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Review Article

# Nature-based solutions for sustainable cities: A review of the state of the art of green roof research

**Agustina GUTIERREZ*[1,2], Vanesa Y. BOHN[3], Pablo MARINANGELI[1,4]**

[1]*Center for Renewable Natural Resources of the Semi-Arid Zone, CONICET – UNS, Bahía Blanca, Argentina*
[2]*Department of Biology Biochemistry and Pharmacy, National University of the South, Bahía Blanca, Argentina*
[3]*Universidad Nacional del Sur (UNS), CONICET, DGyT, Bahía Blanca, Argentina.*
[4]*Department of Agronomy, National University of the South, Bahía Blanca, Argentina*

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## ABSTRACT

The study of green roofs is an interdisciplinary field recognized for its eco-friendly roofing solutions. Green roofs offer ecological, economic, and societal benefits, making them an effective way to address urbanization's negative impacts. This review explores the evolution of green roofs from ancient prototypes to modern innovations. Using the Google Scholar database, we conducted a bibliometric analysis of 50 articles to assess publication rates in the "green roof" area. Descriptive statistics were used to identify key contributors, ecosystem services, research methodologies, and spatial scales in green roof studies. Our analysis showed a rise in research on green roof technology in the early 21st century, with the United States and China leading this research. Urban heat island mitigation emerged as a primary research focus for green roofs, with cities being the most studied spatial scale. The most common keywords were "green roofs," "urban," and "energy." This study thoroughly reviews the past and present state of green roofs, showcasing a range of indicators that provide valuable insights for future research and emerging trends in the area.

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## 1. INTRODUCTION

Green roofs have their roots in ancient practices, but their popularity has increased in modern architecture due to their environmental and aesthetic benefits. Throughout history, humans have sought refuge from the harsh forces of nature, activating an innate survival instinct that led to the invention of shelters since ancient times. The constant evolution of human ingenuity has facilitated ongoing improvements in the quality of households, protecting unpredictable factors. Initially, simple tent-like structures evolved into more complex wall-and-roof house arrangements. The progression towards increasingly sophisticated accommodation has presented new challenges, met with continuous innovations. Despite cultural diversities, solutions to similar environmental challenges and resource limitations have tended to converge [1]. The desire for comfort would drive wall and roof technology advancements to compress the diurnal indoor temperature range within the human comfort zone. Materials and construction methods were tested and refined to enhance functions. The harsh climate of the Arctic lands and the scarcity of suitable construction materials would cause people to utilize the natural soil and grass to build houses [2, 3], and this is how the ancient prototypes of green roofs were born [4].

***Corresponding author.**
*E-mail address: aguti@criba.edu.ar

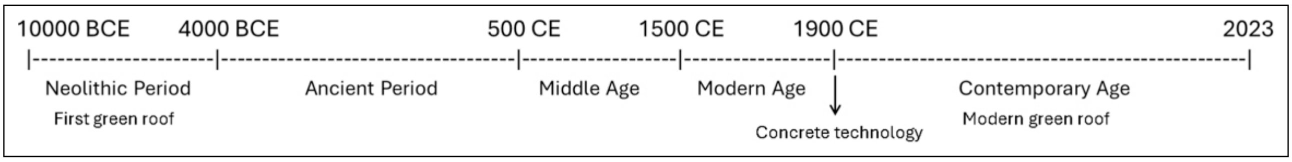


**Figure 1**. Timeline of the history and evolution of green roofs. Elaborated through bibliographic compilation. BCE (Before the Common Era) and CE (Common Era).

In modern times, more than half of the world's population is concentrated in cities. Urban life has separated people from nature. The rapid urban development, modification of landscapes, and various anthropogenic activities have resulted in a series of negative environmental consequences such as global warming, air pollution, depletion of the stratospheric ozone, the rise of the Urban Heat Island effect, excessive noise, and a decrease in biodiversity [5–8], contributing even to degradation of the mental and psychological health of citizens [9, 10]. However, environmental awareness in recent years has triggered innovations to reduce the massive and aggravating environmental impacts of buildings [11, 12]. Thinking about sustainable cities by adopting nature-based sustainable strategies has become one of the significant challenges in recent decades in mitigating environmental problems. These solutions involve diverse approaches, such as constructing energy-efficient buildings, implementing techniques to mitigate air and water pollution, creating green spaces in urban areas, and expanding green infrastructure. Green roofs are constructed systems that offer a nature-inspired response to environmental problems. These artificial ecosystems act as a tool that mimics and harnesses the benefits of natural ecosystems to provide various environmental and social solutions.

Green roofs significantly contribute to climate change mitigation by providing ecosystem services: absorbing carbon dioxide ($CO_2$) and other greenhouse gases and reducing emissions [13]. The provision of thermal insulation due to these systems helps regulate temperature, reducing the need for energy for heating and cooling in buildings, thus reducing fossil fuel consumption [14]. By absorbing solar radiation and utilizing the water evaporation process through plant transpiration, green roofs reduce the environment's temperature, creating cooler and more pleasant microclimates in densely built urban environments [7]. Green roofs contribute to water management by retaining and filtering rainwater, reducing runoff, and relieving the burden on urban drainage systems. This helps prevent floods and decreases water pollution by filtering contaminants from rainwater [6]. Improving air quality by trapping suspended dust, heavy metals, and other atmospheric pollutants [15, 16]. Green roof technology promotes biodiversity by providing habitats for various plants, insects, and birds in urban environments, enriching native biological diversity, and acting as aerial biological corridors [17, 18]. Green roofs increase the efficiency of solar panels because plant shade reduces the environmental temperature around photovoltaic panels, improving their efficiency [19]. The quality of life is enhanced by offering green and natural spaces for recreation and connection with nature [10].

