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Thermal Performance of Green Façades: Research Trends Analysis Using a Science Mapping Approach

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Abstract: Buildings consume a significant part of the world's resources and energy. The growing environmental awareness and urgent need to reduce energy consumption have highlighted the importance of introducing innovative solutions as nature-based systems in new buildings' construction and retrofitting. In this regard, green façades that integrate vegetation into building envelopes are attractive. This paper presents a bibliographic analysis, based on science mapping, of the available literature on green façades from 1999–2022 with a focus on the thermal effect on the building and on the surroundings. The objective of this study is to reveal the structure and the evolution of the research activity in the field, outlining the main research topics and the future research directions. The analysis was performed on a dataset of 270 documents. The results indicate a growing interest in this topic over the last six years and the multidisciplinary dimension of the studies. The keyword cluster analysis indicates the emergence of three main search topics: thermal behavior and energy modeling; urban design and large-scale effects; sustainable buildings management. A greater future dissemination of green façades could be enabled by further research results based on the application of a multidisciplinary approach and of standardized methods.

Keywords: building energy efficiency; energy saving; bibliometric analysis; thermal comfort; urban heat island effect; vertical greenery systems

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1. Introduction

According to the United Nations, 55% of the world's population in 2018 resided in cities. It is estimated that the urban population may reach on average about 68% by 2050, with a percentage close to 87% in more developed regions and 66% in less developed ones [1]. Urban areas account for 75% of global primary energy consumption. In developing countries, the annual growth in energy demand is about 7% against an almost stable supply [2]. The population growth and rapid urban expansion have led to a reduction in urban green areas and to an increase in the presence of artificial surfaces made of non-reflective and water-resistant materials. These are characterized by the high absorption of solar radiation and high heat storage capacity. The presence of these artificial surfaces at the expense of vegetated spaces, combined with urban structures implicating low sky view factors, are identified as significant causes of the urban heat island (UHI) effect [3]. The UHI phenomenon consists of extended heat stress in the built environment, and causes increases in urban peak electricity demand due to a greater use of air conditioning for cooling. Urban green infrastructures (UGIs), bringing vegetation inside urban areas, can provide several significant benefits at both the urban and building level [4], contributing to a reduction in energy consumption and pollutant discharge to receiving waters, and to the removal of air pollutants [5,6]. Within these, vertical greenery systems (VGSs), involving the application of vegetation layers on the building's envelope, have an important role, with the benefits of not requiring valuable urban land use [7–9]. VGSs are commonly categorized into green façades (GFs) and living walls (LWs) [10,11], according to the different locations of the growing medium for plant roots. Thus, GFs and LWs are defined as “green” and “living”, respectively, since these are characterized by the presence of a layer of vegetation that, depending on the type of VGS, is applied in different ways to the building walls. In GFs, plants can be rooted in the ground at the base of the building or in growing media placed in pots set at different heights of the building’s walls. Plants can be evergreen or deciduous, climbing or cascading. The GF system can be direct or indirect. The direct GFs involve the use of self-climbing plants attached directly to the building envelope surface. The indirect GFs incorporate supports, such as steel cables or trellises placed at small distances from the wall surface, for the vertical growing of climbing or hanging plants. LW systems are characterized by the vertical positioning of the growing medium in front of the building wall. Panel, felt or container systems are commonly used for carrying the growing media; these can be attached vertically to a free-standing frame or directly to the wall. A greater variety of plants can be used in LW systems than GFs. On the other hand, GFs are the simplest technology in the field of engineered VGSs, and have a wider application potential due to their simplicity, cost-effectiveness, and ease of installation and maintenance [12].

GFs can increase the energy efficiency of buildings by creating comfortable conditions and reducing energy use for air conditioning systems due to the shading, cooling, insulation and wind barrier effects [13–15]. Considerable reductions in the temperature of the external surface of the wall covered by vegetation [14,16,17] and lower temperatures within the air gap between the wall and vegetation [15,18] have been found. Smaller heat fluxes in GFs compared to an uncovered wall have been assessed, especially in warm periods [19].

Different solutions for reductions in heat stress have been compared in urban street canyons, and GFs were found to significantly improve outdoor thermal comfort [20]. A mitigation of heat stress at the pedestrian level can be achieved by planting trees and greening façades, while negligible contributions were made by green roofs [21]. GFs were found to be more effective in lowering the radiation temperature and the perceived temperature at street level when implemented at this level [22].

Numerous reviews have been carried out in the past on VGSs, with a focus on thermal performance and energy saving [11,23–26]. The bibliometric analysis approach was also recently used to analyze broader research areas, such as all VGSs typologies [27–29], as well as greenery systems including green roofs [30] and green buildings [31]. A more in-depth bibliometric analysis, based on science mapping, of the research field of GFs and their thermal performance is still missing.

Mathematical and statistical methods, as well as data mapping techniques, can be applied to analyze the quantity and quality of the scientific production, and to provide a graphical representation of the structure and trends of scientific activity within a specific discipline, an area of research or a topic; this approach, referred to as bibliometric analysis, comprises performance analysis and science mapping techniques [32–34]. This methodology enables comparative analyses of productivity and cooperation at the level of research groups, scientific institutions, or countries. It is useful for detecting research trends and developing or regressing areas, as well as for the presentation, assessment and tracking of scientific activities and projects [35].

The current study presents a bibliometric analysis of the scientific research published in 1999–2022 on the GFs thermal effects on the buildings, and on the external environment. Science mapping can offer a useful alternative instrument for examining the pertinent literature and detecting the structure and development of the research activity. The purposes of this study are: (1) the identification and quantification of temporal and geographic dynamics in the pertinent literature, where mainly research outcomes are reported; (2) to point out the main research topics and their evolutionary trends; (3) to highlight the main recent and future research directions in the field of GFs thermal performance at the building and urban level. The results may be valuable to scientists as well as to research project-funding institutions and policymakers who wish to increase their comprehension of research patterns related to GFs, with a focus on thermal and energy performance.

The paper is organized into four main sections. Section 1 includes an introduction to the research theme and the aims of the study. In Section 2, there is a description of the implemented methodology: the criteria for data selection (Section 2.1) and the approach followed for the bibliometric and cluster analysis (Section 2.2). Section 3 reports the main results of the study. Section 3.1 includes the main findings of the bibliographic analysis with reference to the trends in publishing over the years, subject areas, geographic distribution and collaborations among researchers, the most productive research institutes on the topic, and publication sources. In Sections 3.2 and 3.3, the main research topics and trends are discussed. Section 3.4 deals with the main research gaps and potential aspects to be investigated in future studies. Section 4 summarizes the main findings arising from the bibliographic analysis, the main trends and themes, and further research efforts needed.

2. Materials and Methods

2.1. Data Collection

Elsevier's Scopus and Thomson Reuters' Web of Science are multidisciplinary databases that are frequently used for bibliometric analyses. The Scopus database was chosen for this study since it is one of the largest repositories of abstracts and citations of peer-reviewed literature. Moreover, while 99% of the journals indexed in Web of Science overlap with Scopus, only 34% of the journals indexed in Scopus are also indexed in Web of Science [36]. Bibliographic data related to the thermal performance of GFs were identified by accessing the Scopus database on 31 March 2023. The publication time span of the documents was set by excluding the current year to capture the entire temporal evolution of the topic, and to derive data representative of whole years. The string that was used for identifying the relevant scientific publications was set up by considering the main keywords regarding the analyzed research field: "green façade", "plant-covered wall", "vegetated wall", "vertical green*", "green wall", and "vertical greenery system" were used to search documents focused on green façades, and "energy", "thermal", "cooling", "heating", "heat transfer", "heat flux", "surface temperature", "heat island effect", "urban heat island", "urban temperature", "air temperature", "mean radiant temperature", "wind speed", and "physiological equivalent temperature" were used to search documents focusing on green façades' thermal or energy performance. These keywords were chosen by reviewing the publications retrieved in the Scopus database on the analyzed research field using different research queries, and selecting the keywords and their synonyms, which, combined in a search query, led to the largest and most consistent research papers on green façades' thermal or energy performance. Some terms were used with an asterisk to increase the number of the search results by returning documents associated with the derived words. It was decided to include "plant-covered wall", "vegetated wall", "vertical green*", "green wall", and "vertical greenery system" in the set of keywords of the search string to adopt a more generic terminology than the expression "green facades", as the latter was not always used by the entire scientific community. The search was performed in the combined fields of title, abstract and keywords. The search was restricted to the retrieval of publications classified as article, review, book chapter, book, conference paper and data paper. A total of 703 results were initially obtained.

