climate change, and the many other global challenges we face."

António Manuel de Oliveira Guterres, Secretary-General of the United Nations

1.1 Introduction

This thesis chapter compiles the motivation of this thesis, the goals, and the path followed along with its development. Moreover, the state-of-the-art regarding the thesis topic is summarised within this chapter since it provides the background in which the thesis is framed.

1.1.1 Statement of the problem

Cities are the largest, most ambitious and most complex concept of humanity. Cities have been the scene of the greatest progress of human beings, and within them, the political, economic, financial, scientific research, and technological production. However, cities are also the largest concentrations of waste, consumption sinks, and critical points of pollution of the planet. Thus, humanity faces challenges of an unprecedented dimension in this urbanisation process that it has just started.

The incremental changes to the urban population resulted in unprecedented urbanisation, leading to the radical territorial expansion of urban settlements, especially in developing countries [1]. The last report by Sustainable Development Goals (SDG) warned that climate change exacerbates the frequency and severity of natural disasters, affecting more than 39 million people in 2018 [2]. Moreover, the same document stated that 2019 was the second warmest year on record. On the other hand, the Fifth Assessment Report (AR5) [3] of the Intergovernmental Panel on Climate Change (IPCC) notes that humanity is on its way to potentially increase the temperature to beyond 4ºC by the end of this century. The impacts of climate change on human populations will be severe, especially for the most vulnerable populations and places. The so-called urban sprawl caused the loss of natural habitats, biodiversity, vegetation and permeable soils that were irremediably replaced by sealed surfaces, buildings, and roads [4].

In terms of the urban climate, the combined effects of urbanised land, densification of cities, and human activities raise the amount of anthropogenic heat liberated to the atmosphere [5,6]. Moreover, lower evaporative cooling affects natural ventilation and alters the urban heat balance by increasing the available sensible heat emerging from pavements and buildings [7,8]. Consequently, urban cores experience higher ambient temperatures than their naturals surroundings, the well-known phenomenon of urban heat island (UHI) [9,10], as seen in Figure 1. The interest in UHI considerably grew in the last decades as it addresses two major environmental problems: global warming and human over-population [5].

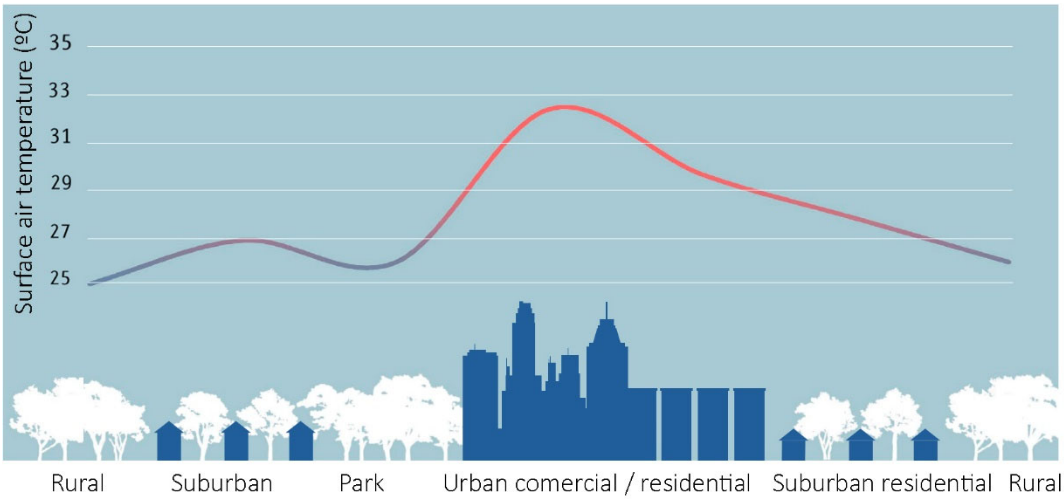

Figure 1. The urban heat island effect [11]

Confirming the chance of such occurrences with a high level of confidence, the Intergovernmental Panel on Climate Change (IPCC) [3] asked for multidisciplinary approaches to facilitate climate change adaptation. Moreover, the same IPCC document stated that buildings accounted for 32% of the total global final energy use, and this energy is predicted to at least double by mid-century. This high energy consumption is contributing to the increasing in both global average temperature and greenhouse gas emissions. Therefore, the research community effort to discover new technologies that can reduce energy consumption becomes a key point to achieve this goal without compromising the thermal comfort needs [7].

Finally, the world recently recognised the importance of these issues with the approval of the 2030 Agenda for Sustainable Development [2]. Governments pledged to ensure progress on 17 Sustainable Development Goals (SDGs) (Figure 2) and their 169 targets. Going forward, it will be critical to choose interventions that aim to achieve different goals and objectives at the same time to achieve maximum impact.

Figure 2. The Sustainable Development Goals (SDGs) [12]

Humanity, therefore, mainly faces two challenges that urban centres can help to be addressed: it is necessary to adapt to climate change, but it is also necessary to mitigate the forces of origin human beings producing it. Re-thinking urban areas and urban planning processes could help achieve a development path that would maintain temperature increases global average of 2 to 2.4ºC over pre-industrial levels [13]. Despite increasing concerns about climate change and recognising the need for mitigation, greenhouse gas emissions continue to increase [14,15]. Governments face significant challenges in agreeing on the necessary emissions reductions and effective means of making such reductions.

In this context, urban green infrastructure and urban green areas are relevant strategies for controlling the urban heat island [16,17]. Due to its abundant vegetation and its permeable surface, the parks present a different behaviour from the rest of the urban spaces. In this sense, the possibility of using parks, as well as other innovative ways to green the built environment, such as green facades and green roofs, has been studied as a strategy to reduce the UHI of cities [18–20]. The specialised literature recognises that vegetation is one of the main components of the urban space causing cooling [21,22], contributing to mitigation and adaptation to climate change in cities.

1.1.2 Green infrastructure

The disappearance of ecosystems and the replacement of vegetated surfaces by buildings and other impervious surfaces such as parking lots, roofs and streets, suppose for a territory a global loss [23] of its capacity to, for example, (1) purify the air through vegetation, (2) serve as a habitat for wildlife species, (3) control the excess run-off and the consequent problems of flooding, (4) moderate air temperatures by means of evapotranspiration and shading associated with vegetation, and (5) the ability to maintain ecological cycles without naming the intangible benefits that vegetation can provide to human health [24], especially mental health. All of the above affects the possibility of maintaining self-sustaining urban ecosystems that do not require energy or material subsidies [25–27].

Among several mitigation technologies and strategies that could be implemented in the urban contexts, *greenery* (including urban parks, trees, green roofs and vertical greenery systems) was identified as a nature-based and efficient solution for reducing urban temperatures and mitigating the adverse effects of UHI [11,16,28] (Figure 3). Greenery was defined by the European Commission [29] as “the interconnected network of natural and engineered features and spaces capable of providing a broad range of ecological, economic, and social functions and services, maintaining natural processes, and protecting the biodiversity of the urban and rural setting”. Therefore, *greenery* plays a crucial role in delivering more sustainable and resilient settlements as they can be implemented to reduce carbon emissions and remedy the negative consequences of urban warming and climate change [30,31].

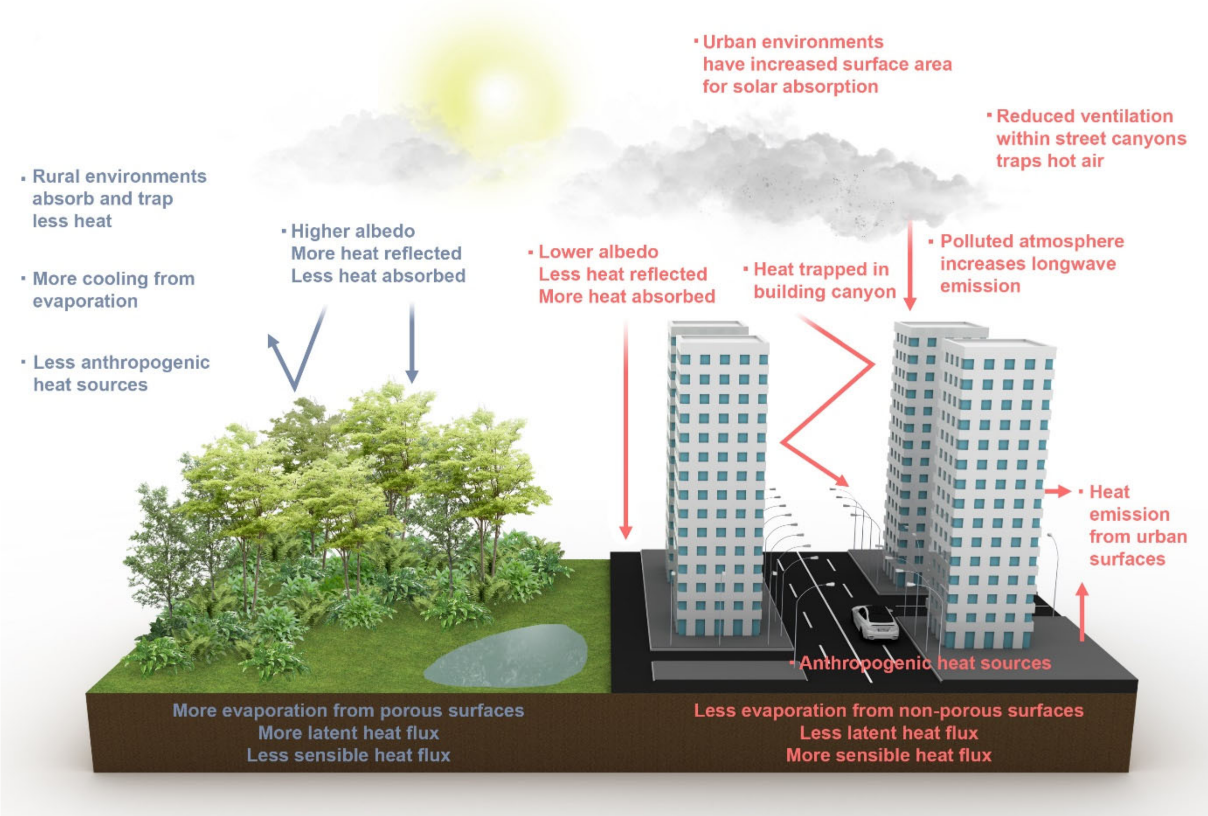

Figure 3. Factors contributing to the urban heat island effect. Highlighting significant changes in heat and air movement when rural land is urbanised. Red boxes indicate warming mechanisms, and blue boxes indicate cooling mechanisms [11]

The integration of vegetation in architecture is a sustainable resource that improves the quality of buildings and cities [32,33]. Both subjects merge in a symbiotic process that benefits from all the virtues of the living element, that is, vegetation. The way to integrate vegetation into buildings is by making it part of the thermal envelope itself. It can be one more component in the facades (Figure 4). Either as a thermal mattress or as a protection element. But it can also be part of the roofs of buildings as a support for the growth of species promoting biodiversity. Therefore, it is a subject that deserves to be investigated in-depth and in a broader way.