The potential of the green roof technology to retain stormwater runoff in urban areas was evaluated by quantitative and experimental methods at Michigan State University, United States [20]. Some studies included comparing the percentage of water retention in green and standard roofs. The results corroborated the capability of the green roof to mitigate the runoff. Another topic related to the ecosystem services of green roofs was studied. Heat island, defined as the difference between urban land use and rural area temperature, is a phenomenon of high interest in the context of climate change. Green roofs and increased vegetation surfaces in urban areas appear as an alternative to mitigate the heat island. A developed study in India's metropolitan and tropical regions [21] used ENVI-met software. They also studied measures to mitigate the impacts of several greening and heat island impacts. The methods for the study included satellite image processing to estimate the thermal ones and the effect of concretization. In conclusion, the authors indicated that the land surface temperature is affected by different factors, such as the heat related to anthropogenic actions and land cover.

Based on a bibliographic compilation, this article aims to analyze the historical evolution of green roofs from their origins in prehistory to the present day. It also aims to provide a detailed understanding of current trends in the evolution of this technology to support research development and guide future studies on these systems. The specific objectives include (1) identifying countries that have made significant contributions to green roofs, (2) using keyword analysis to pinpoint specific areas related to ecosystem services influenced by green roofs, (3) examining the methodologies employed in research, and (4) determining geographical spatial scales in the study of green roofs.

## 2. METHODOLOGY APPLIED FOR THE REVIEW PROCESS: EVOLUTION AND TRENDS IN GREEN ROOF RESEARCH

This review on the evolution of green roof technology from the Neolithic Period (pioneering cases) to the present (current cases) (Fig. 1) uses a two-stage information search criterion:

### 2.1. Exploring the Evolution of Green Roofs: From Neolithic Origins to Contemporary Trends (10000 BCE - 1900 CE)

The information search criteria for these pioneering cases were more inclusive than for current cases due to the lack or limited availability of information. Information was obtained through digital libraries, current scientific articles, books, and book chapters. A chronological summary of the evolution of green roofs was compiled for this first stage of the review.

### 2.2. Analyzing Green Roof Research Trends: A Contemporary Review

The information search criteria for these current cases involved collecting and classifying scientific articles found in Academic Google Web using advanced search criteria and the following keyword: green roofs. Only papers published in the English language were considered, while book chapters, reports, or books were excluded from consideration. The first fifty manuscripts, found in the relevant order, were selected for careful reading and tabulation of information. The evaluated data and features were Journal, authors, year of publication, country of the first author, manuscript title, manuscript type (investigation or review), ecosystem services identified at the research, primarily used methodologies, analyzed features of the green roof and its advances on the research, study area, DOI, keywords and general/additional characteristics. Some tables and graphics were elaborated from this information to characterize the primary green roof investigations. In several cases, the features were counted and alphabetically ordered (i.e., keywords) to elaborate a description with the percentage of predominant classes. A qualitative description was also elaborated based on this information. It is hoped that the bibliographic analyses conducted and the structured presentation of information, as provided in this study, can serve as a wellspring of inspiration for shaping new questions and will be helpful for new investigations into green roof technology.

## 3. REVIEW RESULTS

### 3.1. The Evolution of Green Roofs from Prehistory to the Present

#### *3.1.1. Exploring the Evolution of Green Roofs: From Neolithic Origins to Contemporary Trends (10000 BCE - 1900 CE)*

Neolithic Period from 10000 to 4000 BCE:

The first constructions in which plant covers are found date back to the Neolithic era (3500 BCE) and were funerary buildings. These constructions are known as "Corridor Tombs" and consist of a narrow passage of large stone blocks and one or several funerary chambers covered with earth and vegetation. Two of the most famous examples are Newgrange (in Ireland) and the Corridor Tomb (in Anglesey, Wales) [22].

Ancient Period from 4000 BCE to 500 CE:

The concept of green roofs has ancient origins, dating back to the early days of civilization. The earliest green roofs can be linked to the construction of monumental religious edifices known as ziggurats in Mesopotamia. They were like stepped pyramids made of stones, bricks, and earth that ended on a flat surface, with different vegetation planted. These structures were built approximately between 4000 and 600 BCE [23].

The Hanging Garden of Babylon was built around 500 BCE, is considered one of the Seven Wonders of the Ancient World, and is an example of a green roof in ancient times [24]. This garden was installed on the roof of a sturdy building supported by masonry columns and arched beams with lush vegetation that needed deep soil for tree growth. It was irrigated through a system of pumps and pipes that took water from nearby Euphrates [25]. This structure, a pioneer in landscaping and engineering, stood out from the surrounding desert landscape. This ancient garden represented the origin of the idea of covering roofs for aesthetic purposes, as well as the technology to create an elaborate garden in a building designed and reinforced to support its lush vegetation.

The Villa of Mysteries is a well-known archaeological site in Pompeii, an ancient Roman city near modern-day Naples, Italy. This villa is famous for its well-preserved frescoes, notably paintings depicting a mysterious religious ritual. The Villa of Mysteries is believed to have been built in the 2$^{nd}$ century BCE and was buried by the eruption of Mount Vesuvius in 79 CE, preserving it for centuries until its rediscovery. The luxurious villa had a roof garden that functioned as an outdoor living room and was the center of social activity. The garden was supported by an arched stone colonnade [26]. This case represents the earliest record of roof greening on domestic structures in cities. The tradition of Roman roof gardens might have been maintained from the beginning until the fifteenth century CE, coinciding with the fall of the Eastern Roman Empire to the Ottoman Turks.

Middle Ages (from 500 CE to 1500 CE) and Modern Age (from 1500 CE to 1900 CE) periods:

Green roofs have been a common construction practice in the Scandinavian countries, Iceland, and the Faroe Islands since the Middle Ages. Covered with grass, these systems allowed for better thermal conditioning inside homes. Studying these roofs has revealed certain regularities in different typologies, with solutions still considered valid today. These construction systems are regarded as prototypes of modern green roofs [27].

