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A Comprehensive Review of Different Types of Green Infrastructure to Mitigate Urban Heat Islands: Progress, Functions, and Benefits

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Abstract: Climate change and rapid urbanization increase/amplify urban heat islands (UHIs). Green infrastructure (GI) is an effective and popularly strategy used to moderate UHIs. This paper aims to better understand the progress of different GI types (urban parks, urban forests, street trees, green roofs, green walls) in mitigating UHIs, and what benefits they provide. Firstly, this paper used CiteSpace to analyze 1243 publications on the Web of Science from 1990 to 2021, then analyzed the function/regulation of ecosystem services/benefits and values of GI types in reducing UHIs. The historical review results show that research on all GI types showed rapid growth since 2013, and their GR increased rapidly. The highest-ranking keywords were urban heat island/heat island, climate/climate change/microclimate, and temperature/land surface temperature/air temperature. "Design," "vegetation," "quality," and "reduction" are the top four strongest keyword bursts. The most published countries are the People's Republic of China, USA, Australia, Germany, and Italy, and the top three institutions are the Chinese Academy of Sciences, Arizona State University, and the National University of Singapore. *Landscape and Urban Planning*, *Building and Environment*, *Energy and Building*, and *Urban Forestry and Urban Greening* are the most published journals. In urban areas, different GI types as a form of ecosystem hardware provide multiple functions (reduced land surface temperatures, lower building energy usage, improved thermal comfort and enhanced human health, reduced morbidity and mortality, etc.). GI thus provides a regulated ecosystem service to ameliorate UHIs primarily through temperature regulation and shade. At the same time, GI provides benefits and values (ecological, economic, social, and cultural) to humans and urban sustainable development. GI types determine the functions they provide, afford corresponding regulated ecosystem services, and provide benefits and values in a logical/recycle system. Overall, this review highlights the development and importance of GI, as well as the relationship of GI types and functions of regulating the ecosystem service benefits and values to mitigate UHI, and advances the study of climate change adaptation in cities.

Keywords: green infrastructure; urban heat island; comprehensive review; ecosystem services; benefits and values

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1. Introduction

Rapid urbanization has caused land-use change, replacing green spaces and vacant land with urban infrastructures, and climate change has increased the frequency of extreme climatic events and the intensity of heatwaves, which has strongly impacted the urban thermal environment, resulting in higher land surface temperatures and higher thermal absorption of solar radiation [1–3]. This phenomenon leads to what is known as the urban heat island (UHI), whereby urban areas have higher temperatures than surrounding non-urban areas [4]. UHIs affect human health and human thermal comfort, intensifying the peak temperature during the day and night in high-density urban areas [5–7]. Moreover, it also causes a series of problems such as increased energy consumption, altered water quality, and lower air quality [3,8–10], which can seriously threaten the ecological environment and sustainable development of the city [11].

In recent years, GI has been considered an effective and adapted strategy to moderate and mitigate the UHI effect that has been used in many countries [12–15]. GI, defined as a "strategically planned network of natural and semi-natural areas (with other environmental features) designed and managed to deliver a wide range of ecosystem services," is a network system of green space which includes different types such as urban parks, urban forests, urban streets, green roofs, and green walls [16]. Different GI types play their own role and are different elements in the urban ecological system; urban parks and urban forests as the green points, urban streets and green walls as green lines, and urban forests as green polygons in the city with the different shape, size, and structure, but are in the green space system to provide multiple benefits to a city, which also could combine the different GI types together to be a points–lines–polygons cascade system, to enhance the functions or ecosystem services or benefits of each other [5,16–19]. For example, planning green infrastructure in a decentralized way could enhance the resilience and sustainability of one area [15].