It was found that the adopted search criteria led to the inclusion of some articles that only mentioned the use of GFs as one of the technologies for energy efficient buildings or for the enhancement of urban air quality. Other articles were only related to LWs, green roofs, and building-integrated microalgae photobioreactors. Therefore, these articles were manually removed, and finally, the 270 most relevant publications on the thermal performance of GFs were screened for scientometric analyses. The data used in this study consisted of bibliographic information that included the titles, keywords, year of publication, authors and related affiliations.

2.2. Bibliometric and Cluster Analysis

The trends of productivity of this topic were analyzed according to the number and type of publications over the years, the detection of the subject areas most affected, the most active countries and institutions, the most frequent sources of publication, and their citation impact. The VOSviewer software version 1.6.19 [37] was used for creating and visualizing bibliometric networks based on the 270 retrieved publications. A keyword co-occurrence analysis and a co-authorship analysis of the found publications were undertaken, and bibliometric maps were produced to illustrate, in two dimensions, the research area of GF thermal effects on buildings and the outdoor environment. The knowledge structure of the research topics was identified, and a map was constructed illustrating the trend of co-occurrences of keywords in publications over the years.

The network of keywords representing the different research topics on GF thermal effects was created by allocating keywords into a cluster based on their co-occurrence in publications. The same color was assigned to keywords belonging to a general or specific research topic, so that the keywords were grouped into clusters highlighting the main research topics. In the present study, keywords recurring at a minimum of five times were included. Some terms not relevant for the analysis, such as country names or geographic areas, were omitted through the appropriate VOSviewer software functionality. Duplicated keywords, such as the singular and plural of a term, or synonymous terms, were formerly combined into a single keyword to carry out a closer evaluation of the relative weights of keywords in thematic clusters.

A co-authorship network was built and used to identify the characteristics of international collaboration in research on the topic. All papers were considered, including those with more than 25 authors. In the current study, countries with a minimum of five papers were considered. Different colors highlight clusters of countries that usually work together.

Figure 1 provides a graphical summary of the methodology adopted in the current study to perform the bibliometric analysis and scientific mapping.

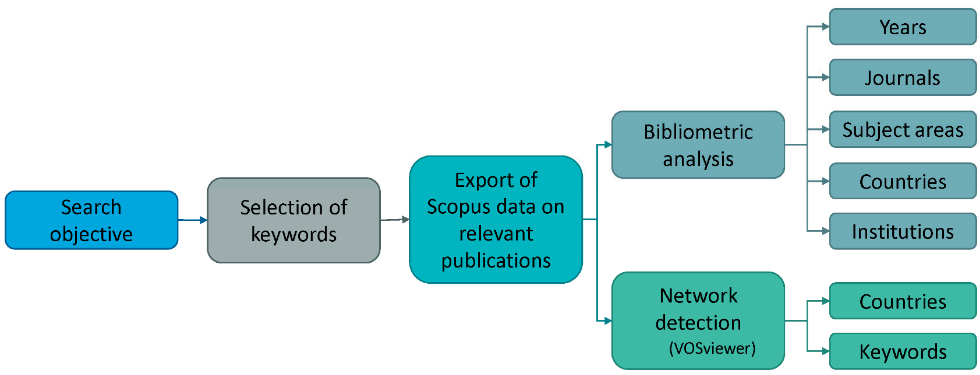

Figure 1. Workflow for data processing and analysis.

3. Results

3.1. Publication Trends

3.1.1. Annual Trend of Published Documents

A total of 270 documents were found and analyzed. Most of the documents (69% of the total publications) were published in journals as original articles and reviews, while the remaining ones were published in books (12%) or in conference proceedings (19%). The first document appeared in 1999, but the scientific production on the topic only began to be continually present from 2008 onwards. It is for this reason that the first half of the considered period (1999–2010) was characterized by a number of documents per year varying in the range 0–4 and an average of 1.0 per year (Figure 2). The second period (2011–2022) presented a significant increase in the number of papers published per year, within a range of 4–38, a mean per year of 21.5, and with 70% of the documents published in journals. This indicates that the interest in the topic of GFs has increased significantly over the past twelve years; in particular, in 2017–2022, 73.3% of the overall production was published.

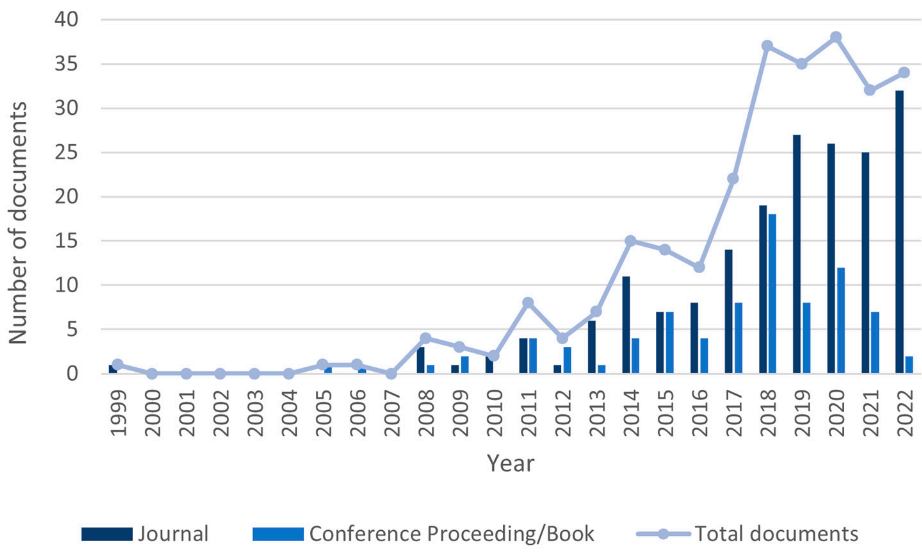

Figure 2. Trends in the number of publications per year (continuous line) and the number of articles published in indexed journals with respect to other papers reported in conference proceedings and book chapters (columns) during the period 1999–2022.

3.1.2. Subject Areas

Figure 3 shows the subject areas in which the retrieved documents were classified by Scopus. It is worth mentioning that the journals supporting multidisciplinary research were classified at the same time in several subject areas. Over the entire examined period, the highest percentage of publications fall in the Engineering subject area (28.1%), with 22.2% in the Environmental Sciences. These are immediately followed by Energy (13.7%) and Social Sciences (13.7%). Other less represented areas are Agricultural and Biological Sciences (5.1%), Earth and Planetary Sciences (3.8%), Business, Management and Accounting (2.7%) and Computer Science (2.3%). It is worth mentioning that Physics and Astronomy accounted for a high percentage before 2005 due to only one article being published in 1999 [38] in *Experimental Heat Transfer* (Taylor & Francis), a journal falling under the subject areas Physics and Astronomy, and Engineering. The evolution over the years of the distribution of papers in the different subject areas (Figure 4) shows that the Engineering area has become preponderant at the expense of the Environmental Science area. This analysis highlights the increasing multidisciplinary aspect of the research on the thermal performance of GFs given the interaction between different topics.

3.1.3. Most Prominent Countries/Regions and International Collaboration

Each country's scientific production was analyzed considering the affiliation country of the authors. More than 50 countries were involved in publishing documents on GFs' thermal performance, thus researchers' interest in the topic appears to be widespread in many countries. Figure 5 presents the most engaged countries/regions ($n = 17$), identified as participating in at least 5 papers. The top contributing country is Italy ($n = 57$; 21.1%), which significantly outperforms China ($n = 37$; 13.7%), despite the large population disparity of the two countries. The United Kingdom ranks third, with a percentage share of 8.5% ($n = 23$). Spain ($n = 22$; 8.1%) closely follows the United Kingdom. It is worth highlighting that over 80% of the publications in Italy and China were published in the most recent sub-period examined.