In the case of the Baltic Countries, the different layers were supported on a structure of sloping wooden planks. To improve the watertightness provided by the slope, overlapping pieces of birch bark were placed on the wood. Subsequently, a layer of grass was incorporated in the reverse position (leaves down, roots up), and immediately, another layer was placed in the usual position. The reason for putting these two layers in opposite positions was to create a vegetal layer resistant to erosion since, after a year, the roots of the upper layer had penetrated the lower layer, giving rise to a compact substrate [28, 29].

In Iceland, variations were observed in the materials used for the structure. The wooden planks were replaced with branches, and the pieces of birch bark (which acted as waterproofing) with a layer of peat. Today, many of the abandoned houses are restored as museums. Currently, the National Museum of Iceland is in charge of maintaining ten 'greenhouse' farms in different parts of the country, and others are under the protection of municipal museums and private organizations [30].

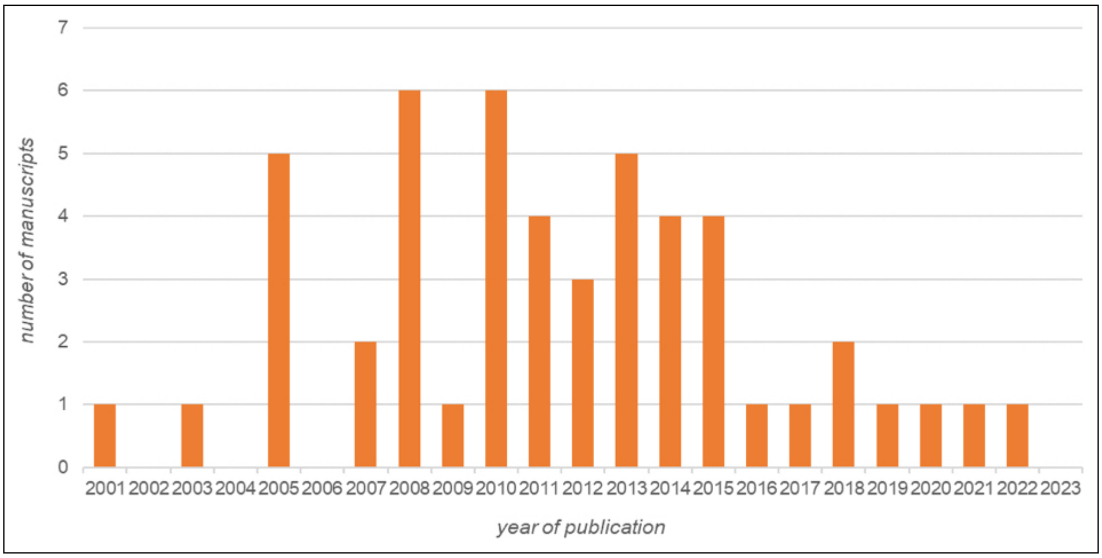


**Figure 2**. Distribution of the most significantly published manuscripts on Green Roof technology from 50 relevant papers. Compiled from a search and selection of documents in Google Scholar.

Green roofs were incorporated into structures across various regions of medieval Europe. The Mont Saint Michel in Normandy, France, has an old garden on the roof. Initially established as a small church in 708 CE [31], the roof garden was added to a building constructed in the century XIII (1200 – 1300 CE), and it has grass and shrubs. It is considered the earliest surviving green roof in a non-rural environment. The Guinigi Tower is one of the most iconic landmarks in Lucca city (Tuscany, Italy). The tower is renowned for its unique feature of oak trees planted on its rooftop. It provides a distinctive silhouette against the skyline, serving as one of the oldest remaining examples in an urban context. The tower was constructed in the late century XIII, around 1384. It is 40 meters high and has 230 steps leading to its summit.

The tower served as a symbol of prestige for the Guinigi family and as a practical means of defense during a tumultuous period in Italian history. Both places (The Mont Saint Michel and The Guinigi Tower) have recognition as World Heritage sites [32, 33]. The Palazzo Piccolomini in Pienza (Tuscany, Italy) was constructed in 1463 and was the residence of Pope Pius II. This palace included a rooftop garden with a geometric layout with trees and shrubs [34], employing landscape design to connect architecture with nature.

Around the 20th century, concrete technology gave rise to the exponential development of cities and modern green roofs that involved roofs with flat concrete platforms with innovative waterproofing and drainage [35]. This new architecture promoted the idea of compensating for the loss of nature in the construction of cities [36]. Rapid industrial growth in Berlin (Germany) demanded fast and low-cost solutions. The workers and their families lived in houses with large roofs that were waterproofed with tar. But tar is a combustible material, with the risk of fire and considerable damage. H. Koch, an ingenious roofer, invented 1880 a new method of protecting tar with a layer of sand and gravel mixture, which is inert and non-flammable. Subsequently, other German cities adopted this roofing technique, which could offer an additional advantage of improved thermal insulation [37]. These porous materials can retain water for survival plants and delay water flow during rainfall [38]. The species composition was mainly herbaceous and could survive under stressful substrate and environmental conditions.

#### *3.1.2. Analyzing Green Roof Research Trends: A Contemporary Review (1900–2023)*

Until now, there was empirical knowledge that using vegetation on roofs provided environmental and energy benefits. But starting in the 1990s in Germany, research and scientific knowledge on green roof technology was promoted, and since then, there has been a growing interest around the world in the implementation of this sustainable practice in urban design and architecture (Fig. 1). From then until the present day, technological innovations, modern and efficient novel materials, the selection of suitable vegetation, and the ongoing discovery of new green roof design strategies make this green technology a powerful tool with multiple benefits in terms of ecosystem services to achieve more sustainable and resilient cities. At the beginning of the 21st century (2000), the first scientific works on green roofs began to appear with exponential growth in the first 15 years (Fig. 2). This knowledge drove the implementation of this technology in urban areas, providing different ecosystem services. Also, the search showed that the highest amount of research on green roof technology was distinguished from 2008–2013 (Fig. 2).