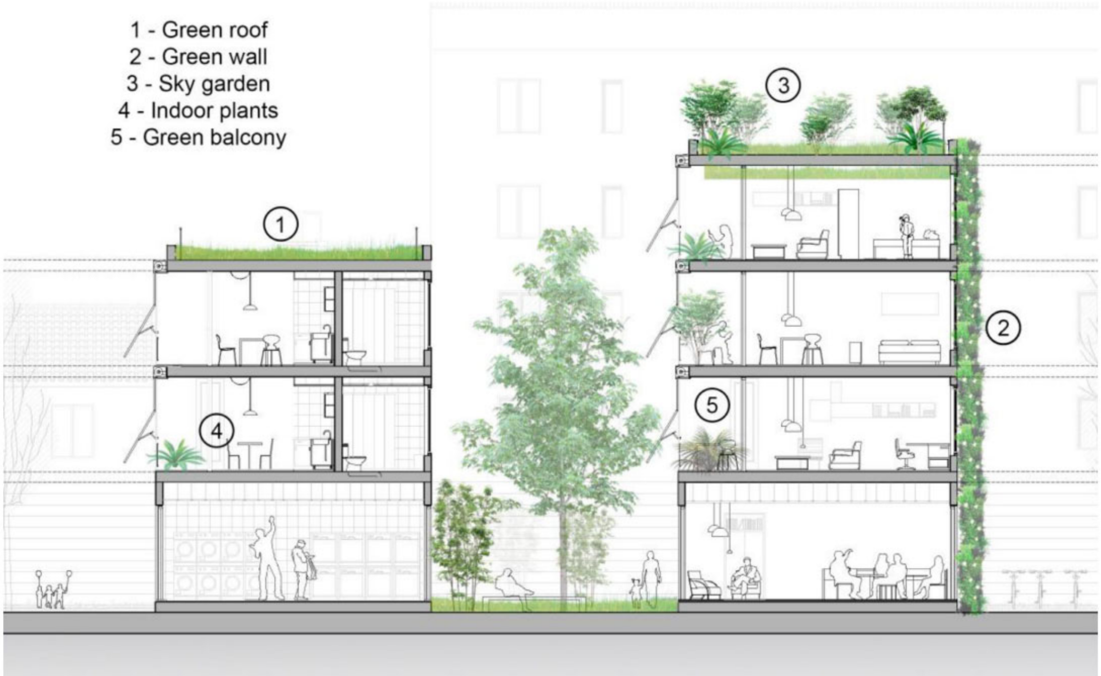

Figure 4. Integration of greenery in buildings [34]

Therefore, to study the research trends and gaps worldwide in the field of "greenery in architecture" is absolutely necessary. More widely, the following section shows the most studied topics in the last years in "greenery" research and the main gaps in the literature.

Paper 1. Trends and gaps in global research of greenery systems through a bibliometric analysis

1.1.3 Overview

Many studies in the literature identified the main findings, gaps, trends, and overviews in different research fields. However, the rapid progress and development of science and technology have improved the research objects, goals, and treatment of that massive amount of data. In recent years, a new way appeared through a bibliometric approach that studies extensive literature that could be difficult to summarise by traditional review methods. Bibliometrics (also called scientometrics) is the branch of bibliology that studies the scientific production contained in various types of documents through statistical methods (quantitative analysis of publications) [35]. This methodology extends to all scientific areas and is frequently used to evaluate the results of peer-reviewed research. Finally, the bibliometric methodology gives shape, structure, and direction to the research domain and its developments and advances [36].

The methodology that a bibliometric analysis on average follow could be summarised as seen in Figure 5.

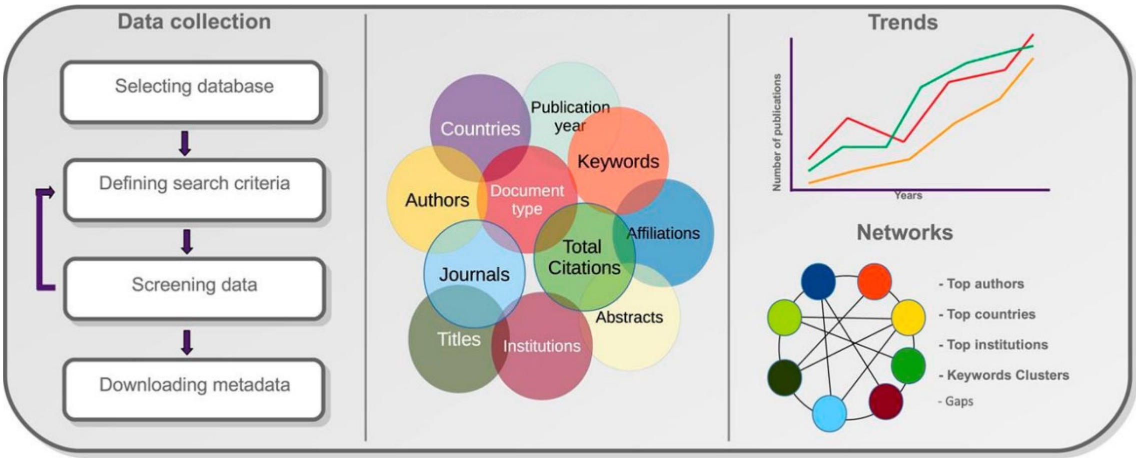

Figure 5. Overview of a bibliometric analysis (adapted from [37])

1.1.4 Contribution to the state-of-the-art

The holistic evaluation through a bibliometric approach generated distilling evidence to both academics and industry practitioners on the state-of-the-art research on greenery systems. By combining a bibliometric analysis with qualitative discussion, a more holistic science mapping is achieved. Therefore, the review pursued the following research objectives: (I) identifying trends and geographic patterns in the literature regarding the greenery systems research; (II) identifying the most productive researchers and the most influential papers; (III) to generate a geospatial network of the active research countries, researchers and keywords; (IV) to examine the highest impact journals in greenery systems research and the main subject categories; and (V) to deduce the main gaps and emerging research themes from the keyword analysis.

The methodology of this study follows the steps seen in Figure 6. The first step was the selection of the database. The Scopus database was selected in this study because it is the largest database of peer-reviewed documents delivering a comprehensive overview of the world's research output in the engineering areas [38]. Moreover, no specific start date was selected in order to identify the earliest paper in literature. Therefore, the second step was the use of keywords for the search. Since "greenery" is a too generic term, keywords as "building and built environment" were added to link with the keyword "greenery" and, therefore, obtain the most consistent results concerning the central topic of this study.

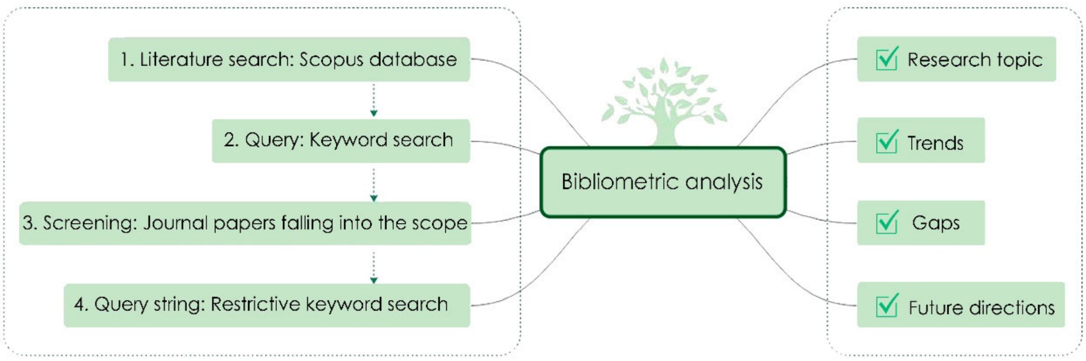

Figure 6. Overview of the methodology of the bibliometric analysis of the greenery systems topic [20]

Once the research was done, the first publication was found in 1974, which means that the studied period encompasses (1974 – 2019) with a total of 1918 documents. Moreover, VOSviewer [39] was used in this study to develop a visual representation.

The results showed that there was year-on-year growth in the interest and publication of greenery systems research. Research into this topic is diverse, highlighting the versatility of the concept, which has supported and hindered its uptake in different locations. Although the first document was found in 1974, over 86% of the relevant documents were published since 2009. Moreover, content analysis of titles, keywords and abstracts revealed that most of the research has focused last decade was focused on the study of green roofs (see Figure 7), which might be due to new policies implemented by governments in some countries. Previously this topic was dominated by water run-off, while recent contributions acknowledge greenery as an effective microclimate mitigation strategy, especially in urban areas.