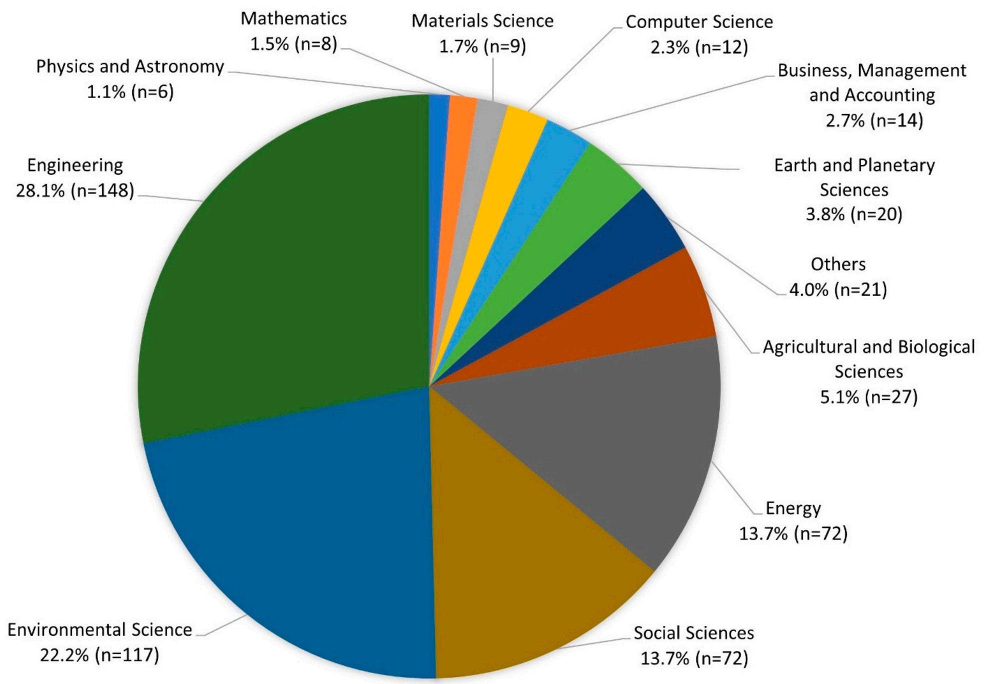

Figure 3. Distribution of the publications on green façades' (GFs) thermal performance by Scopus subject areas in 1999–2022.

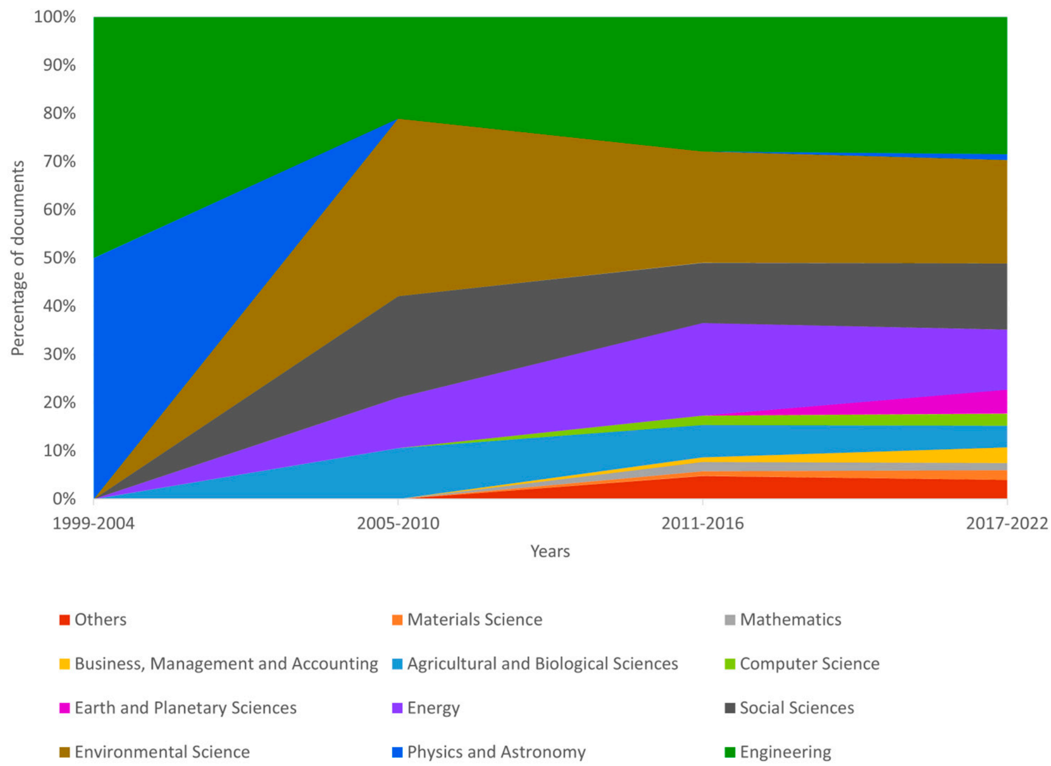

Figure 4. Trend of the distribution of the publications on GFs' thermal performance by Scopus subject areas in 1999–2022.

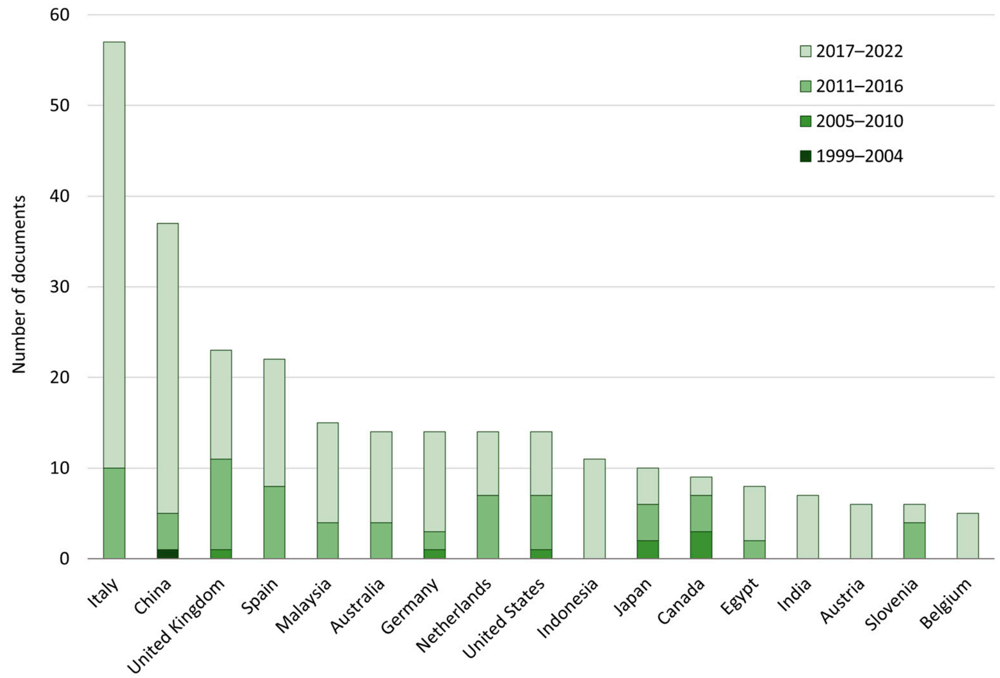

Figure 5. Countries/regions publishing at least five documents related to GFs' thermal performance from 1999 to 2022 (countries related to the authors' affiliations).