Different GI types play multiple functions in mitigating UHIs, serving to lower land surface temperatures and easing the urban thermal environment by increasing cooling, such as increasing shaded areas from tree canopies and the evaporation of various types of vegetation; improving the surface energy balance, as by increasing the absorption and reflection of solar radiation from trees or different types of vegetation; and affecting air movements and heat exchange, as by covering areas with vegetation to retain water for evaporation and to quickly absorb and retain heat when exposed to solar radiation [20–25]. Additionally, GI can reduce air pollution, carbon emissions and carbon sequestration, stormwater runoff, heat-stress-associated mortality, and illness, and is thus beneficial for human health, the ecological environment, and sustainability development [26–28]. As a system, GI fulfills its purposes by providing regulative ecosystem services to UHIs (ecosystem services are "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life") [29–32] and by providing multiple benefits (environment, economic, social, and cultural) to cities or human beings, providing practical and significant value to the urban ecosystem [5,7,33].

There is much research showing that different types of GI can significantly mitigate the hot urban climate during summer by cooling, thereby directly and indirectly reducing the UHI [6,34]. GI seems to be an effective adaptive measure for climate change in most countries, especially China [3,9], showing resilience to both long-term adaptations of climate change and short-term UHI effects, improving human well-being, and increasing urban sustainability. For example, Yu et al. (2022) showed that urban greening effectively reduced the near-surface temperature (0.45 °C) and improved human thermal comfort [35]. Similarly, Yang et al. (2022) showed that the proportion of vegetation coverage was significantly negatively correlated with surface temperature ($R > 0.328$), and the landscape pattern of urban and suburban vegetation coverage had different regulating effects on the surface UHI [36]. A study performed by Leal Filho (2021), from 2018 to 2019 across 14 cities in 13 countries, provided an integrated overview of cities in developed and developing countries that face urban heat island effects on their territories [4].

This study aims to provide a comprehensive review of the effects of five different GI types in mitigating UHI effects in studies from 1990 to 2021 based on the Web of Science, by using CiteSpace to analyze and visualize the research status, trends, and hotspots, and to determine the overall state of research [37–39]. Thereafter, a statistical summary and review are presented of the functions, regulating system service, benefits, and value of different GI types in mitigating UHI. This review aims to enable researchers to understand the overall state of research in this field through an accurate and systematic analysis of current publications, to clarify the relationship between GI types-functions-ecosystem service-benefits and values, and to identify knowledge gaps and potential directions of cooperation across different disciplines.

2. Materials and Methods

The WOS Core Collection (formerly the Institute for Scientific Information Web of Knowledge) is the most used and authoritative research literature search platform for information on more than 100 subjects, and the world's most trusted scientific and publisher-independent global citation database. This database covers essentially all languages and documents (articles, conference papers, books, etc.). This paper is based on the citation indexes including SCI-Expanded (Science Citation Index Expanded, 1900–present), SSCI (Social Science Citation Index, 1900–present), A&HCI (Arts and Humanities Citation Index, 1975–present), and ESCI (Emerging Sources Citation Index, 2015–present) in the "Web of Science Core Collection."

We searched for research publications published in peer-reviewed journals in English from 1990 to 2021, available from the ISI Web of Science databases using the following search keywords [39–41]: term1: urban heat island (UHI) OR urban thermal environment (UTE) OR land surface temperature (LST) AND term$2_{(1–6)}$: term2_1-green infrastructure (GI) OR term2_2-urban parks (UPS) OR term2_3-urban forests (UFS) OR term2_4-green streets OR street trees (UTS) OR term2_5-green roofs OR eco-roof OR living roof OR vegetate roof OR roof garden OR roof greening (GR) OR term2_6-green wall OR vertical greenery system OR green facades (GW) AND term3: ecosystem services(ESS) OR benefits OR values. We searched term1 and term$2_{(1–6)}$ and term3 six times separately, and downloaded the six different databases from WOS for the historical review analysis of GI types. Consequently, the search topic (which includes title, abstract, author keywords, and keywords plus) used these terms. The search date was October 2021.