### 3.2. Current Trends in the Evolution of Green Roofs: Implications for Research and Future Studies

As was previously mentioned, the 50 selected manuscripts with Green Roof technology as the main topic were analyzed. They arise from a total of more than 46.000 manuscripts. The 50 cases were chosen without restrictions about the date from a search by Google Scholar.

**Table 1.** Potential future research directions in the field of green roof technologies

| Research Lines | Description |
|---|---|
| Analysis of socioeconomic factors | Investigate how government policies, funding, and economic incentives have influenced the development of green roof technologies over the decades. |
| Ecological and performance assessment | Conduct comparative studies to evaluate the environmental performance of green roofs across different climatic and urban contexts, along with their effects on biodiversity and air quality. |
| Public perception and adoption | Investigate the views and acceptance of green roofs among architects, urban planners, and the general public and the barriers that prevent their adoption. |
| Effects on public health | Study how implementing green roofs can contribute to the health and well-being of urban communities, evaluating psychological and physical benefits. |
| Technological innovations | Explore new technologies and materials that can improve the efficiency and sustainability of green roofs, such as automated irrigation systems or more resilient native plants. |
| Maintenance and management models | Develop management and maintenance models for green roofs that maximize their useful life and effectiveness, including sustainable and cost-effective practices. |
| Impact of climate change | Investigate the resilience of green roofs against the effects of climate change, analyzing their potential to mitigate this phenomenon. |

**Table 2.** Classification of 50 selected papers focused on the topic of Green Roofs, categorized by the country of origin of the first author. The percentage reflects the proportion of manuscripts from each country. Compiled from a Google Scholar search

| The origin country of the first author | Percentage (%) of manuscripts (n=50) | Bibliographic reference |
|---|---|---|
| Australia | 2 | [39] |
| Belgium | 2 | [40] |
| Canada | 10 | [41–45] |
| China | 16 | [46–53] |
| Corea | 2 | [54] |
| France | 2 | [55] |
| Greece | 2 | [56] |
| India | 2 | [57] |
| Israel | 2 | [58] |
| Italy | 10 | [59–63] |
| Japan | 2 | [64] |
| Portugal | 2 | [65] |
| Russia | 2 | [66] |
| Spain | 2 | [67] |
| Sri Lanka | 2 | [68] |
| Sweden | 6 | [69–71] |
| United Kingdom | 8 | [72–75] |
| United States | 26 | [76–88] |

The results showed that the most relevant 50 papers were published since 2001, without finding an older manuscript among those selected. Of the 50 manuscripts, the highest number was published in 2008 and 2010 (6 papers for every year) and 2005 and 2013 (5 papers for every year). More than 50% (26 papers) of the 50 manuscripts were published between 2010 and 2015, indicating a significant rise in interest in green roof technology. During 2002, 2004, 2006, and 2023 years, the bibliographic search on Google Scholar did not yield results (Fig. 2). These results suggest that there may have been a decline in research due to insufficient funding and/or institutional support during those years, along with the necessity for a more robust regulatory and scientific framework to facilitate the study of this emerging technology. To address this issue, we developed Table 1, which catalyzes further exploration in these areas, encouraging researchers to investigate the advancement of green roof technologies more deeply.

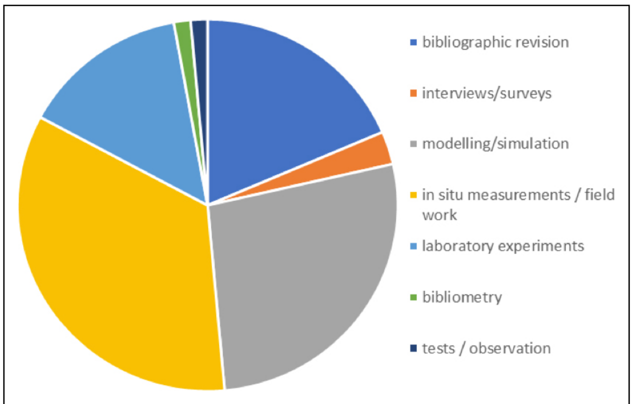


**Figure 3**. Overview of the methodologies categorized into general groups found in the 50 most relevant published manuscripts on Green Roof technology. Compiled from a search conducted on Google Scholar.

From the analyses of the selected 50 papers related to the Green Roof study, we determined some features that allow describing and identifying essential information. From a geographic perspective, the topic was studied by authors from the United States in 26% of the cases, China in 16%, Canada and Italy in 10%, and the United Kingdom in 8%. In contrast, the remaining percentage (approximately 70%) was represented by works written by authors from Sweden, Spain, Portugal, Japan, Russia, India, Israel, and others (Table 2).

These geographic trends show that the United States and China have led the development of green roof technologies and applications. This suggests significant differences in the adoption and design of green roofs worldwide. This opens