Figure 6 shows a network map representing the international cooperation between the most productive countries/regions on GFs' thermal performance (participating in at least five papers). The dimension of each label is proportional to the number of publications of each country, whereas the thickness of each curved line connecting two labels represents the number of collaborations between two countries. The various clusters formed by sets of countries are highlighted by different colors. We can distinguish three major clusters. The first cluster (green) is led by Italy, the most productive country, which presents a strong collaboration with Spain and the Netherlands with five and six documents co-authored with Italy, respectively. The second cluster (violet) is headed by China, while the third (yellow) is led by United Kingdom. Italy published up to 35.1% of its documents in collaboration with nine other countries, China published 33.3% with six other countries, and the production of the United Kingdom was characterized by a higher rate of cooperation, with 47.8% of their documents produced in co-operation with eight other countries, respectively. On the contrary, Austria did not undergo collaborations with other countries.

Figure 6. Collaborative network between countries/regions based on publications on GFs' thermal performance from 1999 to 2022.

3.1.4. Most Prominent Research Institutions

The most active institutions, identified as publishing at least five documents on the thermal performance of the GFs from 1999 to 2022, are depicted in Table 1. The top positions in the ranking are occupied mainly by Italian institutions, just as Italy ranked first among the most productive countries. The University of Bari Aldo Moro, Italy (*n* = 22, 8.1%), ranks first followed by the University of Lleida, Spain (*n* = 15, 5.6%), ENEA Italian National Agency for New Technologies, Italy (*n* = 14, 5.2%), the University of Genoa, Italy (*n* = 10, 3.7%), and the Delft University of Technology, The Netherlands (*n* = 9, 3.3%). The total documents published by these institutions achieved h-index values ranging from 5 to 11. With respect to the total number of citations, the University of Lleida, Spain (1044), the University of Genoa, Italy (869), the Delft University of Technology, The Netherlands (852) and the University of Sheffield, United Kingdom (810) emerge as the institutions with the highest impact on the research on the thermal performance of GFs. These institutions also received a high average number of citations per document, varying in the range 69.6–135.0.

Table 1. The most productive institutions publishing at least 5 documents on the thermal performance of green façades (GFs) from 1999 to 2022.

Institution	Country	N. of Documents			Total Number of Citations	Average Number of Citations *	Documents h-Index
		Total	Journal	Book—Conference Proceedings			
University of Bari Aldo Moro	Italy	22	14	8	283	12.9	11
University of Lleida	Spain	15	10	5	1044	69.6	10
ENEA Italian National Agency for New Technologies	Italy	14	9	5	92	6.6	5
University of Genoa	Italy	10	7	3	869	86.9	7
Delft University of Technology	The Netherlands	9	9		852	94.7	8
Polytechnic University of Catalonia	Spain	8	6	2	441	55.1	6
South China University of Technology	China	7	5	2	84	12.0	4
University of Sheffield	United Kingdom	6	3	3	810	135.0	4
Technical University of Munich	Germany	6	4	2	287	47.8	4
University of Ljubljana	Slovenia	6	5	1	86	14.3	5
University of Diponegoro	Indonesia	6	5	1	44	7.3	4
University of Science Malaysia	Malaysia	5	4	1	22	4.4	2
The Education University of Hong Kong	China	5	4	1	104	20.8	4
University of Salento	Italy	5	3	2	22	4.4	3

* Number of citations divided by the number of articles.

3.1.5. Most Prominent Publishing Sources

The examined documents on research on GFs' thermal performance were published in more than one hundred sources. The major characteristics of the Scopus indexed sources publishing more than three papers on GFs' thermal performances along with their number of publications, as well as the relative Scopus CiteScore (CS), SCImago Journal Rank (SJR), and Highest CiteScore Percentile (HP), are presented in Table 2. CS is an indicator of the citation impact of scientific journals based on the number of citations of a paper by a journal over four years, divided by the number of the indexes of the same paper in Scopus published in those four years. SJR is a bibliometric measure of the level of influence of a scientific journal. SJR is calculated considering the number of citations and the importance of the journals from which the citations come; it measures weighted citations received by the serial. The HP is derived from the CiteScore metric and it is an indicator of the journal's relative position in the subject area in which the source has the best ranking [39]. It can be observed that the journal with the highest number of publications is *Building and Environment*, with a percentage share of 13.0% of the total publications. *Building and Environment* achieved the first position in all the sub-periods except the first (1999–2004), when only one document was published on *Experimental Heat Transfer* (published by Taylor & Francis). It is followed by *Energy and Buildings* and *Sustainability (Switzerland)*, with a percentage share of 7.4% and 4.4%, respectively. It is worth mentioning that the high rankings of *Energy and Buildings* and *Sustainability (Switzerland)* are due to the documents published in the last sub-period analyzed (2017–2022), despite the existence of these journals since 1979 and 2009, respectively. *Building and Environment* is an international journal that focuses on research on building science, urban physics, and human interaction with the built environment; it is characterized by an SJR of 1.498, ranking after *Renewable and Sustainable Energy Reviews* (3.678), *Applied*

Energy (3.062), and *Journal of Cleaner Production* (1.921), which also presents the highest CS, and *Energy and Buildings* (1.682). All these journals ranked in the 97–99th CS percentiles. The second most highly publishing journal is *Energy and Buildings*; it is an international journal publishing studies on innovations toward the reduction in buildings' energy demand and the improvement of indoor environment quality. The third is *Sustainability (Switzerland)*, a peer-reviewed international and cross-disciplinary journal with a focus on the different aspects of sustainability and sustainable development.

Table 2. Major characteristics of the top Scopus-indexed sources publishing studies on the thermal performance of the GFs.

Source [a]	Publisher	N. [b]	N. [b] 2005–2010	N. [b] 2011–2016	N. [b] 2017–2022	CS [c]	SJR [d]	HP [e]
Building and Environment	Elsevier	35	3	9	23	10.7	1.498	98
Energy and Buildings	Elsevier	20		2	18	11.5	1.682	97
Sustainability (Switzerland)	Multidisciplinary Digital Publishing Institute (MDPI)	12			12	5.0	0.664	86
Iop Conference Series Earth and Environmental Science	Institute of Physics Publishing	10			10	0.6	0.202	20
Acta Horticulturae	International Society for Horticultural Science	9		2	7	0.5	0.163	15
Energy Procedia	Elsevier	8		7	1	n.a.	0.533	n.a.
Renewable and Sustainable Energy Reviews	Elsevier	8		4	4	28.5	3.678	97
Journal of Cleaner Production	Elsevier	6				15.8	1.921	98
Applied Energy	Elsevier	5		1	5	20.4	3.062	99
Ecological Engineering	Elsevier	5		3	2	7.7	1.015	91
Journal of Building Engineering	Elsevier	5		1	4	6.4	1.164	98
Lecture Notes in Civil Engineering	Springer Nature	5	2	1	2	0.5	0.133	9
Wit Transactions on Ecology and the Environment	WIT Press	5			5	0.8	0.173	20
Buildings	Multidisciplinary Digital Publishing Institute (MDPI)	4			5	3.8	0.565	90
International Journal of Design and Nature and Ecodynamics	International Information and Engineering Technology Association	4		4		1.5	0.252	54
Iop Conference Series Materials Science and Engineering	Institute of Physics Publishing	4		2	2	1.1	0.249	35
Nature Based Strategies for Urban and Building Sustainability	Joe Hayton	4	1	2	1	n.a.	n.a.	n.a.
Procedia Engineering	Elsevier	4		1	3	n.a.	0.334	n.a.
Urban Ecosystems	Springer Nature	4			4	5.1	0.730	89
Urban Forestry and Urban Greening	Elsevier	4			4	7.7	1.233	93

[a] Top sources publishing more than 3 documents. [b] N.: number of documents. [c] CS: CiteScore 2021. [d] SJR: SCImago Journal Rank 2021. [e] HP: Highest CiteScore Percentile 2021. n.a. = not available.

3.2. Main Topics and Research Trends of Vertical Greenery Systems

The cluster analysis on keywords from the 270 documents concerning the research on GFs' thermal performance allows us to obtain the network map in Figure 7. A keyword is associated to each circle in the map, and circle diameter represents keyword frequency. The reciprocal positions of the keywords are also relevant, and refer to their relatedness: the closer two keywords are, the larger the number of documents where those keywords are found. The lines linking the circles show the co-occurrence of the two keywords, and the thicker the lines are, the more often the two keywords are found together. The keywords with a minimum number of five occurrences found in the analyzed documents number 117. These are grouped in three clusters, representing three crucial research themes, and are identified by different colors: thermal behavior and energy modeling; urban design and large-scale effects; sustainable buildings management. These three main topics are distinguishable, but not absolutely distinct from each other, since there is overlapping due to their close interconnections and some research aspects are common to the three clusters.