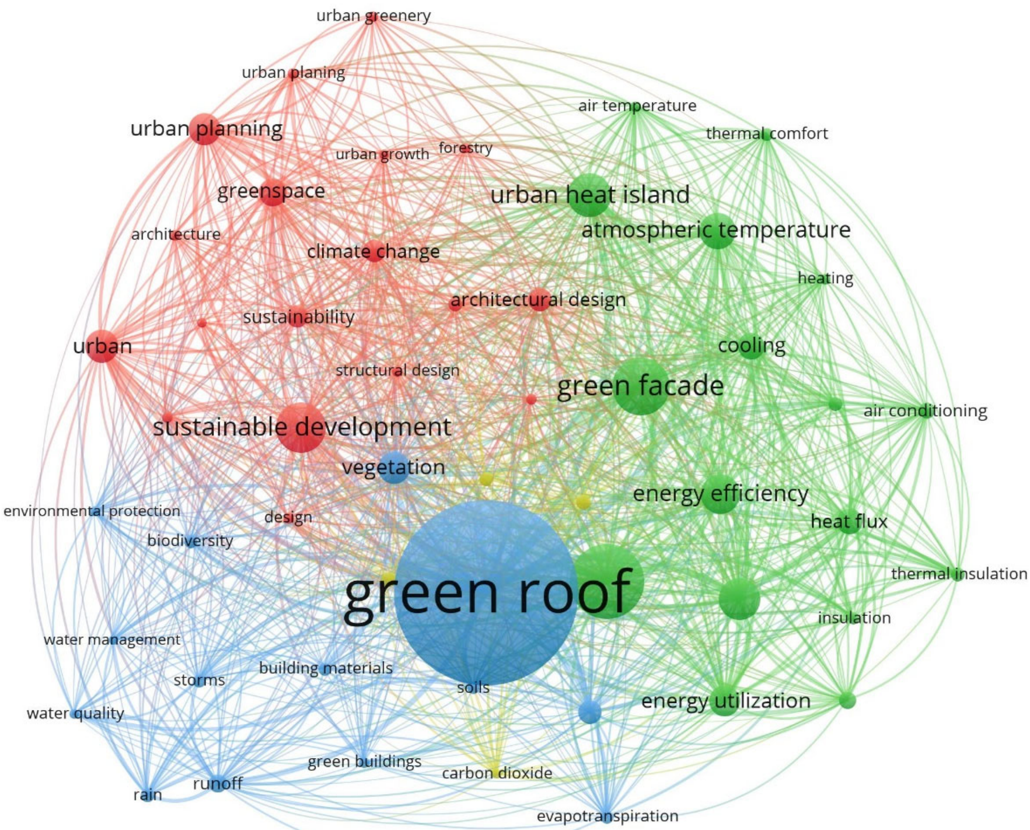

Figure 7. Co-occurrence map and link of the most frequent keywords of the query [20]

The main distribution areas of study are environmental science and engineering. The United States was the most productive country, representing almost 20% of the total documents. Over 86% of the relevant documents were published since 2009. Finally, the main gaps found in this study that allows identifying the framework for future research directions were the following:

- The first knowledge gap was related to the environmental impact of those systems. Adopting LCA analysis for the labelling of green products could increase their use since green labels can boost consumers confidence. Further research on this topic is needed to achieve more friendly materials for those systems.
- The second gap was the real performance of vertical greenery systems. Although there are many studies concerning those systems in literature, there are still controversial results and statements about the thermal behaviour, especially in winter. For that reason, rather than hiding or ignoring unfavourable results, new data is essential to provide an opportunity for the emerging living wall industry.
- The third gap was related to the cost, one of the main factors hindering greenery systems proliferation. The investment and maintenance of those systems are usually higher than other systems, affecting the final election that either buildings or urban context might have.
- The fourth gap was related to the outdoor thermal comfort and air quality improvement and its potential as an urban heat island mitigation. Although there are many studies about the "cooling effect" of greenery, there are still controversial opinions in the literature about their effects, especially depending on the climate zone.
- And the last knowledge gap was associated with the benefits to human health. One of the most intangible effects that greenery, in general, may provide. There is still scarce empirical evidence about how greenery could promote health benefits.

1.1.5 Contribution of the candidate

The candidate worked on the query string and did the search. Afterwards, she analysed the results and proposed and conceived the way the review is structured and drowned the conclusions exposed.

1.1.6 Journal paper

The scientific contribution from this research work was published in the Journal Sustainable Cities and Society in 2021.

Reference:

M. Chàfer, L.F. Cabeza, A.L. Pisello, C.L. Tan, N.H. Wong, Trends and gaps in global research of greenery systems through a bibliometric analysis, Sustain. Cities Soc. 65 (2020) 102608. https://doi.org/10.1016/j.scs.2020.102608.

Sustainable Cities and Society 65 (2021) 102608

Contents lists available at ScienceDirect

Sustainable Cities and Society

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Trends and gaps in global research of greenery systems through a bibliometric analysis

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ARTICLE INFO

Keywords:
Bibliometric analysis
Greenery systems
Green roof
Green facade
Research trends

ABSTRACT

This study presents a critical review analysis of greenery systems research through a bibliometric approach. The purpose of this study is to provide a holistic overview by (i) the development of the field; (ii) the research trends and the main issues; and (iii) the main gaps still observed in the literature. Therefore, this paper provides the past, the present and the potential future of this scientific topic and serves as an orientation and guide for researchers who aim for a better understanding of the main progress and gaps. A detailed analysis of 1918 documents found in the Scopus database for the 1974–2019 period was conducted. Content analysis of titles, keywords and abstracts revealed that most of the research has focused on the study of green roofs. Previously this topic was dominated by water runoff analysis, while recent contributions acknowledge greenery as an effective microclimate mitigation strategy, especially in urban areas. The United States was the most productive country, representing almost 20 % of the total documents. Over 86 % of the relevant documents were published since 2009. Overall, research on this topic is increasing, with new methods and directions but some gaps remain particularly on the areas of environmental impact, costs, health, outdoor thermal comfort, and vertical greenery systems.

1.2 PhD objectives

Climate change mitigation strategies are necessary. Moreover, after reviewing the state-of-art about greenery systems, which was one of the main objectives of this PhD thesis, it was understood the hot and emerging topics and the main gaps where more research was needed. Since many gaps were found in this review, and it would be too ambitious to study all of them, this thesis aims to increase knowledge on the effectiveness of different greenery systems to support decision-making in the context of urban climate change mitigation and adaptation.

The second objective of the thesis was to experimentally demonstrate the effectiveness of two different vertical greenery systems, either in winter and summer, considering internal heat loads inside the buildings in the continental Mediterranean climate as a novelty of the thermal performance of the VGS.

The third objective is related to the second objective and was to conduct an extensive life cycle assessment of the two vertical greenery systems studied above. This study filled one of the gaps found in the state-of-the-art by thoroughly tracking and quantifying all impacts in all phases of the building life cycle related to the manufacturing and construction stage, maintenance, use stage (operational energy use experimentally tested), and final disposal.

The fourth objective, extend the greenery system to a small and “local” outdoors. The aim of the study was to see the local cooling effect of the greenery in a designed pergola compared to another exactly built but, the second one, without vegetation.

The five and last objective of this thesis is in a more extended urban context. The main objective of the study was to analyse the cooling effect of the greenery, in terms of the urban park, but in a tropical climate. Moreover, it was also studied how the temperatures of the urban park and other urban morphologies affected the microclimate during the day.

Chapter 2

PhD thesis structure and methodology

2.1 PhD thesis structure

First, this PhD thesis is based on five papers, four of them published in SCI journals, while the last one is under review.

As seen in Figure 8, this thesis is divided into five chapters. Chapter one details the introduction, the research background, the PhD objectives pursued, as well as the state-of-the-art through paper 1 [20]. The second chapter describes the PhD thesis structure and the methodology followed along with the thesis. Chapter three gives the four other papers which the thesis consists of. In the fourth chapter, the global thesis conclusions are stated.