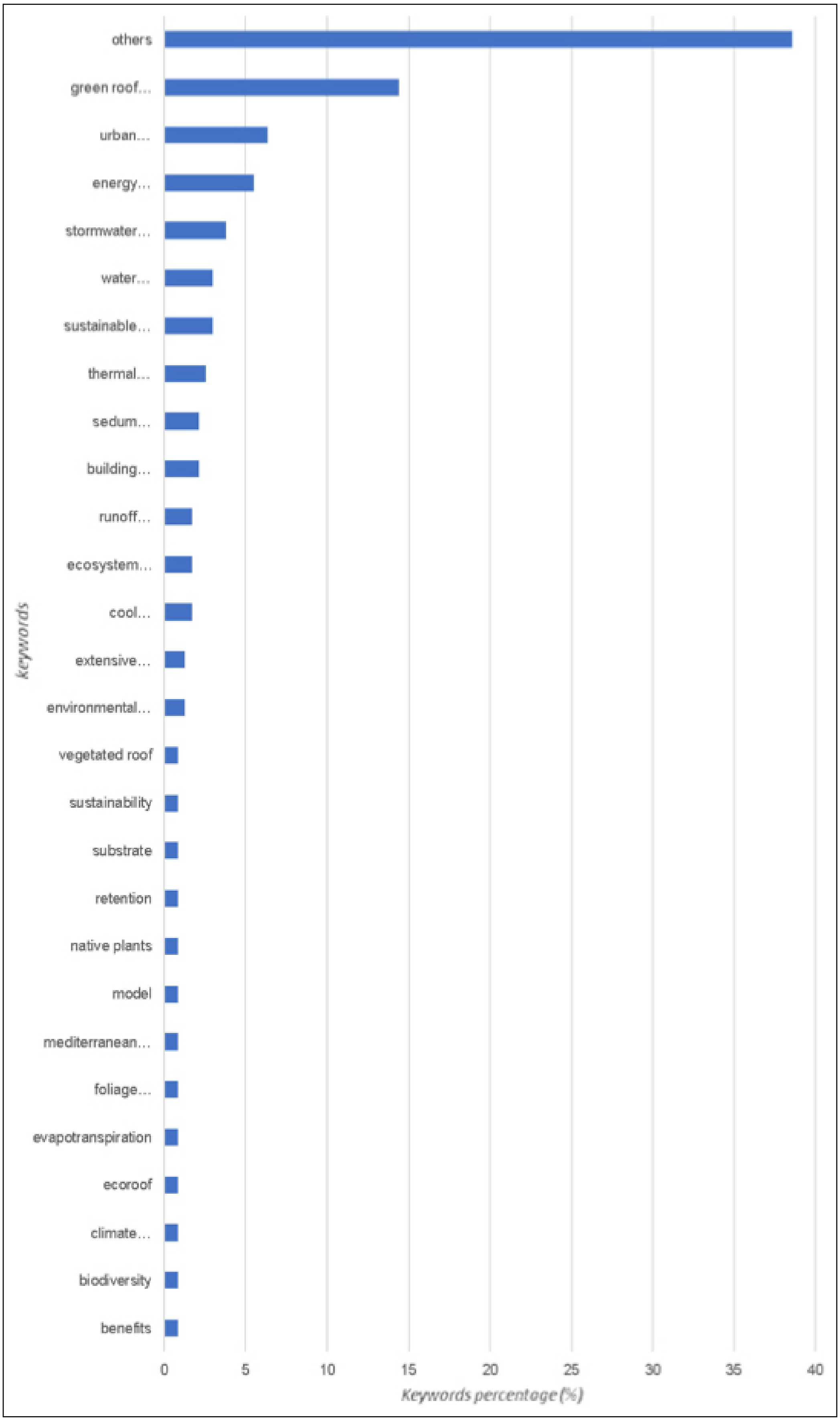


**Figure 4**. Analysis of 235 collected keywords from the 50 manuscripts, presented as a percentage. The ellipsis indicates that the keywords share a common starting term (Appendix 1). The "Others" category includes keywords that appeared only once. Compiled from a Google Scholar search.

doors to studies on the influence of government policies and climatic conditions. The variety of countries implies a range of approaches and solutions, which could facilitate comparative research assessing the effectiveness of green roof systems across different climates and urban contexts.

An interesting feature extracted from this review was the ranking of the applied methodologies (Fig. 3). The variety of methods observed reflects a multidimensional approach to the study of green roofs and indicates multiple avenues for future research. The predominance of in-situ measurements and fieldwork in the evaluated studies (as mentioned in 24 cases, approximately 34%) suggests that empirical studies are essential to understanding the physical and meteorological characteristics of green roofs [62], as well as their energy performance during different seasons [56]. This highlights the need to expand and replicate such studies in diverse locations and climatic conditions to obtain more representative data and assess the local effects of green roofs.

Approximately 27% of the analyzed articles utilize modeling and simulation, which are beneficial for complementing in situ measurements. An example is the study published by [51] in which the capacity of green roofs to moderate temperatures was studied in Hong Kong. Other authors [50] combined in situ measurements with modeling and simulation to evaluate the effects of the green roof on $CO_2$ concentration in the urban environment. In different research, modeling and simulation were applied to study the water retention capacity of green roofs [73], to analyze the benefits of green roofs in water regulation [75], to determine the water and nutrient retention [82], to evaluate the cooling potential of green roof and solar thermal shading in buildings [57]. This methodology can be applied to predict the behavior of green roofs under different scenarios and conditions, which is crucial to optimize their design and functionality. In this context, researchers could continue to develop more sophisticated models that integrate climatic and urban variables to predict better the impacts of green roofs on thermal regulation, water retention, and $CO_2$ concentration in urban environments.

Bibliographic revision accounted for over 18% of the studies assessed. Some features of the green roof distinguished in the bibliographical reviews included analyzing the efficiency of the different plant designs according to their effects on green roofs' hydrology and runoff [83], examining urban drainage [70], and evaluating primary layers such as waterproof and anti-root membranes, drainage layers, substrate, and vegetation [59]. Also, the main properties of an optimal substrate for optimal vegetation growth [68], evaluation of irrigation strategies in semiarid environments [40], and the effects of vegetation on green roof ecosystem services [42] were studied through bibliographic compilation. The importance of this methodology of compiling and analyzing information can assist researchers in identifying gaps in knowledge. This approach allows them to focus future efforts on areas that require more attention, such as assessing ecosystem services provided by green roofs.