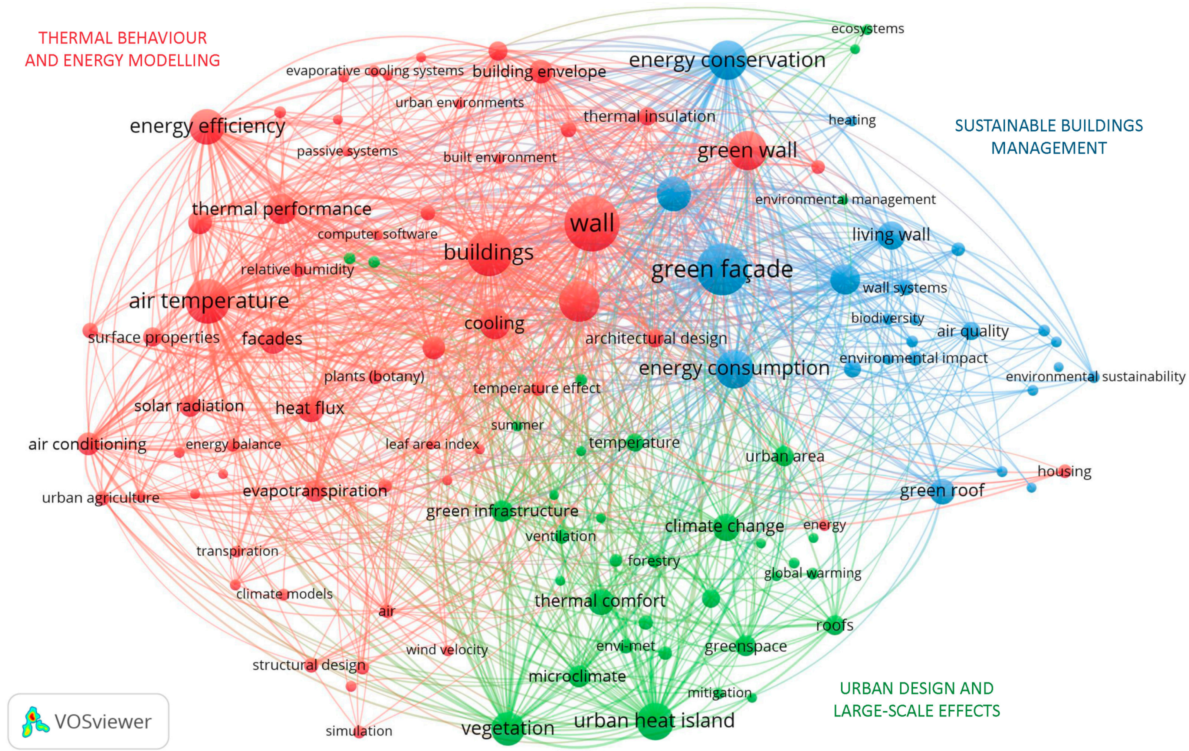

Figure 7. Keywords network based on the GFs' thermal performance publications from 1999 to 2022.

3.2.1. Thermal Behavior and Energy Modeling

The cluster related to the thermal behavior and energy modeling of GFs (the red one in Figure 7) consists of 58 keywords. The most recurrent keywords are: "wall", "buildings", "air temperature", "energy efficiency", "vertical greenery system", "green wall", "thermal performance", "heat flux", "façades", and "cooling". The common thread of this research theme is the thermophysics of the GFs. The different aspects of the energy functioning of the GFs and of the buildings equipped with them are investigated. These studies include analytical and experimental investigations on heat and mass transfer, considering the peculiarities of the specific type of GF, the characteristics of the whole building, of the envelope, of the surfaces and of the plant, together with the context and the climate parameters. There are also studies focused on software simulations. The analyses carried out allow us to point out the main effects provided by these greenery systems on the building and the microclimate.

Many research works have proposed mathematical models useful to describe the heat fluxes in GFs, thus assessing their thermal performance [40–43]. The different heat transfer mechanisms have been investigated: solar radiative exchange [44], long-wave radiative transfer [45,46], and convective heat flux [47]. The latent heat transfer due to the plant's evapotranspiration has also been studied and quantified [41,48,49]. The effects of GFs on the building envelope and on the nearby air have been studied through experimental monitoring and simulation analyses. In particular, researchers found a cooling effect provided by the greenery, through shading and evapotranspiration, that allows a reduction in surface and air temperature and increases in the relative humidity in warm periods [50–54]. GFs can be beneficial even in cool periods, by acting as a thermal and wind barrier, thus providing surface and air warming and improving thermal insulation [55–59]. Therefore, many authors have agreed to consider GFs as effective passive sustainable technologies for buildings. Researchers have studied how the effects of greenery are related to plant parameters, and especially to the leaf area index (LAI) [60–62]. Computational fluid dynamics (CFD) simulations have also been chosen as analysis tool, conducted to assess the effects of vegetated walls on the building thermal performance [63,64]. All the analyses performed have the ultimate goal of understanding how GFs work, in order to enable their best design and application.

3.2.2. Urban Design and Large-Scale Effects

The cluster focused on urban design and large-scale effects (in green in Figure 7) is composed of 35 keywords. The most frequently recalled keywords are: "urban heat island", "climate change", "vegetation", thermal comfort", "green infrastructure", "microclimate", "greenspace", and "urban area". In this research theme, GFs are analyzed as a type of green infrastructure and a strategy to make urban areas greener. The ways vegetation should and could be included in urban design and planning are studied. Attention is focused on the contributions that GFs can make to a scale larger than that of a single building. The aspects related to the general topic of the climate change and the urban climate issues are of particular relevance. Researchers were especially interested in the effects of GFs, as adaptation, mitigation, and protection strategies, on typical urban environment criticalities. Urban thermal aspects and comfort conditions are particularly addressed. Studies on this theme also include software simulation analyses.

Researchers investigated the effects of GFs in terms of UHI mitigation at the pedestrian level, also through the analytical hierarchy process approach and based on ENVI-met software outputs [65]. Depending on building height, coverage percentage and LAI are closely related to the extent of the UHI mitigation: the higher these values, the higher the mitigation. The introduction of GFs has a positive impact, especially on air and surfaces temperature [66], mean radiant temperature [22], wind flow [67] and relative humidity [68].

GFs provide a cooling effect and an improvement in the thermal comfort, thus significantly alleviating the heat stress [69,70] and reducing the discomfort rate in the physiological equivalent temperature [71]. An average UHI mitigation up to 5 °C was found in different climate zones, with the best results, temperature reductions up to 8 °C, in highly urbanized areas with narrow streets and high buildings [72].

The urban effects of GFs concern not only the thermal and energy aspects, but also their contributions to addressing other typical problems of cities. Vegetation on buildings' walls is efficient in reducing noise impacts [73], stormwater runoff and CO_2 emissions in urban environments [74]. Implementing urban greeneries is considered and demonstrated as increasingly essential to establishing sustainable cities and communities through the integration of green landscape elements [75]. Therefore, researchers are still working to help designers and planners in incorporating GFs in urban environments. One of the main issues related to the effects of GFs on urban environments, and thus to their real application, is the close connection of the experimental results to the GF, urban and climate contextual peculiarities of the tests. Therefore, researchers have been focusing on dynamic modeling algorithms to overcome this problem [76].