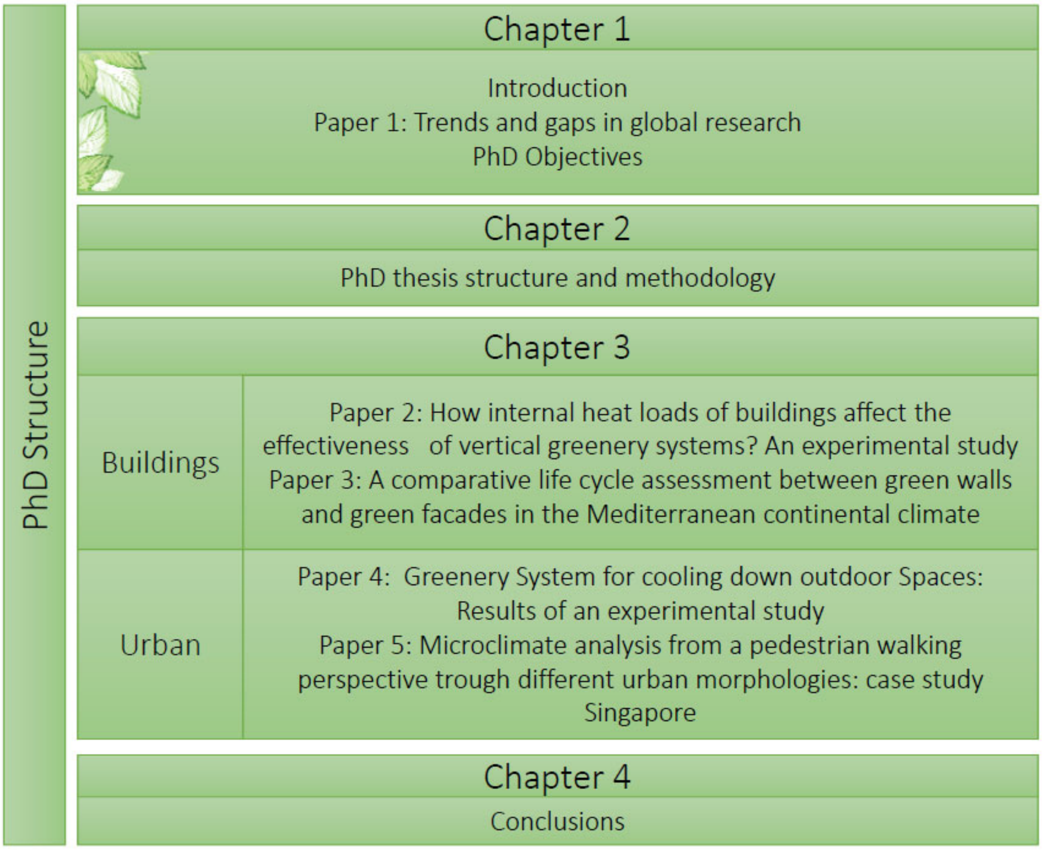

Figure 8. Scheme of the PhD thesis structure by chapters

2.2 Methodology

The PhD thesis aims to experimentally test the environmental and thermal performance of greenery systems in buildings and in the urban context. The research developed on the existing literature allowed to find the main gaps and, therefore, to extend the state-of-the-art about the topic. As pointed out in paper 1, there is a need to further experimental research on greenery as a strategy for climate change mitigation.

Therefore, this thesis is divided into two parts, as mentioned in the PhD structure. One focusing on the greenery applied to the facade of the building and, the second the greenery applied as a strategy in the urban context. Moreover, the thesis consists of three main frameworks: literature review through a bibliometric analysis, experiments at a pilot plant scale, and experimental research in the urban context.

The first part of the thesis is at building scale. The tests were carried out at the GREiA research group experimental set-up at Puigverd de Lleida, Spain, under continental-Mediterranean weather conditions, Csa (warm temperate, dry and hot summer) according to Köppen-Geiger climate classification [40]. In this experimental set-up, 22 house-like cubicles have been tested during the last decade with active and passive technologies [41]. In this context, three cubicles were considered: the cubicle with a green wall, the cubicle with a green facade, and the last, the cubicle with any VGS. A sketch of the facility and the distribution of the 22 cubicles is shown in Figure 9, where the cubicles used for the tests are highlighted in green circles. Moreover, Figure 10 shows an aerial view of the real set-up.

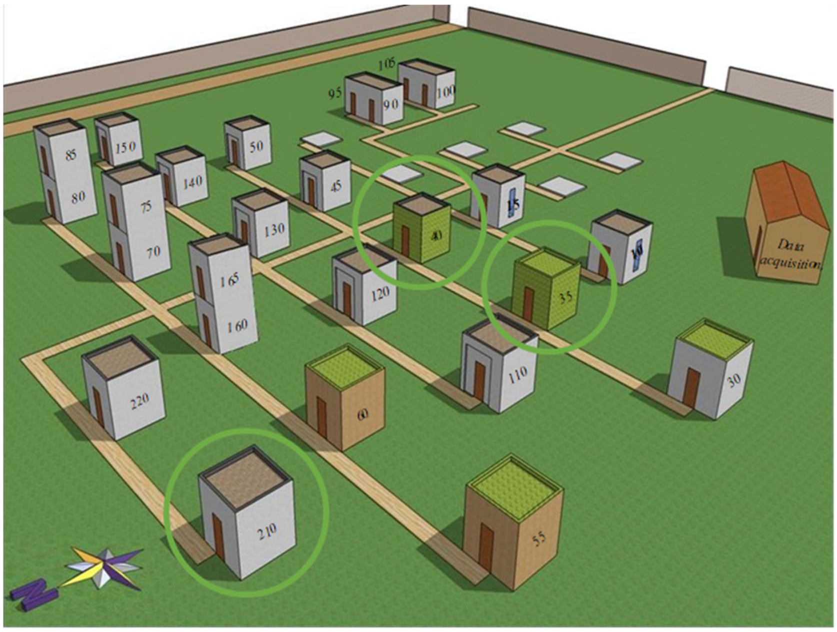

Figure 9. Lay-out sketch of the experimental set-up

Figure 10. Aerial view of the experimental set-up

Paper 2 focused on these three house-like cubicles mentioned above in order to see the effectiveness of two different vertical greenery systems. Since the thermal response of different passive and active energy-saving systems implemented on building envelopes are highly affected by internal heat gains, the objective of this paper was to evaluate the influence on the thermal performance when internal heat loads are considered. To do that, another house-like cubicle without any greenery system implemented was also analysed (Figure 11). The experimental set-up allowed to conduct two different types of experiments. Controlled temperatures with internal loads and free-floating tests also with internal loads were studied. In the experiments with controlled temperatures, heat pumps were used to maintain the indoor environment at a constant comfort temperature during the entire experiment. Then, the electrical energy consumption of the heating, ventilation, and air conditioning system (HVAC) of all tested cubicles are compared using different temperature setpoints for summer and winter conditions. A domestic heat pump was installed in each cubicle to cover the heating and cooling demands. To measure and analyse the thermal behaviour of these cubicles, data was registered every 5 min interval.

Figure 11. On the left, the intensive green wall. On the right, the green facade

Paper 3 analysed the life cycle assessment of the cubicles mentioned above (Figure 11). The LCA methodology was used to quantify and compare the potential environmental impacts of the different greenery systems. This study was based on ISO 14040 and ISO 14044 standards [42,43]. According to the standards, a life cycle assessment includes four main steps: goal and scope definition, analysis inventory, life cycle impact analysis and interpretation of the results. All materials involved in each cubicle and each green facade system were studied in detail. Afterwards, the behaviour of these facades was analysed through real experimentation in the pilot plant. Therefore, it was possible to calculate all the processes involved in the cradle to gate approach of each system, making a comparison between them and seeing which materials or processes were the most significant.

In urban areas, environmental quality is compromised by local and temporary overheating phenomena and air pollution concentration minimising urban space resilience to climate change-related hazards. Therefore, Paper 4 was the first paper analysing greenery systems in the urban context at lab scale in the same pilot plant at Puigverd de Lleida.

The proposed study concerned the analysis of a greenery system for enhancing outdoor thermal conditions and local warming mitigation for pedestrians for the continental Mediterranean climate compared with the same system without greenery.

Figure 12. On the top, the experimental set-up, the first sketch design of the concept is on the bottom.

Five sensors to measure air relative humidity (% RH) and temperature (◦C) were installed. Two sensors were installed under the greenery system, two more under the ropes system, and the last one in the area without any shadow system in order to be compared. The sensors were placed at 1.60 m height from the ground (human torso height for a standard man) and in the middle between the bench/pergola and the house-like cubicle, namely at a distance of 2.25 m from the cubicle wall (Figure 13).

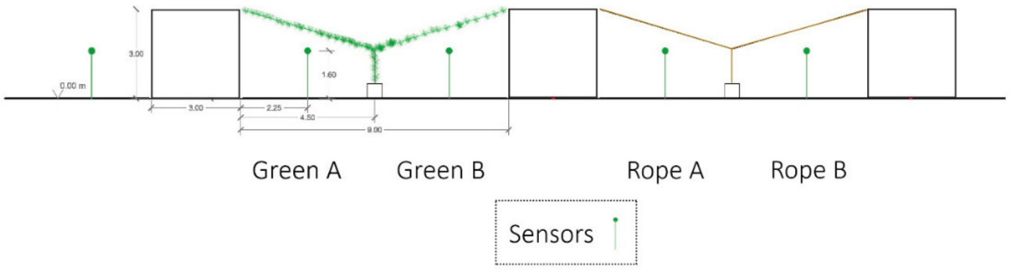

Figure 13. Sensors location in the experimental set-up

The last study aimed to explore and analyse the effect of greenery on a city scale and in a tropical climate. Therefore, the study was conceived in Singapore city-state. In high-density cities like Singapore, pedestrians experience highly variable microclimatic conditions within short distances of a daily walk and are frequently exposed to extreme conditions. Continuous field measurement through different land uses to collect microclimate weather conditions at 1.6 m height to investigate the spatial and temporal microclimate parameters in Singapore and to determine the relationship between urban morphology parameters and microclimate parameters. A tripod designed by the author of this thesis was used to calculate all the variables and parameters needed for the study. It was selected a short path for the experimentation as seen in Figure 14, and it was done in three different times a day.