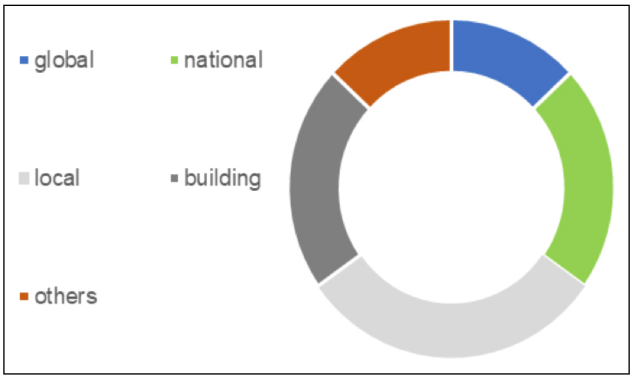


**Figure 5**. Percentage of works grouped by geographical applied scale: global, national, local, building, and others.

The laboratory experiments represented 14% of the cited methodologies. As an example, this methodology was applied with modeling and in situ measurements to study the effects of the green roof on the $CO_2$ concentration in the urban environment [50] and to calculate the thermal and energetic properties of the green roofs [46]. This methodology can provide controlled data on the performance of materials and systems used in green roofs and the impact of specific variables, such as temperature and humidity, on plant growth. This could be useful for future studies and developing new technologies for constructing and maintaining green roofs.

The low representation of interviews, surveys, and observations indicates significant potential for incorporating qualitative approaches in green roof research [41]. These methods could provide valuable insights into social acceptance and user behavior, enriching an understanding of the impact of green roofs at the community level (Fig. 3).

Analyzing keywords from the 50 manuscripts reveals important insights for future research on green roofs. A total of 235 keywords were collected, although it is notable that four manuscripts did not include any keywords (Fig. 4).

The most frequently cited keyword was "green roofs", which accounted for 14.5% of the total, followed by "urban" at 6.4%, "energy" at 5.5%, and "stormwater" at 3.8% (Fig. 4). The high percentage of keywords categorized as "others", suggests that there is a wide range of topics being explored within the field. Still, many of these areas may lack enough focus or recognition in existing literature. These findings can guide researchers in identifying key themes and gaps in the current body of knowledge. For instance, the prominence of keywords related to energy and stormwater indicates that these areas of interest warrant further investigation, particularly their impact on urban environments. Additionally, the low representation (less than 3%) of terms like "sustainable", "thermal", and "sedum" suggests that these topics may be underexplored and could benefit from more detailed studies. Overall, this keywords analysis can help researchers prioritize their future efforts by focusing on the popular themes already being investigated and the less common areas that may offer new opportunities for

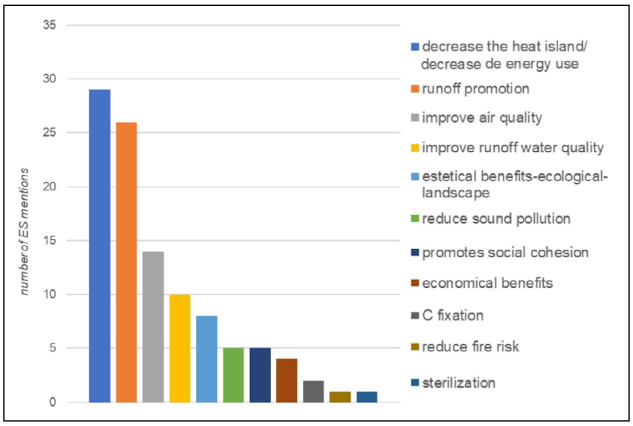


**Figure 6**. The quantity of mentions and citations for each ecosystem service (ES) identified in the 50 analyzed manuscripts is recognized as typical services green roofs provide. Compiled from a Google Scholar search.

exploration in the study of green roofs. By addressing these gaps and expanding the scope of research, scholars can contribute to a more comprehensive understanding of the benefits and challenges associated with green roofs in the urban environment.

From a geographical perspective (Fig. 5), the most usual spatial scale of the manuscript study area was the local one (around 30% of the analyzed cases). As an example, some works studied green roof technology at a scale of 4 localities of the United Kingdom [75]: the city of Hong Kong [47, 48, 51, 53] and the cities of Florida, Chicago, and Houston [86]. It would be advantageous for future researchers to explore specific cases in towns or regions. This is relevant because local conditions, such as climate, native vegetation, and urban infrastructure, can significantly impact the effectiveness of green roofs, and exploring successful local practices could promote their adoption in areas with similar conditions. Furthermore, by looking at similarities and differences between national and building studies (21% in each). As examples of studies at a national scale, there are cited studies in China [50, 52] and Japan [62, 64], and some examples of building scale studies are the works of [86, 88] and [54, 56], which studies were in buildings of Italy and Greece, respectively. Researchers could conduct comparative analyses to reveal how different countries' policies, regulations, and ecological functions affect the implementation of this technology, contributing to the development of standardized practices tailored to specific contexts. However, only 13% of the studies have been conducted globally. Some examples of this category are presented in the studies in the Mediterranean area [59, 61] and in another paper in which the study area is North America [79]. This approach could include research on how green roofs may contribute to global problems, such as climate change and rapid urbanization, through meta-analyses that consider data from diverse regions. The representation of 13% of studies at other scales, such as districts or geographic areas, indicates significant potential to investigate green roofs in less conventional contexts. Moreover, this analysis could foster an interdisciplinary approach involving economists, sociologists, and urban planners to develop more holistic and sustainable solutions.