Nevertheless, for completeness, the existence of some limitations in GFs' implementation in urban areas needs to be mentioned. These involve some economic, political, social and practical issues, and sometimes the coexistence of different limitations. The most addressed limit in the published documents is the economic one. There is a general lack of willingness as well as means to pay for a GF, considering the overall costs for planning, realizing and maintaining it, and given the long payback period and the non-monetary benefits provided [77–81]. The economic aspect is often closely related also to political and administrative issues. These mainly consist of insufficient strategies and regulations to promote GFs' implementation, such as incentives, financial support and simplified administrative procedures [79,82,83]. The inadequate institutional support for this technology is also responsible for social concern about the implementation of GFs. In fact, the main social limitations to the spread of GFs are due to the insufficient political and economic support, together with a lack of information and knowledge of the technology and of all its practical and economic aspects and real benefits [80,84,85]. Sometimes, even the aesthetic perception of disorder provided by vegetation represents a limit to GFs' implementation [86]. Technical and practical aspects give rise to other concerns and are other limitations to the spreading of

GFs. Mainly, there is a concern about the potentially unsuccessful application of green technology, especially due to possible vegetation problems or to extreme weather events [87]. Context and building wall characteristics can make it difficult to implement GFs [77,78]. People are also worried about the presence of unwanted and potentially harmful flora and fauna, and about fire protection [83,87,88]. However, the biggest problem seems to come from the lack of technical guidelines and strong expertise in GFs' implementation and management [25,77,86].

3.2.3. Sustainable Buildings Management

"Green façade", "energy conservation", "energy consumption", "energy savings", and "sustainable development" are the main keywords of the cluster, including 24 words, centered on sustainable buildings management (in blue in Figure 7). This research theme deals with the contributions the GFs can make to the sustainability of new and existing buildings, and consequently of the environment. This topic is particularly noteworthy in the current contexts characterized by the challenges of the energy crisis, climate changes, the loss of green spaces, and consequently, uncomfortable indoor and outdoor environments [89]. The energy aspects are investigated the most by researchers, but are not the only ones. Researchers have investigated the long-term energy benefits, in terms of energy savings for buildings air conditioning, deriving from the integration of GFs into the building's envelope. Results depend on the GF typology and technology, on the building characteristics and on the climate context [23,90,91]. The application of GFs as a retrofitting strategy on uninsulated walls allows for a reduction in the heat fluxes [92], providing energy savings not only in warm periods [93–96], but even throughout the year [97] and in extreme climate context [98], thanks to the reduction in energy demand for cooling and heating [57,99–101]. To evaluate the overall sustainability of GFs, a life cycle assessment methodology has been chosen by many researchers to point out if, when and to what extent these systems are sustainable. It was found that the environmental benefits, mainly deriving from the energy savings for buildings' air conditioning, can balance the environmental burden depending on the system characteristics, and that GFs can be a sustainable option for improving urban environments [102,103]. The sustainability of GFs is not only related to the reduction in energy consumption and costs, but also to the altering of the micro-climate, to the improvement of the air quality and the enhancing of the biodiversity in the areas of application [104]. In particular, concerning the air quality, there is growing concern due to the serious effects on health of volatile organic compounds found in built environments. In this regard, researchers are making progress in the direction of innovative GFs acting as active botanical biofilters, able to remove or reduce the compounds' concentration [105].

3.3. Research Trends

The publications that have received a minimum of 50 citations and at least an average value of 50 citations per year are reported on Table 3. Four papers received more than 250 citations. The paper with the highest number of citations (n = 544) is also the one with the highest average number of citations per year (68.0) [106]. It was published in *Landscape and Urban Planning* in 2015, and it is the result of international cooperation between researchers working at the University of Melbourne and Monash University, Australia, and the University of Sheffield, United Kingdom. This study firstly provides a review on the potential of UGI to mitigate high temperatures in cities experiencing hot and dry summers. A hierarchical decision framework was then developed to assist green space managers, planners and designers in the most effective means of inclusion of UGIs into already existing urban areas, with the main objective of contributing to an improved urban climate. The proposed framework uses census data and remotely sensed thermal data to prioritize neighborhoods, and then street canyons for surface temperature mitigation. The most suitable UGI types for various circumstances are recommended. The application of the framework is also shown using the city of Port Phillip, Melbourne, Australia, as a case study.

Table 3. Published papers that received at least 50 citations and at least an average value of 15 citations per year (by the end of 2022).

Year	Authors	Countries [a]	Title	Journal	TC [b]	Avg. C [c]
2015	Norton B.A., Coutts A.M., Livesley S.J., Harris R.J., Hunter A.M., Williams N.S.G. [106]	Australia, United Kingdom	Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes	*Landscape and Urban Planning*	544	68.0
2010	Wong N.H., Kwang Tan A.Y., Chen Y., Sekar K., Tan P.Y., Chan D., Chiang K., Wong N.C. [14]	Singapore	Thermal evaluation of vertical greenery systems for building walls	*Building and Environment*	371	28.5
2011	Perini K., Ottele M., Fraaij A.L.A., Haas E.M., Raiteri R. [58]	Italy, The Netherlands	Vertical greening systems and the effect on air flow and temperature on the building envelope	*Building and Environment*	296	24.7
2011	Pérez G., Rincon L., Vila A., Gonzalez J.M., Cabeza L.F. [13]	Spain	Green vertical systems for buildings as passive systems for energy savings	*Applied Energy*	258	21.5
2014	Pérez G., Coma J., Martorell I., Cabeza L.F. [23]	Spain	Vertical Greenery Systems (VGS) for energy saving in buildings: A review	*Renewable and Sustainable Energy Reviews*	251	27.9
2018	Besir A.B., Cuce E. [107]	Turkey	Green roofs and facades: A comprehensive review	*Renewable and Sustainable Energy Reviews*	230	46.0
2008	Kohler M. [108]	Germany	Green facades-a view back and some visions	*Urban Ecosystems*	226	15.1
2013	Perini K., Rosasco P. [109]	Italy	Cost-benefit analysis for green façades and living wall systems	*Building and Environment*	211	21.1
2011	Ottelé M., Perini K., Fraaij A.L.A., Haas E.M., Raiteri R. [10]	Italy, The Netherlands	Comparative life cycle analysis for green façades and living wall systems	*Energy and Buildings*	204	17.0
2010	Kontoleon K.J., Eumorfopoulou E.A. [43]	Greece	The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone	*Building and Environment*	201	15.5
2017	Coma J., Pérez G., de Gracia A., Bures S., Urrestarazu M., Cabeza L.F. [95]	Spain	Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades	*Building and Environment*	192	32.0
2015	Raji B., Tenpierik M.J., Van Den Dobbelsteen A. [110]	Netherlands	The impact of greening systems on building energy performance: A literature review	*Renewable and Sustainable Energy Reviews*	190	23.8
2016	Zölch T., Maderspacher J., Wamsler C., Pauleit S. [21]	Germany, Sweden	Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale	*Urban Forestry and Urban Greening*	192	27.4
2017	Aflaki A., Mirnezhad M., Ghaffarianhoseini A., Ghaffarianhoseini A., Omrany H., Wang Z.-H., Akbari H. [111]	Malaysia, New Zealand, United States, Canada	Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong	*Cities*	172	28.7
2014	Cameron R.W.F., Taylor J.E., Emmett M.R. [112]	United Kingdom	What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls	*Building and Environment*	179	19.9
2013	Susorova I., Angulo M., Bahrami P., Brent Stephens [42]	United States	A model of vegetated exterior facades for evaluation of wall thermal performance	*Building and Environment*	163	16.3
2016	Omrany H., GhaffarianHoseini A., GhaffarianHoseini A., Raahemifar K., Tookey J. [113]	Malaysia, New Zealand, Canada	Application of passive wall systems for improving the energy effciency in buildings: A comprehensive review	*Renewable and Sustainable Energy Reviews*	150	21.4
2016	Hoelscher M.-T., Nehls T., Janicke B., Wessolek G. [114]	Germany	Quantifying cooling effects of facade greening: Shading, transpiration and insulation	*Energy and Buildings*	153	21.9
2014	Hunter A.M., Williams N.S.G., Rayner J.P., Aye L., Hes D., Livesley S.J. [115]	Australia	Quantifying the thermal performance of green façades: A critical review	*Ecological Engineering*	155	17.2
2018	Taleghani M. [116]	United Kingdom	Outdoor thermal comfort by different heat mitigation strategies- A review	*Renewable and Sustainable Energy Reviews*	141	28.2
2017	Pérez G., Coma J., Sol S., Cabeza L.F. [94]	Spain	Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect	*Applied Energy*	116	19.3
2017	Cuce E. [16]	Turkey	Thermal regulation impact of green walls: An experimental and numerical investigation	*Applied Energy*	94	15.7
2018	Vox G., Blanco I., Schettini E. [117]	Italy	Green façades to control wall surface temperature in buildings	*Building and Environment*	85	17.0
2019	Radić M., Dodig M.B., Auer T. [118]	Germany	Green facades and living walls-A review establishing the classification of construction types and mapping the benefits	*Sustainability (Switzerland)*	78	19.5
2021	Wong N.H., Tan C.L., Kolokotsa D.D., Takebayashi H. [119]	Singapore, Greece, Japan	Greenery as a mitigation and adaptation strategy to urban heat	*Nature Reviews Earth and Environment*	55	27.5

[a] Countries of the authors' institutions. [b] TC: total number of citations. [c] Avg. C: average number of citations per year.