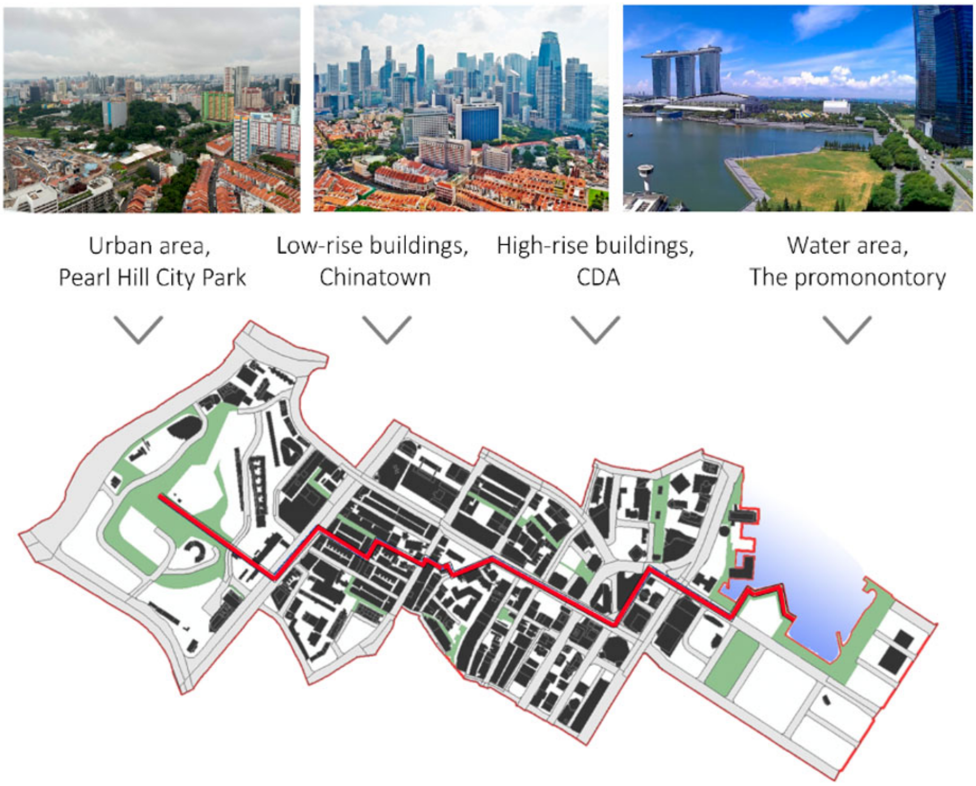

Figure 14. The studied path in Singapore

Chapter 3

Papers comprising this PhD

3.1 Paper 2: How internal heat loads of buildings affect the effectiveness of vertical greenery systems? An experimental study

3.1.1 Overview

As stated in the introduction chapter, many technologies can reduce energy consumption in buildings. These technologies can be divided between passive and active, which have been widely investigated. Within these passive technologies, vertical greenery systems (VGS) stand out as one of the most promising solutions. According to Wong et al. [44], VGS involve any way to set plants in a building facade.

Notwithstanding, current research regarding living walls benefits and challenges suggests that they can improve thermal performance in buildings, enhance air quality, modulate run-off, etc. [45]. There are still some issues that VGS have to deal with [46]. Among them, thermal performance in winter is still controversial in the literature, especially in the Mediterranean climate. As Pérez et al. [27] stated in their review, most studies found in the literature correspond to existing facades and are limited to the summer period. Therefore, many questions are still not answered. Among these questions, it has been found that the consideration of the internal heat loads inside the buildings has often been deemed, leading to a gap between building design and operational energy consumption [47].

3.1.2 Contribution to the state-of-the-art

This study provides a further step in the thermal behaviour of the VGS in the Mediterranean continental climate. The scope of this study was (i) to experimentally compare the thermal performance of two different vertical greening when implementing the internal heat gains, (ii) to compare the differences in energy consumption between the facades with internal heat gains and without the internal heat gains (optimal conditions), and (iii) to extend the scarce literature available regarding the heating period with these systems for the abovementioned climate.

Three identical house-like cubicles were used to carry out this study. The difference between them was the VGS applied to the facades. One with a green facade, the other with a green wall and the last one without any VGS (Figure 15).

The internal loads that may exist in a real building were simulated using an infrared radiator HJM mod. 301 (1000 W), which can be adjustable at different outputs. A timer was used to adjust the timing as a Spanish office profile (9.00 a.m. – 14.00 p.m. and 16.00 p.m. to 19.00 p.m.) to perform a real scenario. The considered case is an office with one person, a computer with a screen and the lighting, resulting from a total power of about 330 W (equivalent to 57.3 W/m^2) (Figure 16). This scenario was determined based on ASHRAE standards [48].

(a) Reference cubicle.

(b) Green wall in summer

(c) Green wall in winter

(d) Green facade in summer

(e) Green facade in winter

Figure 15. Studied cubicles in the experimental set-up in Puigverd de Lleida.

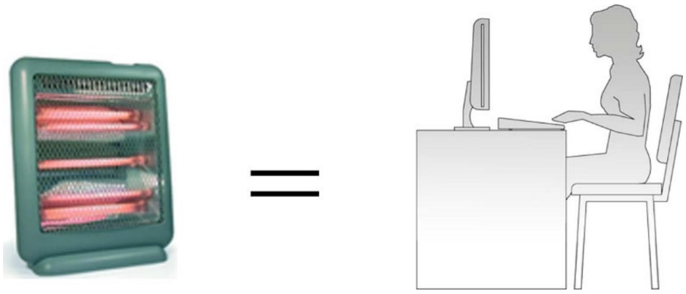

Figure 16. Infrared radiator HJM model 301. Equivalent power of office profile.

The following experiments were carried out in the experimental set-up in both summer and winter periods:

- Internal loads and controlled temperature: heat pumps were used to set the cubicles internal temperature at 24 ºC in summer (cooling) and 22 ºC in winter (heating). Then, the energy consumptions of the heat pumps were compared.
- Internal loads and free-floating conditions: no heating, ventilation and air conditioning system was used during these experiments. The evolution of indoor and outdoor temperatures of all cubicles was compared.

The conclusions drawn from this study are the following. The first conclusion is the need of considering these internal heat gains to the overall final performance, which is experimentally tested in this study. The second conclusion is the effectiveness of the VGS compared to the reference building in summer conditions although the implementation of the internal heat loads. The effectiveness of the green wall decreased 22.5%, and the green facade decreased the effectiveness 26.7% compared to the reference cubicle when the internal heat loads were considered. However, there is still significant potential in energy savings.

The third conclusion, for winter purposes, no energy savings were found; both systems were slightly punished in the winter period. Finally, the green wall showed the highest thermal stability, especially at night in winter when the outside temperature drops drastically at night.

3.1.3 Contribution of the candidate

The candidate led the long-term experimental research, the analysis of the tests, the figures presented, as well as the writing of the scientific article.

3.1.4 Journal paper

The scientific contribution from this research work was published in the journal Renewable Energy.

Reference:

J. Coma, M. Chàfer, G. Pérez, L.F. Cabeza, How internal heat loads of buildings affect the effectiveness of vertical greenery systems ? An experimental study, Renew. Energy. 151 (2020) 919–930. https://doi.org/10.1016/j.renene.2019.11.077.

Renewable Energy 151 (2020) 919–930

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

ELSEVIER

How internal heat loads of buildings affect the effectiveness of vertical greenery systems? An experimental study

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ARTICLE INFO

Article history:
Received 2 May 2019
Received in revised form
8 October 2019
Accepted 15 November 2019
Available online 18 November 2019

Keywords:
Vertical greenery systems
Passive energy savings
Internal heat loads
Buildings
Occupancy

ABSTRACT

Nature-based solutions applied to the building skin, such as green roofs and vertical greenery systems, are standing out as the most promising by contributing with thermal improvements at building scale. From previous research done by GREiA research group at the University of Lleida (Spain), energy savings up to 58% were obtained by implementing vertical greenery systems on external building walls for cooling purposes. However, since there exist other passive and active energy saving technologies in the literature review that were limited their cooling and heating capacity after implementing internal heat loads, new experimental tests for two different vertical greenery systems simulating the heat loads in both, summer and winter were conducted in this research. Additionally, these experiments also improve the scarce and controversial literature for winter conditions. The results demonstrated that considering internal loads in experimental investigations is crucial for the results of the effectiveness of the green walls and green facades. The energy savings of VGS were reduced between 22.5% and 26.7% because of the internal loads for cooling purposes, and increased about 3.6% and 3.1% for heating.

3.2 Paper 3: A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate

3.2.1 Overview

The built environment is responsible for a high global share of environmental, economic and social impacts. Therefore, the standard practices of the construction of buildings are jeopardising the chances for future generations to meet their own needs [49]. Hence, since building operational energy is being reduced, materials and embodied energy are becoming increasingly more important for resource-efficient construction [50].

In this context, life cycle assessment (LCA) applied to buildings aims to assess the potential environmental impacts of buildings over the complete life cycle, from materials production to the end-of-life and management of waste disposal [49]. As defined by ISO 14040:2006 and 14044:2006 [42,51], LCA is "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". In order to obtain the environmental impacts of any system, four iterative phases are involved [52], as shown in Figure 17.

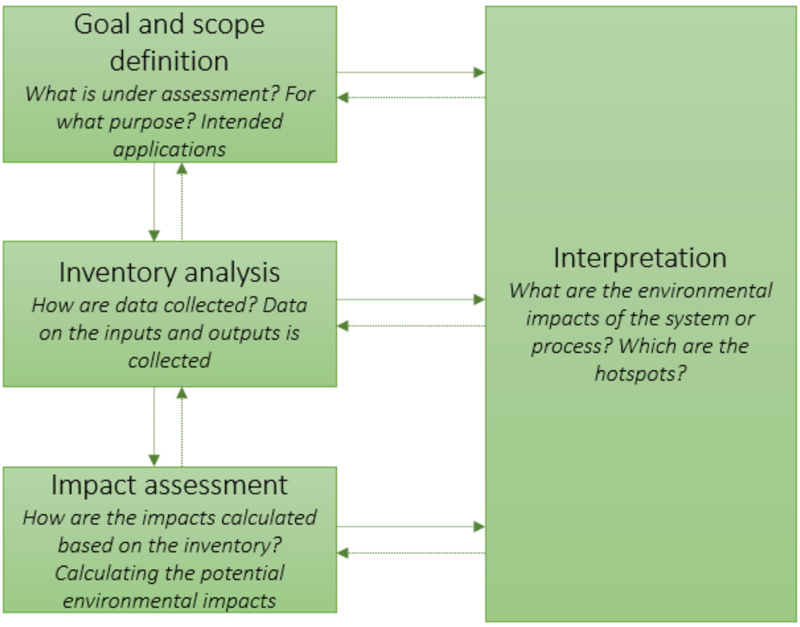

Figure 17. Phases of the LCA methodology

Importantly, transparency in the assumptions and methodologies used ensures a reproducible analysis and proper interpretation of results and careful consideration of several aspects of the natural environment, human health and resources help to give a holistic assessment [53].