The results regarding the ecosystem services (Fig. 6) related to green roofs provide a solid foundation for future research in this field. The most mentioned ecosystem services were the reduction of the urban heat island and the reduction of various energy sources [39–43, 45–52, 54–58, 60–70, 72, 74–81, 84–88]. It is crucial to delve deeper into the reduction of urban heat islands and the improvement of air and water quality [41, 42, 44, 47, 49, 52, 54, 55, 60, 61, 65, 67, 70, 72, 73, 78, 81, 82, 85], through more specific studies that quantitatively measure their impact in different urban environments. Moreover, the reference to the relationship between runoff benefits and substrates indicates the necessity to explore various substrate types and their ideal composition to enhance water retention and improve plant drought tolerance [39–45, 47–52, 54, 56, 58, 60–62, 65, 68–70, 72, 73, 75–88]. There is also an opportunity to evaluate the cost-benefit of implementing green roofs in urban areas [55, 57, 65, 67, 78], including return on investment analyses and case studies in various cities. Identifying aesthetic and ecological benefits [41, 49, 56] indicates a need to explore how green roofs affect urban biodiversity, including studies on the flora and fauna that establish themselves in these environments. Furthermore, considering their ability to mitigate the impacts of acid rain and improve water quality [41, 49, 52, 54, 65, 70, 72, 73, 81, 82] and air quality [41, 42, 44, 47, 49, 52, 55, 60, 61, 65, 67, 73, 78, 85] highlights the importance of investigating their effectiveness under diverse climatic and geographic conditions. Lastly, an interdisciplinary approach integrating knowledge from ecology, engineering, economics, and urban planning could further enrich this research, addressing the challenges and opportunities comprehensively presented by green roofs. Ultimately, these findings provide a clear view of the current benefits of green roofs and outline key areas for future research that could significantly contribute to the sustainable development of cities.

## 4. DISCUSSION

This study compiles information summarizing the evolution of green roof technology from prehistory to the present based on the analysis of 50 selected papers. Over the past 22 years, research on green roofs has evolved significantly, as reflected in identifying the global distribution of study sites, research areas, applied methodologies, and geographical scales.

Historically, green roofs have transformed from rudimentary structures to complex, sophisticated designs integrating engineering with landscaping to enhance urban sustainability [19, 28, 89, 90]. Their consistent goal has been to provide ecological benefits, maintain biodiversity, regulate temperature and environmental humidity, and improve air quality. During the Neolithic and Ancient periods, green roofs offered refuge for plant life in urban and rural environments, contributing to ecosystem health.

In the Middle Ages, green roofs not only improved the thermal insulation of homes but also played a vital role in sustainable water management by retaining and filtering rainfall [89]. Modern green roofs address environmental challenges such as biodiversity loss, air pollution, and climate change [91, 92]. These installations are built with advanced waterproofing and drainage technologies, allowing them to reduce the environmental footprint of urban buildings.

The 21st century marks a significant growth period for green roof research, with a notable increase in article publications since 2001, particularly in 2008 and 2010. However, publication frequency has declined since 2015, with no relevant works detected for 2023 [93, 94]. Geographically, the United States stands out as the country with the most research participation, followed closely by China, confirming that investment in research and development and favorable government policies are key to leadership in this technology [93].

Regarding the methodologies used, green roof studies primarily rely on in situ measurements and fieldwork, complemented by modeling and simulation, which aligns with current trends in scientific research [95–99]. The most common keywords were "green roofs", "urban", "energy", and "stormwater", and the common research areas focused on urban heat island mitigation, energy efficiency in buildings, stormwater management, air quality improvement, and urban biodiversity. These areas remain of great interest due to a growing awareness of climate change and the pursuit of solutions to environmental problems [100–102].

Furthermore, our research highlights that green roof technology studies tend to concentrate on local spatial scales, indicating a focus on specific geographic areas such as individual cities or local regions. Recently, integrating photovoltaic systems with green roofs in urban settings has emerged as a crucial aspect of sustainability and green innovation [103]. This combination offers significant advantages, including reductions in carbon emissions and conservation of natural resources, promoting a more sustainable and environmentally friendly future. Together, these technologies are transforming the appearance of cities and how we live, work, and thrive in harmony with our environment.

Our study showed that the lack of research and decision-making in some regions of this green technology delays the growth of the green roof industry and its implementation in many places worldwide. Analyzing the effectiveness of different economic incentives and public regulations could provide valuable information for policymakers to design more effective strategies to promote the use of this technology. Therefore, future research must focus on how public policies can facilitate their implementation. We propose key aspects that should be addressed in future research. First, the current green roof policies should be assessed at national, municipal, and community levels. This includes classifying policies into regulations that establish mandatory standards for the implementation of green roofs and regulations that are recommendations or guidelines that encourage their adoption. It is also important to consider financial incentives, such as grants and tax credits, that promote installing these systems and financing demonstration projects showing green roofs' benefits. In addition, an analysis of the advantages and disadvantages of each policy or incentive should be carried out to identify which are the most effective. Another key aspect is identifying common elements and shared standards in policies that have proven successful. By addressing these key aspects in future research, it will be possible to promote the massive implementation of green roofs worldwide and contribute significantly to climate change mitigation, promoting a more sustainable environment for future generations.

## 5. CONCLUSION

Our study highlights the importance and evolution of green roof technology as well as current trends in research, geographical origin of the studies, geographical applied scales, study methodologies, and areas of interest in this field. Throughout history, technology has evolved and improved. With the advancement of modern science, this deep-rooted cultural heritage has been revitalized and rejuvenated, maintaining the goal of providing green roofs with ecosystem services that benefit wildlife, the environment, and humans. It has been identified that the most cited studies in the literature are related to the ecosystem services associated with their environmental benefits, such as heat island reduction and stormwater management. This result suggests the need for the scientific community to diversify study areas to gain a more comprehensive understanding of the potential of green roofs in urban environments. The quantification of the analyzed features and the analysis of the information collected in this work give a perspective for future studies and projects regarding green roofs. We believe that the studies on the economic and social aspects of green roofs have not received the same attention, leaving this important line of study in the background. The same is true for studies on public policies that play a crucial role in implementing green roof technology in cities facing environmental and urban planning challenges. Establishing a regulatory framework that encourages the adoption of these systems facilitates their integration into construction projects. It enhances the associated benefits, such as efficient stormwater management, improved air quality, and promoting biodiversity. Economic incentives, building regulations, and awareness programs promote a culture of sustainability and urban resilience. Therefore, collaboration between governments, urban planners, and communities is essential to establishing effective policies that promote the adoption of green roofs, thus consolidating their role as an innovative and necessary solution to face the challenges of contemporary urban development.

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## ETHICS

There are no ethical issues with the publication of this manuscript.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

## USE OF AI FOR WRITING ASSISTANCE

Not declared.