The second most cited paper (371 citations) was published in 2010 in *Building and Environment* by researchers working at the National University of Singapore, in cooperation with members of the National Parks Board and Building and the Construction Authority, both institutions from Singapore [14]. The thermal impacts of eight different VGSs on building performance and the surrounding environment based on the surface and ambient temperatures were studied in Singapore, a tropical climate. The VGSs analyzed were chosen for coming from various regions of the world. The performance of a simple GF system was compared with that of several sophisticated LWs. It was found that the GF can allow a 4.36 °C reduction in the average wall surface temperature in the summer period, even without the insulating effect of the substrate and the cooling effect from the evaporation of moisture of the substrate, as in LWs, and has almost no effect on ambient temperature. Maximum reductions up to 11.58 °C and 3.33 °C in the wall surface temperatures and in the ambient temperature, respectively, are observed for the LWs.

The third most cited paper (296 citations) was published in 2011 in *Building and Environment* by researchers working at the University of Genoa, Italy, and at the Delft University of Technology, The Netherlands [58]. Three real-scale VGSs, namely, a direct GF, an indirect GF and an LW, were analyzed and compared to bare facades in early autumn to investigate the contributions of the green layer to the thermal performance of the building envelope. The building surface and air temperature, and the wind speed pattern inside and in front of the greening systems, were measured. The three systems acted as natural sunscreens by allowing building surface temperature reductions. The direct GF and the LW also acted as effective wind barriers, since a reduction in the air wind speed values was assessed inside the foliage and the air gap, for the direct GF and the LW, respectively, thus affecting the building wall's total thermal resistance. Energy savings were obtained due to the lower surface temperatures of the building envelope in warm climates and to the increased thermal resistances in both warm and cold climates.

The fourth most cited paper (258 citations) was published in 2011 in *Applied Energy* by researchers belonging to the University of Lleida and the Polytechnic University of Catalonia [13]. A classification of VGSs for buildings is provided, and the mechanisms that influence their use as passive system for energy savings in buildings are reviewed. The classification aims to clarify concepts related to VGSs for buildings, and enables a comparison of results in future research studies. The experimental results for a double-skin GF in a dry Mediterranean Continental climate show that a modified microclimate is produced in the airgap between the wall and the green layer. The airgap was characterized by higher humidity and lower temperature in warmer months in comparison to external ambient climate parameters. Moreover, the building wall surface temperatures decreased due to radiation interception by the vegetation.

Figure 8 reports the keywords year map based on all 155 publications on GFs' thermal performance retrieved from the Scopus database in 2012–2021. The map is based on the occurrence of the different keywords and the average year of publication of documents with the specific keywords. The size of the keyword labels is proportional to the frequency of the keywords.

The most frequently used keywords in the early publications are identified with blue and dark green colors ("buildings", "wall surface temperature", "plants", "vegetation", "cooling systems", "transpiration", "building envelope", "summer", "energy savings"). Early publications were mainly aimed at evaluating and comparing the thermal effect on buildings of different VGS to a greater extent for cooling and to a lesser one for heating periods. The benefits of passive cooling delivered by GFs have generally been evidenced by: conducting a comparison of the surface temperature of a control wall with that behind the vegetation [120]; estimating the heat transfer through the control façade and the GF [42]; evaluating the reduction in energy consumption of heating or cooling systems [57]; simulating GFs' thermal response [121,122]. The real scale analysis of the application of LWs and GFs on experimental houses-like cubicles highlighted a greater heating and cooling performance for LWs than GFs [95]. The higher potential energy saving in the cooling period than in the heating one was assessed, especially in climates with high solar irradiance [95]. Covering small-scale physical models with ivy in the winter of a warm and temperate climate showed the highest energy savings during extreme weather events determined by cold temperatures, rain or strong wind [57]. Plant species' influence on cooling potential was explored in relation to the main cooling mechanisms by distinguishing the shading, evapo-transpirational and evaporational cooling from the medium, proving that various means and levels of cooling may vary when considering different plant species [112]. Significant relationships were found first between the overall cooling effect and the percentage coverage of vegetation over walls, and then with leaf solar transmittance [123]. The selection of the most suitable plant species, depending on the climate conditions, building characteristics, system configuration and desired effects, is crucial for the success of the GF application. Plants used for GFs were of both evergreen and deciduous species, based on the time of the year the effects were to be assessed. In fact, evergreen plants maintain their leaves throughout the year, while deciduous ones lose these in the fall season. The plant species selected for GFs by different authors are listed in Table 4. It can be observed that the species used for direct GFs are few in comparison with those used for the double skin typology. This is mainly due to the constructive system; the direct GF requires plants able to climb on the wall, while the double skin GF, thanks to the supporting structure, allows the use of several different species.

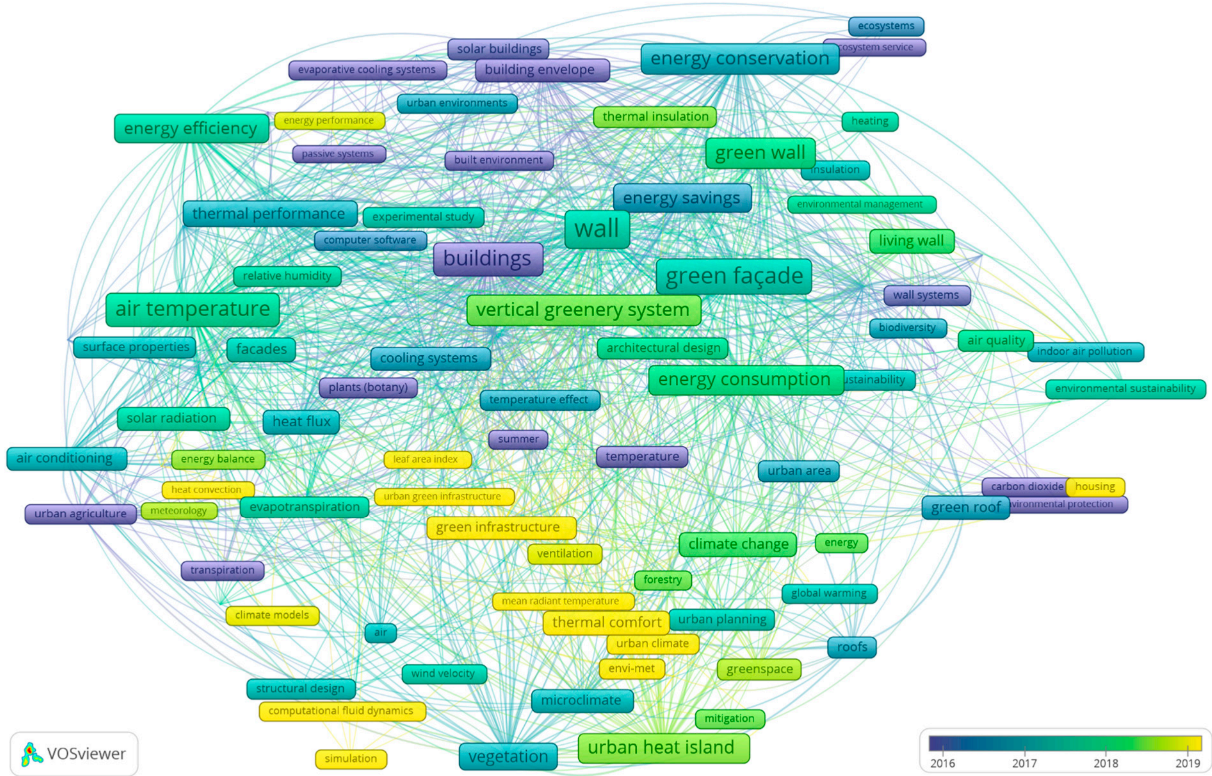

Figure 8. Keywords year map based on publications on GFs' thermal performance (the blue and dark green colors represent earlier, while light green and yellow ones stand for more recent, terms).