Finally, LCA was widely acknowledged as an optimal decision support tool for identifying the important environmental factors in product systems. In that context, there is a lack of information on the environmental impacts of the vertical greenery systems.

3.2.2 Contribution to the state-of-the-art

As mentioned in the PhD thesis introduction and in the bibliometric study, one of the main gaps regarding the VGS is the environmental impact through a life cycle assessment (Figure 18). The objective of this study is to assess a comparative LCA and to determine and quantify the environmental impacts between a green wall and green facade compared to a reference wall, in order to benchmark with other green walls systems by comparing environmental performance and energy consumption with real data from the experimental set-up. The lifetime considered is 50 years, which is the expected life of a building. This study is the first in the literature, encompassing all the stages in the life cycle perspective.

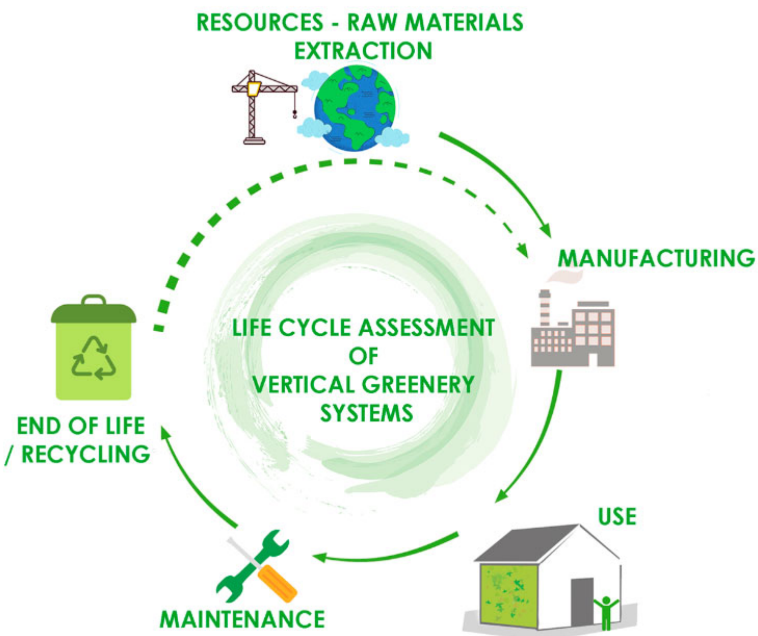

Figure 18. The system boundary of the study

The case study of the facades is the same as the previous paper [54]. The first step was to do a detailed inventory of all materials involved in the construction of the green wall and the green facade and the reference in order to be comparable. The Ecoinvent database 3.7 [55] was used to obtain the environmental impacts, and the quantitative indicators used in the study were ReCiPe 2016 and the IPCC 2013.

This life cycle analysis provided new insights into the knowledge in the literature regarding vertical greenery systems. As seen in Figure 19, the contribution of the use stage is dominant in all impact categories, overshadowing the importance of other stages, particularly the maintenance stage and the final disposal. The use stages had an impact of about 85%, while the manufacturing stage varies from 12% to 18%.

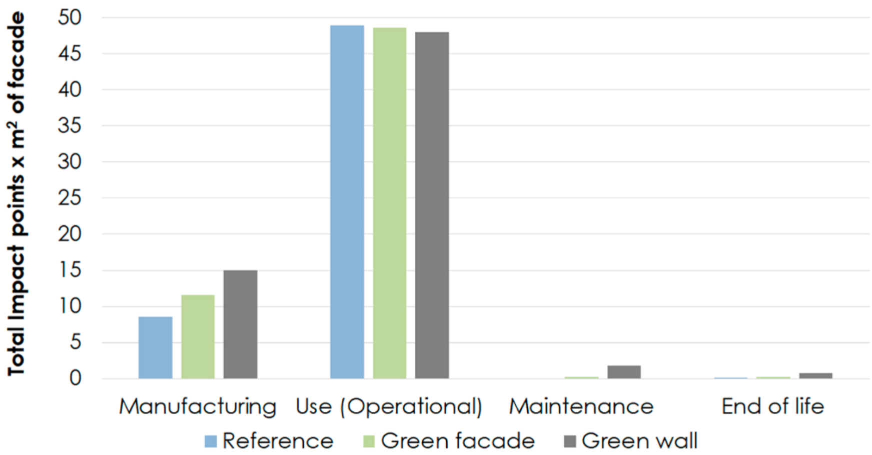

Figure 19. Total impact points per stage

The green wall system is not as sustainable as the green facade due to all the supporting material. Although in this study, the green wall was done with recycled polyethene and recycled substrate (which decreased the impact notably), more research is needed for all the support materials, especially for the stainless steel support that the boxes are supported. The same issue can be applied to the green facade, which has a stainless steel mesh; almost all its environmental impact is due to the supporting system. Moreover, in terms of water supply and fertilisers, the green wall showed an important environmental impact.

Moreover, the results highlight that the reduction in energy consumption for heating and cooling is a significant factor in reducing the buildings life cycle environmental impacts. When adding VGS, there is an annual reduction of about 1% in the environmental burdens; however, the reduction is almost 50% in summer. That means that more research should be done to adapt the VGS for its use in winter in the Mediterranean climate. Finally, with the choice of more sustainable materials and reducing the energy demand in winter, the VGS, especially the green wall, would become a more sustainable option in terms of environmental impacts thanks to the energy savings potential in the cooling period.

Finally, it is worth mentioning that focusing only on the environmental impacts would risk underestimating the intangible benefits that VGS provide as CO_2 absorption, biodiversity, run-off, etc. This issue highlights the potential tensions between sustainability and the need to promote resilience, particularly when prioritising land.

3.2.3 Contribution of the candidate

The candidate led the complete life cycle analysis, performed the inventory, analysed data and results, the figures presented, and the writing of the scientific article.

3.2.4 Journal paper

This paper published to the journal Energy and Buildings.

Reference:

M. Chàfer, G. Pérez, J. Coma, L.F. Cabeza, A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate, Energy Build. (2021) 111236. https://doi.org/10.1016/j.enbuild.2021.111236.

Energy & Buildings 249 (2021) 111236

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate

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ARTICLE INFO

Article history:
Received 12 February 2021
Revised 17 June 2021
Accepted 25 June 2021
Available online 28 June 2021

Keywords:
Life cycle assessment (LCA)
Green wall
Green facade
Environmental impact
ReCiPe
GWP

ABSTRACT

The building and construction sector is a large contributor to anthropogenic greenhouse gas emissions and consumes vast natural resources. Improvements in this sector are of fundamental importance for national and global targets to combat climate change. In this context, vertical greenery systems (VGS) in buildings have become popular in urban areas to restore green space in cities and be an adaptation strategy for challenges such as climate change. However, only a small amount of knowledge is available on the different VGS environmental impacts. This paper discusses a comparative life cycle assessment (LCA) between a building with green walls, a building with green facades and a reference building without any greenery system in the continental Mediterranean climate. This life cycle assessment is carried according to ISO 14040/44 using ReCiPe and GWP indicators.

Moreover, this study fills this gap by thoroughly tracking and quantifying all impacts in all phases of the building life cycle related to the manufacturing and construction stage, maintenance, use stage (operational energy use experimentally tested), and final disposal. The adopted functional unit is the square meter of the facade. Results showed that the operational stage had the highest impact contributing by up to 90% of the total environmental impacts during its 50 years life cycle. Moreover, when considering VGS, there is an annual reduction of about 1% in the environmental burdens. However, in summer, the reduction is almost 50%. Finally, if the use stage is excluded, the manufacturing and the maintenance stage are the most significant contributors, especially in the green wall system.

3.3 Paper 4: Greenery system for cooling down outdoor spaces: results of an experimental study

3.3.1 Overview

Urban overheating is one of the most documented phenomena of climate change. Urban greenery is a natural solution to cool cities and provide comfort, clean air and significant social, health and economic benefits [8]. Therefore, in such context, outdoor spaces are becoming increasingly less comfortable and even dangerous for citizens, significantly if they are affected by general energy poverty with no chance for active systems management for heating and cooling or health vulnerability.

Among other solutions, greenery is one of the most accepted and implemented system to counteract the damage caused by the extreme heat waves and urban heat island effect in cities [56]. Therefore, the study of green infrastructures providing benefits not only in terms of outdoor thermal comfort, but also for the built environment located in their close proximity may represent a further mitigation and well-being opportunity [57,58].

Within this background, there is a lack of information about how greenery shading systems can influence the local microclimate in terms of experimental tests.

3.3.2 Contribution to the state-of-the-art

This study aimed to further expand empirical research regarding the cooling effect of vegetation through an experimental analysis. The scope of this study was to experimentally compare two identical shadow systems that may be used in the outdoors but which differ in the presence of vegetation and, therefore, to analyse the reduction of temperatures that "green pergolas" may provide to the local microclimate. The concept of this study is presented in Figure 20. The main idea of these systems was to be "not only a pergola" but also a place where people can sit and gather and socialise in the urban space.