## PEER-REVIEW

Externally peer-reviewed.

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**Appendix 1.** A compilation of keywords (listed in alphabetical order) extracted from the 50 manuscripts analyzed, along with their respective bibliographic references. Compiled from Google Scholar search

| Keywords | Bibliographic references | Keywords | Bibliographic references |
|---|---|---|---|
| Advanced modification | [54] | Ecosystem | [79] |
| Aesthetic | [67] | Ecosystem functioning | [42] |
| Air pollution | [41, 50] | Ecosystem services | [45, 77] |
| Albedo effect | [49] | Energy | [56] |
| Architectural design | [87] | Energy budget model | [48] |
| Architecture | [58] | Energy conservation | [47, 60] |
| Attention restoration | [39] | Energy consumption | [48, 61] |
| Average quantification | [65] | Energy efficiency in buildings | [63] |
| Barriers | [53] | Energy model | [86] |
| Benefits | [54, 65] | Energy performance | [46, 84] |
| Best management practice | [81, 82] | Energy Plus | [86] |
| Biodiversity | [49, 58] | Energy saving | [62] |
| Biophysical properties | [48] | Energy-efficient construction technologies | [66] |
| Building | [87] | Environmental effects | [60] |
| Building energy | [86] | Environmental impact | [87] |
| Building energy modeling | [84] | Environmental psychology | [42] |
| Building energy simulation | [44] | ESP-r | [44] |
| Building envelope | [44] | Evapotranspiration | [55, 62] |
| Calibrated thermal energy | [63] | Evolution | [54] |
| CAM | [49] | Experimental validation | [55] |
| Canopy | [57] | Extensive | [79] |
| Chamber experiment | [50] | Extensive green roof | [47, 53] |
| China | [52] | Field measurement | [50] |
| Climate | [40] | Foliage | [57] |
| Climate change | [51] | Foliage density | [55] |
| CO2 absorption velocity | [50] | Green Building | [66] |
| Commercial products | [59] | Green roof | [39–41, 43, 46, 50–52, 54–56, 60–62, 64, 65, 68–75, 77, 81–87] |
| Compact city | [51] | Green roof materials | [41] |
| Components | [54] | Green rooftop | [57] |
| Conventional roof | [59] | Green walls | [65] |
| Cool green roof | [63] | Guidelines | [79] |
| Cool roof | [46] | Heat flux | [47] |
| Cooling effect | [51] | High reflection roof | [64] |
| Cooling load | [47] | Hong Kong | [53] |
| Critical review | [68] | Human thermal comfort | [51] |
| Data variability | [65] | Hydrology | [83] |
| Deficit irrigation | [40] | Intensive green roof | [48] |
| Design | [67] | International market | [59] |
| Detention | [75] | Irrigation systems | [59] |
| Directed attention | [39] | Landscape ecology | [58] |
| Drought tolerance | [45] | Latent flux | [44] |
| Economic benefits | [60] | Lead | [73] |
| Ecoroof | [80, 86] | Leaf area index | [57] |

**Appendix 1 (cont).** A compilation of keywords (listed in alphabetical order) extracted from the 50 manuscripts analyzed, along with their respective bibliographic references. Compiled from Google Scholar search

| Keywords | Bibliographic references | Keywords | Bibliographic references |
|---|---|---|---|
| Life-cycle costs | [65] | Sedum album | [71] |
| Linear programming | [71] | Sedum-moss | [69] |
| Living roof | [58] | Shading | [57] |
| Media | [82] | Simulation | [86] |
| Mediterranean | [61] | Sky woodland | [48] |
| Mediterranean climate | [59] | Stormwater | [61, 71, 75, 83] |
| Metals | [81] | Stormwater capture | [43] |
| Model | [75–83] | Stormwater management | [75] |
| Modular green roof system | [66] | Stormwater runoff | [70,82] |
| Native plants | [45–79] | Substrate | [68,79] |
| Nitrogen | [82] | Succulents | [79] |
| Nonpoint source pollution | [81] | Surface heat budget | [64] |
| North Carolina | [82] | Sustainability | [41,72] |
| Numerical simulation | [50] | Sustainable Building | [61] |
| Nutrients | [81] | Sustainable development | [53, 66, 87] |
| Parametric analysis | [46] | Sustainable ecosystem | [68] |
| Passive cooling | [47] | Sustainable urban design | [51] |
| Peak flow reduction | [82] | Sustainable urban drainage systems | [72] |
| People's preferences | [67] | Sustained attention | [39] |
| Phosphorus | [82] | Thermal fluctuation | [56] |
| Physico-chemical properties | [68] | Thermal insulation performance | [48] |
| Plant communities | | Thermal performance | [46, 47, 60] |
| Plant traits | [42] | Thermally massive systems | [84] |
| Pollution mitigation | | Unit hydrograph | [71] |
| Polymers | [41] | Urban | [70, 81] |
| Precipitation retention | [82] | Urban ecology | [7, 66] |
| Preconceptions | [67] | Urban ecosystems | [45] |
| Promotional policies | [55] | Urban greening | [39, 67] |
| Rainwater runoff | [72] | Urban heat | [65] |
| Recycled components | [59] | Urban heat island | [42, 48, 51, 63, 87] |
| Research and development | [52] | Urban runoff | [69, 73] |
| Research gaps | [68] | Urban stormwater runoff | [82] |
| Reservoir routing | [75] | Urbanization | [77] |
| Retention | [74, 75] | Vegetated roof | [70, 80] |
| Retrofit | [60] | Water balance | [55, 69] |
| Retrofitting | [54] | Water management | [40] |
| Return period | [74] | Water pollution | [73] |
| Roofing | [84] | Water quality | [42, 82] |
| Runoff | [80-83] | Water use | [45] |
| Runoff quality | [70] | Work breaks | [39] |
| Sedum | [45, 49, 81] | | |