The six different databases yielded more than 1000 publications. We screened them by reading the title and abstract of these publications to check whether they studied urban heat islands, land surface temperatures, or thermal environments. All the publications were then downloaded and analyzed. First, following the methods in Shao et al. (2021) [39], all publications were entered into CiteSpace software for visualization for the historical review to present the status and research trends for further analysis, such as the publication year, keywords analysis, source journal, and research hotspots. Thereafter, based on the six GI types databases, we (1) selected the highest-cited publications and review publications from each GI-type downloaded database; then (2) based on comments from experienced scholars and researchers, with the research topic of GI and these five GI types to mitigate the UHI, and also related or focused on the functions, ecosystem services, benefits and value, the other 10 most closely related articles in each GI types from this five important journals, *Landscape and Urban Planning*, *Urban Forest and Urban Greening*, *Building and Environment*, *Science of the Total Environment*, and *Sustainable Cities and Society*, were recommended and downloaded. We then read more carefully to examine whether these publications were discussed, based on the following: (1) the functions of these five different types of green infrastructure; (2) how these five different types of green infrastructure provide regulative ecosystem services; and (3) what the benefits and values of these five different types of green infrastructure are. Finally, we summarized and analyzed these publications on these topics, which are shown below in Figure 1.

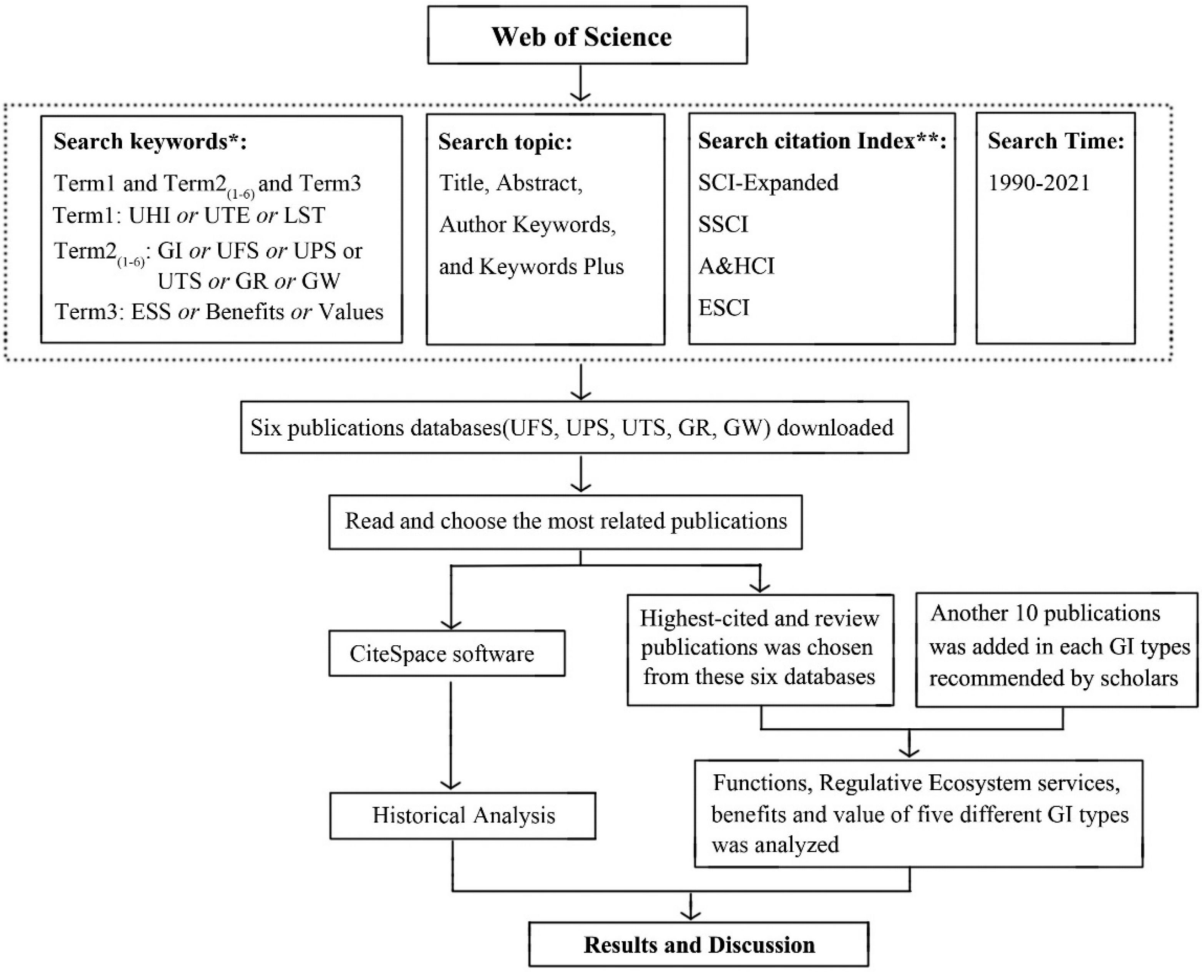