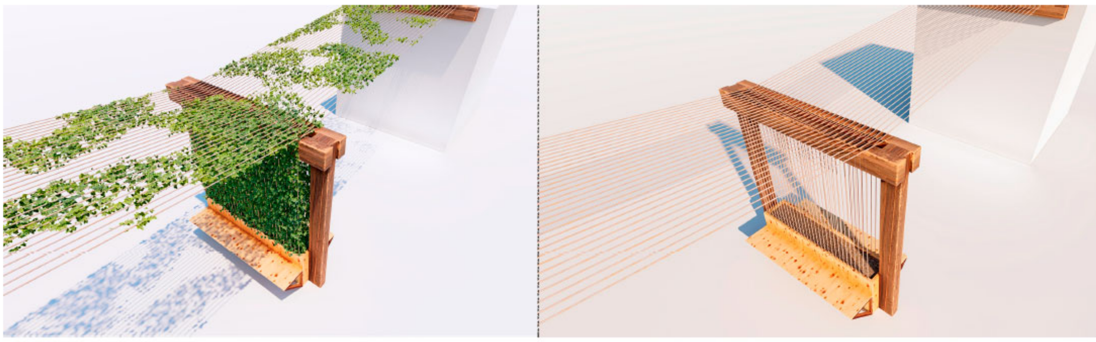

Figure 20. Concept of the two studied pergolas

In this context, two shadow systems were designed and built in an experimental set-up at Puigverd de Lleida, Spain, under the continental Mediterranean climate with dry summers and foggy winters. The two systems were east and west oriented. The selected vegetation was *Wisteria sinesis,* a climbing plant suitable in the Mediterranean continental climate (Figure 21). An irrigation system was installed and programmed to irrigate four times per night in summer.

Five sensors were installed to measure the air temperature (ºC) and relative humidity (% RH). Four of the five sensors were installed under the shadow systems. The last one was installed without any system to see the effect and compare it with the other systems.

Figure 21. Detailed view of the green pergola.

The experimentation took place during June and July 2019 (the hottest month in Lleida). The first experiment was to continuously monitor the air temperature and relative humidity. The second experiment was the comparison of the surface temperatures using an infrared camera.

The results showed the cooling effect of the vegetation creating cool areas beneath the green pergola, which would be a suitable urban solution in otherwise open spaces within an urban area. Results showed that the air difference temperature between the green pergola and the system with the ropes was up to 2.5 ºC during daytime and 3.1 ºC during night-time. Moreover, when comparing the green pergola with the outdoor temperature without any shading system, the difference was up to 5 ºC. The surface temperature (vegetation and ropes) had a difference of temperature up to 5.3 ºC. These findings broadly support the hypothesis that greening can cool the environment, at least at a local scale. This empirical study adds knowledge to the state-of-the-art and to the body of theory to provide a tighter coupling between the theory and empirical research.

3.3.3 Contribution of the candidate

The candidate conceived and designed the study. Moreover, she performed the analysis and the tests and wrote the article.

3.3.4 Journal paper

The scientific contribution from this research work was published in the journal sustainability.

Reference:

M. Chàfer, A.L. Pisello, C. Piselli, L.F. Cabeza, Greenery System for Cooling Down Outdoor Spaces: Results of an Experimental Study, Sustainability 12 (2020) 5888. https://doi.org/10.3390/su12155888.

sustainability

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Article

Greenery System for Cooling Down Outdoor Spaces: Results of an Experimental Study

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Received: 24 May 2020; Accepted: 17 July 2020; Published: 22 July 2020

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Abstract: Urban green infrastructure (UGI) and nature-based solutions (NBS) are increasingly recognized as strategies to address urban sustainability challenges. These solutions are attracting key scientific and marketing attention thanks to their capability to improve indoor and outdoor thermal comfort and environmental quality of spaces. In urban areas, where most of the population worldwide lives, indoor-outdoor environmental quality is compromised by local and temporary overheating phenomena, air pollution concentration, and impervious surfaces minimizing urban space resilience to climate change related hazards. In this view, the proposed study concerns the analysis of a greenery system for enhancing outdoor thermal conditions and local warming mitigation for pedestrians for the continental Mediterranean climate. The system has the purpose of designing an outdoor "alive" shading system to be applied in open public spaces, with producing physical and societal benefits. The experimental results showed that the implementation of the greenery, characterized by lower surface temperatures and evapotranspiration compared to a simple pergola system, allows the reduction of outdoor air temperature under the shading system and, thus, higher relative humidity in summer. Specifically, the hygrothermal cooling and the additional shading thanks to the presence of greenery provide local air temperature reduction up to 5 °C at pedestrian level.

Keywords: greenery; outdoor microclimate; cooling effect; biophilic cities; thermal environment

3.4 Paper 5: Microclimate analysis from a pedestrian walking perspective through different urban morphologies: case study Singapore

3.4.1 Overview

According to the 5th Report of IPCC [3], the temperature in Southeast Asia increased at a rate of 0.14º C to 0.20º C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather [59]. Today, more than half the world population lives in cities and this percentage is expected to increase to 68% by 2050, especially in Africa and Asia [1]. This upward trend of urbanisation, both in terms of area and density, affects the radiant balance of urban areas, anthropogenic heat release, wind flow and the convective heat exchange between the built environment, its rural surroundings, and the atmosphere above [60].

Singapore rapid urban growth rate makes this city an extreme case of urbanisation within Southeast Asia countries [13]. The high pace of urbanisation is causing diminishing forest density in Singapore. It currently has the lowest amount of its original forest area left intact compared to its Southeast Asian neighbours. Consequently, future urbanisation can potentially trigger increasing the UHI effects in Singapore and endangering this city with further environmental issues [14]. Moreover, the mean yearly temperature for Singapore increased by 0.25ºC from 1948-2008 [15].

3.4.2 Contribution to the state-of-the-art

The novelty of the present study was the amalgamation of different measurements in the outdoor environment of Singapore. The study aimed to investigate the effect of different urban morphologies such encompassing high-rise and low-rise buildings, green areas, and water bodies on the urban microclimate in Singapore. For the first time in Singapore, mobile measurements were conducted in the central area to explore the severity of the UHI effect through distinctive urban morphologies mentioned before.

First, a short walking distance path was selected for the study. The path was chosen to encompass a park, low-rise buildings, high-rise buildings, and water in the less possible time (40 minutes by foot) Figure 22. Mobile traverses were conducted during January, February and March 2020. Survey times were afternoon (15.30-16.10), which is considered the hottest time during the day, after sunset evening (19.00-19.40), and after midnight (01.00-01.40) to see the UHI effect.

This study analyses the microclimate conditions through a pedestrian perspective; therefore, a walking tripod with all the sensors was created. A conventional camera tripod was used to be a wearable apparatus; then, all the sensors were fixed there in a polystyrene basement.

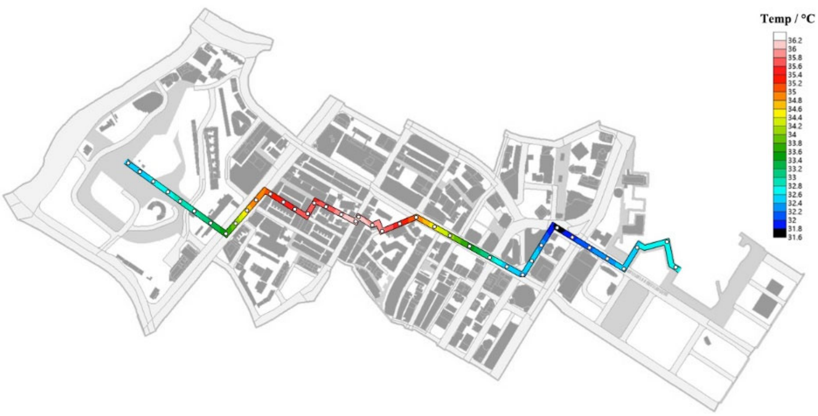

Figure 22. Plotted distribution pattern of average temperature at 15:30 along the path

The shading and the cooling effect of vegetation can reduce air temperature up to 4.5 ºC and 4 ºC during the daytime, respectively. At night, the cooling effect was up to 1 ºC. Thus, it can be concluded that during the daytime, shading the direct sun is the most important factor in providing a cooler air temperature and comfort, especially in the tropical climate:

- There is a good correlation between air temperature and SVF when water bodies are not considered. Results prove that during daytime, when there is solar radiation, the lower the sky openness, the lower the air temperature is. It is due to not only the canyon geometries but also the shading of trees. During night-time, including evening and night data, results show that SVF is not significant in influencing the air temperature.

- Urban parks can provide shading during the daytime and evaporative cooling at night-time. Thus, air temperature throughout the day can be maintained at a cool level.
- Open space has a very high daytime air temperature due to maximum solar heat gain received by the surface. However, in this study, it also has a relatively high air temperature during night-time, which may be due to the anthropogenic heat.
- The water body does not show any correlation between the SVF and the air temperature. Moreover, the water area cools the air temperature during the day, but however, at night, it acts on the other way around being a heat sink in the tropical climate.

3.4.3 Contribution of the candidate

Marta Chàfer conceived and designed the study. After that, she performed the study and designed the mobile, the wearable tripod, and the data analysis and wrote the article.

3.4.4 Journal paper

This paper is under review in the journal Urban Climate.

Urban Climate

Mobile measurements of microclimatic variables through the central area of Singapore

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	microclimate; outdoor thermal comfort; Urban heat island; greenery; transect; sky view factor
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Abstract:	High-density cities, such as Singapore, have to deal with the urban heat island (UHI) effect, which is one of the most critical anthropogenic climate change-related environmental issues for contemporary high-density cities. This study aims to investigate the effect of different urban morphologies such as high-rise and low-rise buildings, green areas, and water bodies on the urban microclimate in Singapore. Mobile measurements were conducted for the first time in the central area of Singapore to explore the severity of the UHI effect through distinctive urban morphologies. The Sky View Factor (SVF) was also calculated. This study revealed a strong relationship between the decrease in air temperature and greenery coverage in the city. Moreover, during the daytime, the air temperature was higher when SVF increased, except for the water body area. Urban parks provided shading during daytime and evaporative cooling at night-time, which lead to a relatively cool level air temperature throughout the day.

Chapter 4

Conclusions

In this highly urbanised world and the rise in concern about climate change has led to the increasing trend of bringing nature back into cities. It is worth mentioning that with the COVID19 crisis, the intangible value of the green areas near our homes has increased exponentially. This year, when this virus has forced humanity to suddenly stop, without previous warning, green spaces have been one of the significant claims after so many hours forced to be locked up at home.