The most recent period is identified by keywords in light green and yellow (Figure 8). Frequent keywords were "urban heat island", "climate change", "energy consumption", "thermal comfort", "ventilation", and "mean radiant temperature". Researchers' efforts were mainly focused on deepening knowledge on the thermal and energy performance of GFs at the building scale in different climates and weather scenarios, and in relation to different GFs typologies [19,93,124–126] and the reduction in energy consumption by air-conditioning systems [95,100]. This period was also characterized by an increase in studies on the effects of large-scale façade greenery on ambient air as it contributes to climate change mitigation and adaptation. The synergistic mitigation effects of turf and GFs, different urban forms and ventilation corridors were found to contribute to improved microclimate and thermal comfort at neighborhood scales [127]. The adoption of cool materials with high albedo and different combinations of building greening solutions were evaluated as cooling strategies in high-rise communities. The cumulative effects of applying multiple strategies were found to be greater than those of individual strategies [128].

Table 4. Overview of the most common plant species investigated in GFs' thermal performance research.

Plant Species	Green Facade Typology	References
Parthenocissus tricuspidata	Direct	[108,129–131]
	Double skin	[94]
Hedera helix	Direct	[16,58,112,132,133]
	Double skin	[18]
Rhyncospermum jasminoides	Double skin	[97,134]
Clemeatis	Double skin	[18,58]
Stachys byzantina	Double skin	[112]
Vitis	Double skin	[58]
Pyracantha	Double skin	[58]
Wisteria sinensis	Double skin	[13]
Ficus pumila	Double skin	[135]
Campsis grandiflora	Double skin	[135]
Bauhinia corymbosa	Double skin	[135]
Pyrostegia venusta	Double skin	[135]
Bitter melon	Double skin	[123]
Ipomea tricolor	Double skin	[123]
Canavalia gladiata	Double skin	[123]
Pueraria lobata	Double skin	[123]
Apios american Medikus	Double skin	[123]
Phaseolus vulgaris	Double skin	[136]
Parthenocissus quinquefolia	Double skin	[137]
Lonicera japonica	Double skin	[13]
Momordica charantia	Double skin	[123]
Pandorea jasminoides	Double skin	[134]

3.4. Knowledge Gap and Future Development of Research

The analysis of research production shows that GFs have received great attention, especially in the last few years, and that research efforts have been made to increase knowledge on this technology and have a well-rounded view. As a passive sustainable technology, thermal behavior and energy aspects, as well as effects on microclimate at the building level and on climate at the urban scale, have been the main focus. However, researchers need to make additional efforts to fill the still existing research gaps with reference to the main research themes identified through the cluster analysis.

To analyze and comprehend the thermal performance of GFs on the whole, and to assure the repeatability of the study, all the influencing factors should be specified in the research papers focused on "thermal behavior and energy modeling" and "urban design and large-scale effects". Thus, a relevant issue related to the analysis of the GFs effects is the need for standardized methods of investigation and assessment, in order to cover different climate contexts and seasons [21,84,138]. One of the main weaknesses of the reported data concerns the plant and substrate characteristics. These aspects need to be more thoroughly investigated and described [90]. In particular, the LAI, which has been commonly recognized as a key parameter for characterizing the green layer and influencing the thermal behavior of the GFs, deserves more in-depth study, in addition to those already carried out, on its values and measurement methods [48,61]. Furthermore, even though the analysis of the literature suggests many works supporting the positive influence of GFs on building and city sustainability, it should be noted that most of these are based on simulations or on experimental tests, but with very short-term ranges. More long-term experimental investigations should be conducted to provide further evidence of the real functioning and effects of GFs in different contexts [24,97].

With a view to overall sustainability, and thus to the main research theme "sustainable buildings management", water requirements should also be considered. In this regard, future designs should promote and be integrated with systems for water use efficiency, such as rainwater and greywater reuse [139].

Given the variable nature of the vegetation component, GFs are very difficult to geometrically characterize, and therefore there is a lack of 3D objects that can adequately and effectively reproduce their properties and geometry. Future research on the three main themes "thermal behavior and energy modeling", "urban design and large-scale effects" and "sustainable buildings management" should address this lack, and provide objects and tools to be used in building information modeling (BIM) technologies, which are increasingly used in building design today. This could be particularly helpful in the design process [140].

Concerning the "urban design and large-scale effects" research theme, when considering the implementation of GFs as a strategy to make cities more climate resilient and to face urban air pollution, further studies are needed to simulate their integration and the provided effects. In particular, the correct description of the interaction of vegetation with air flow is crucial and essential to modeling through CFD. In this regard, knowledge of viscosity and shape resistance is necessary, and further studies should be conducted [63].

A relevant issue related to the implementation of GFs, even if less significant in comparison to the more expensive LWs, which is also one of the main limitations of their application and spread, is the cost of installation and maintenance. This is why a further task of researchers in the field of "sustainable buildings management" should be that of finding more economically sustainable systems, thus achieving the full sustainability of GFs [27,30].

Overall, further research should focus on the deepening, harmonization and standardization of methods and results, insisting on a multidisciplinary approach and taking more account of the economic issue [29,115,141]. In this way, it would be possible to provide designers, planners and policymakers with guidelines for the informed implementation of GFs, thus also encouraging a wider spread of this green technology in future urban and rural planning.

4. Conclusions

Cities must deal with the several challenges arising from climate change and urbanization, and the need for innovative solutions is increasingly emerging, among which urban green infrastructure UGIs must be included. GFs can be also used as nature-based solutions to improve the energy efficiency of buildings, owing to their ability to serve as a thermal screen and provide natural shading.

A bibliometric analysis of the scientific research on GFs' thermal and energy performance published before 2022 was performed. The last period was characterized by a noticeable increase in the number of published papers, with 73.3% of the total output published in the period 2017–2022. This underscores the growing interest of the scientific community in learning more about the thermal benefits that GFs can provide to encourage their wider use in urban areas. An increasing tendency to publish in indexed journals rather than conference proceedings and books can be inferred. A multidisciplinary aspect of the studies has emerged from the identification of the main subject areas involved. The top contributing countries are Italy, China, United Kingdom and Spain, with a percentage share of 43.7% of the relevant documents, and the most productive sources are *Building and Environment*, *Energy and Buildings*, and *Sustainability (Switzerland)*, accounting for 27.8% of the retrieved publications.

The cluster analysis identified three main research themes related to thermal behavior and energy modeling, urban design and large-scale effects, and sustainable buildings management.

Recent research studies are focused on the assessment and modeling of the thermal effects of GFs on buildings in different climates and weather scenarios, and in relation to different GF typologies, as well as the evaluation and comparison of the effects of different greenery systems on surroundings for mitigating UHI and improving the outdoor thermal comfort in urban areas, to ultimately contribute to climate change mitigation and adaptation.

Further research efforts are needed to further investigate, harmonize and standardize methods and results, applying a multidisciplinary approach that also takes economic aspects into account. This would enable a conscious implementation of GFs and a greater dissemination of this green technology in future urban and rural planning.

It is worth mentioning that although Scopus is one of the main sources of bibliographic data, there are still journals not indexed in Scopus, as well as journals not indexed in any other database, and publications in these journals could have been neglected. A more exhaustive study could thus contemplate additional databases for collecting bibliographic data on scientific articles.

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