Figure 1. The diagram of methodology. *: UHI: urban heat island, UTE: urban thermal environment, LST: land surface temperature; GI: green infrastructure, UPS: urban parks, UFS: urban forests, UTS: green streets OR street trees, GR: green roofs OR eco-roof OR living roof OR vegetate roof OR roof garden OR roof greening, GW: green wall OR vertical greenery system OR green facades; ESS: ecosystem services. **: SCI-Expanded: Science Citation Index Expanded, 1900–present, SSCI: Social Science Citation Index, 1900–present, A&HCI: Arts and Humanities Citation Index, 1975–present, and ESCI: Emerging Sources Citation Index, 2015–present.

3. Results

3.1. Historical Review

In the first step, 1243 publications were obtained from the WOS to use in the historical review analysis of the six GI types, followed by the construction of six different databases using the search terms green infrastructure (GI, 218 publications), urban parks (UPS, 225 publications), urban forests (UFS, 271 publications), green streets OR street trees (UTS, 146 publications), green roofs OR eco-roof OR living roof OR vegetate roof OR roof garden OR roof greening (GR, 279 publications), and green wall OR vertical greenery system OR green facades (GW, 104 publications). Then, after screening these publications from the titles and abstracts, a total of 902 publications were retained for further analysis.

3.1.1. Historical Trends

To obtain an overview of the research on different GI types in mitigating UHIs, published publications from 1990 to 2021 were calculated and compiled (Figure 2) to reflect the publication trends.

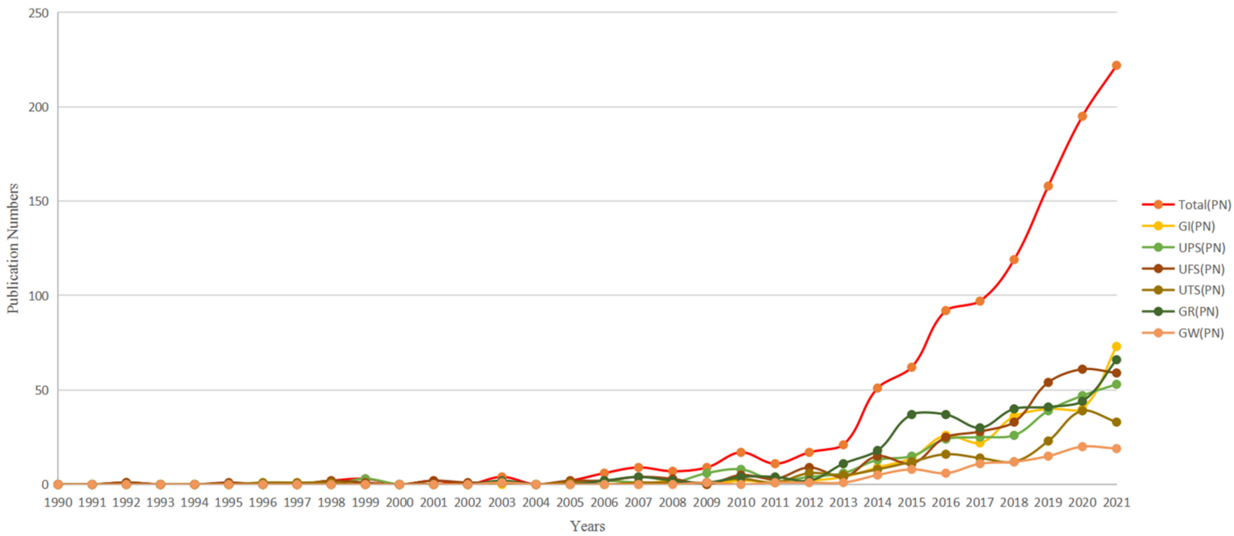

Figure 2. Line chart of publication trend from 1990 to 2021 (number of publications per year). (PN), publication numbers; Total (PN), the publications numbers of all GI types.