The introduction to this thesis placed the search for the enhanced resilience of cities by implementing greenery systems in buildings and in the urban context within a broader global challenge of addressing climate change mitigation. This chapter, therefore, presents the outcomes of the present work in terms of their significance and contribution to knowledge.

Since I have been able to study two completely different climates, it must be said that the tropical climate already has natural green areas due to its temperature and daily precipitation. It is not the same, greening a tropical city where it daily rains, rather than greening a city with a dry climate and hot summers with extreme temperatures with heat peaks by up 40ºC.

The thesis started in chapter one with a complete bibliometric analysis in order to provide a holistic overview of the development of the greenery topic, the research trends and the main gaps observed in the literature. Overall, the research on this topic was increasing, with new methods and directions. However, some gaps still remained, particularly in the areas of environmental impact, costs, health, outdoor thermal comfort, and vertical greenery systems. It was through this analysis that the thesis undertook its study objectives.

This thesis has reflected on the cooling and isolation capacities of vertical greenery systems in the continental Mediterranean climate. In detail, growing vegetation on building walls has many benefits, including reducing daily temperature extremes of the buildings exterior surfaces and reducing the need for energy consumption. Although few researchers focused on how green facades reduce the whole building cooling load, no studies considering the internal loads were found. The research objectives were to experimentally reinforce existing research on the benefits that vertical greenery systems may provide under the Mediterranean Continental Climate. Based on data gathered from the experimental analysis, it was concluded that adding a vertical greenery system to the facades effectively reduced the building energy demand although considering the internal heat loads.

To study more in-depth the environmental burdens that VGS may have, a life cycle analysis of the two systems was carried out to be able to specify the weakest points of the systems and to see where it could be improved. The green wall was clearly penalised for all the material that this system entails. Although the reduction of impacts thanks to the reduction in energy demand is very notable, it is not enough to balance a system that does not have any type of green system. However, as Riley stated in his lessons learnt paper about living walls [46], some of the latest research is less positive than living wall proponents may wish. For that reason, it is crucial to add new data in the literature to provide more reliable information to the industry to develop new technologies about VGS.

Later, it was wanted to tackle the classic pergola that already existed since the Babylonian gardens, but this time with scientific results and to see the real advantages that they can provide in the continental Mediterranean climate. It should be noted that a plant species very adapted to that dry climate mentioned above were chosen, and the results were very positive. Up to 5ºC reduction was reached with the vegetated pergola compared to a pergola with ropes.

Finally, the last experimentation was carried out in the previously mentioned tropical climate in Singapore. Thanks to the 5-month stay that I did there. It was studied how different urban morphologies and urban parks influenced the local temperatures of pedestrians. Quantified results were obtained of the cooling power of parks in the centre of cities as densely crowded as Singapore.

The knowledge generated by the present work narrows the knowledge gaps identified and ratifies the premise that greenery systems can enhance urban sustainability. However, more research should be done, especially in climates as the continental Mediterranean climate.

The research presented in this thesis contributed valuable new information to fellow greenery systems researchers, designers, architects, and proponents. There is an obvious need for greater exchange and communication with practitioners and decision-makers in cities to understand what knowledge is needed.

Other research activities

Other journal publications

The PhD candidate carried out other scientific research besides the one presented in this thesis during the execution of his PhD. The resulting publications are listed below:

1. **M. Chàfer**, F. Sole-Mauri, A. Solé, D. Boer, L.F. Cabeza, Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source, J. Clean. Prod. 231 (2019) 1122–1135. doi:10.1016/j.jclepro.2019.05.304.

2. L.F. Cabeza, **M. Chàfer**, Technological options and strategies towards zero energy buildings contributing to climate change mitigation: a systematic review, Energy Build. 219 (2020) 110009 (1–46). doi:10.1016/j.enbuild.2020.110009.

3. I. Pigliautile, **M. Chàfer**, A.L. Pisello, G. Pérez, L.F. Cabeza, Inter-building assessment of urban heat island mitigation strategies: Field tests and numerical modelling in a simplified-geometry experimental set-up, Renew. Energy. 147 (2020) 1663–1675. doi:10.1016/j.renene.2019.09.082.

4. L.F. Cabeza, **M. Chàfer**, É. Mata, Comparative analysis of web of science and Scopus on the energy efficiency and climate impact of buildings, Energies. 13 (2020). doi:10.3390/en13020409.

5. J. Coma, A. de Gracia, **M. Chàfer**, G. Pérez, L.F. Cabeza, Thermal characterisation of different substrates under dried conditions for extensive green roofs, Energy Build. 144 (2017) 175–180. doi:10.1016/j.enbuild.2017.03.031.

6. L.F. Cabeza, A. Frazzica, **M. Chàfer**, D. Vérez, V. Palomba, Research trends and perspectives of thermal management of electric batteries: Bibliometric analysis, J. Energy Storage. 32 (2020). doi:10.1016/j.est.2020.101976.

7. N. Llantoy, **M. Chàfer**, L.F. Cabeza, A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate, Energy Build. 225 (2020) 110323. doi:10.1016/j.enbuild.2020.110323.

8. I. Villalobos, A. De Gracia, **M. Chafer**, L.F. Cabeza, S. Ushak, Experimental Comparison of Passive Heating/Cooling Space in Lightweight Buildings with Potential Application in Mining Camps, IOP Conf. Ser. Earth Environ. Sci. 503 (2020). doi:10.1088/1755-1315/503/1/012083.

9. L.F. Cabeza, L. Boquera, **M. Chàfer**, D. Vérez, Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis, Energy Build. (2020) 110612. doi:10.1016/j.enbuild.2020.110612.

10. M. Norouzia, **M. Chàfer**, L.F. Cabeza, L.Jiménez, D. Boer, Circular economy in the building and construction sector: A scientific evolution analysis. Journal of Building Engineering. 44 (2021). 102704 10.1016/j.jobe.2021.102704

Contributions to international conferences

The PhD candidate contributed to some international conferences:

1. M. Chafer, A. de Gracia, L.F. Cabeza. A comprehensive study of the construction of the historic and heritage buildings. The influence of the thermal mass. Avances in Thermal Energy Storage - Eurotherm Seminar #112. 2019 Lleida (Spain)

2. I. Villalobos, M. Chafer, S. Ushak; P. Marin, A. de Gracia, L.F. Cabeza. Thermal assessment of using passive PCM technology in lightweight buildings. 11CNIT - XI National and II International Engineering Thermodynamics Congress. 2019 Albacete (Spain)

3. M. Chafer; Coma J; Perez G; Cabeza LF. Thermal performance of different vertical greening systems in winter. The 14th International Conference on Energy Storage. EnerSTOCK2018. Proceedings Book. pp. 1335 - 1344. Çukurova University, 2018. Çukurova (Turkey)

4. J. Coma, M. Chàfer, A. de Gracia, G. Pérez, L.F. Cabeza. Thermal characterization of different substrates under dried conditions for extensive green roofs. 10º Congreso Internacional de Ingeniería Termodinámica. 2017 Lleida (Spain)

5. G. Perez, M. Chàfer, J. Coma, L.F. Cabeza. Thermal performance of different vertical greening systems in winter. 10º Congreso Internacional de Ingeniería Termodinámica. 2017 Lleida (Spain)

6. L.F. Cabeza, M. Chàfer. Almacenamiento de energía térmica (TES) con materiales con cambio de fase (PCM) para la eficiencia energética y el confort en el sector de la edificación. IV Encuentro de Ingeniería de la Energía del Campus Mare Nostrum. 2018 Murcia (Spain)

7. G. Perez, M. Chàfer, J. Coma, S. Burés, M. Urrestarazu, L.F. Cabeza. Winter operation of vertical greenery systems for energy savings in buildings. Advanced Building Skins Congress 2017 Bern (Switzerland)

8. M. Chàfer, C. Piselli, A. L. Pisello, I. Pigliautile, G. Pérez, L.F. Cabeza. Bio-inspired outdoor systems for enhancing citizens thermal comfort in public spaces by learning from nature. 7th International Building Physics Conference Syracuse, New York, (United States)

Scientific foreign-exchange

The PhD candidate did one stay abroad during the development of this PhD thesis.

- **School of design and environment, National University of Singapore (Singapore)**

The research period done by the candidate was carried out at the School of Design and Environment at the National University of Singapore. In this research stay, the candidate worked on the study of the microclimate analysis of the different urban morphologies in the city centre of Singapore through mobile measurements.

Others activities

Projects participation

- Methodology for analysis of thermal energy storage technologies towards a circular economy (MATCE). Ministerio de Ciencia, Innovación y Universidades de España, RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE, 2019-2021.
- Red Española en Almacenamiento de Energía Térmica (RED-TES). Ministerio de Ciencia, Innovación y Universidades de España, RED2018-102431-T, 2020-2021.
- GREiA. Grup de Recerca en Energia i Intel·ligència Artificial (SGR). Generalitat de Catalunya, 2017 SGR 1537, 2017-2020.
- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica (SOPPORTES). Ministerio de Ciencia e Innovación, ENE2015-64117-C5-1-R, 2016-2018.
- Disseny i desenvolupament de sistema nou de recollida per us domestic i/o privat. Urban Refuse Development, SL. C19029
- Anàlisi del cicle de vida entre sistema de re collida pneumàtica de residus i camions. Urban refuse develpment. C17035

Organising committee participation

- Researcher´s Night 2018, 13th edition 2018. Lleida, Spain.
- Researcher´s Night 2019, 14th edition 2019. Lleida, Spain.
- Noon no Noon with energy and environmental challenges 2018, 1st edition 2018. Perugia, Italy

Teaching

- Sustainable Construction 1 at University the Lleida with Prof. Luisa F. Cabeza and Dr. Gabriel Pérez from the course 2017-18 until 2020-21

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