As shown in Figure 1, the annual changes in every GI type and all GI publications showed a continuing upward trend. The Total(PN) line shows that the publication number had a sharp increase, especially from 2013 to the present, indicating a stage of rapid development. From 2005 there were only several publications in the initial development stage, then from 2005 to 2013, there was a slight increase in publications each year in a slow development stage. The first publication focused on GI and UHIs was in 1992, with only one paper published. From 2005 to 2013, the publication numbers were from 2 to 21 publications per year, which indicates that the influence of publications increased yearly and the field of the use of GI to mitigate UHIs constantly developed, with new emergent hotspots. Then, from 2013, there was a significant increase to 195 publications in 2020, showing the interest in GI to mitigate UHIs continued to expand, with the number of researchers in this field increasing annually, and in this period the field has entered a stage of vigorous development.

For different GI types, the lines GI(PN), UPS(PN), UFS(PN), UTS(PN), GR(PN), and GW(PN) showed the same growth trends, and all lines showed volatility around continuous increase. The first publications on GI(PN), UPS(PN), UFS(PN), UTS(PN), GR(PN), and GW(PN) were in 2008, 1992, 1992, 1996, 2003, and 2003, respectively. In general, from 1990 to 2021, GR(PN) increased the fastest and GW(PN) the slowest. All lines show a significant increase in 2021.

3.1.2. Keyword Analysis

Distribution of Publications by Keywords

Keywords indicate the subject of a paper, which appears frequently, lists the most important elements, and provides an abbreviated view of the central content. They are the words used by computer systems to index the characteristics of the content of the paper, allowing them to be conveniently collected by information systems for readers to retrieve. We summarized and visualized keywords regarding GI types in UHI mitigation in the literature in Citespace, as shown in Table 1 and Figure 3. Table 1 shows the frequency of keywords in different GI types, that is, the ranking of the importance of keywords in a certain GI type research. It also indicates the hotspots and the important issues in this GI-type research. Figure 3 shows the same information, and the larger the cross that corresponds and the keywords' font means a greater number of keywords and more frequency of its co-occurrence. Also, the thicker the line that is connected, the stronger the relationship between them, and the more lines connected with a certain cross symbol, the closer the connection between these keywords.

Table 1. Top 15 most frequently used keywords during 1990–2021 for different GI types.

No.	Keywords of GI	Keywords of UPS	Keywords of UFS	Keywords of UTS	Keywords of GR	Keywords of GW
1	Green infrastructure	City	City	Vegetation	Green roof	Urban heat island
2	Ecosystem service	Heat island	Impact	Impact	Urban heat island	Impact
3	Heat island	Impact	Urban heat island	Urban heat island	Impact	Vegetation
4	Impact	Urban heat island	Land surface temperature	Heat island	Mitigation	Green roof
5	Climate change	Park	Forest	Temperature	Performance	Thermal performance
6	Vegetation	Vegetation	Heat island	City	Benefit	Building
7	Climate	Climate	Climate change	Environment	Heat island	Facade
8	Temperature	Thermal comfort	Ecosystem service	Climate	Energy	Temperature
9	Mitigation	Temperature	Temperature	Microclimate	Temperature	Living wall
10	Benefit	Environment	Urbanization	Thermal comfort	Vegetation	Green wall
11	Urban	Green space	Vegetation	Ecosystem service	City	Roof
12	Space	Ecosystem service	Land use	Street	Climate	Performance
13	Green roof	Area	Climate	Design	Roof	Green facade
14	Land surface temperature	Land surface temperature	Pattern	Outdoor thermal comfort	Thermal performance	Climate change
15	Infrastructure	Air temperature	Urban forest	Street canyon	System	Energy performance

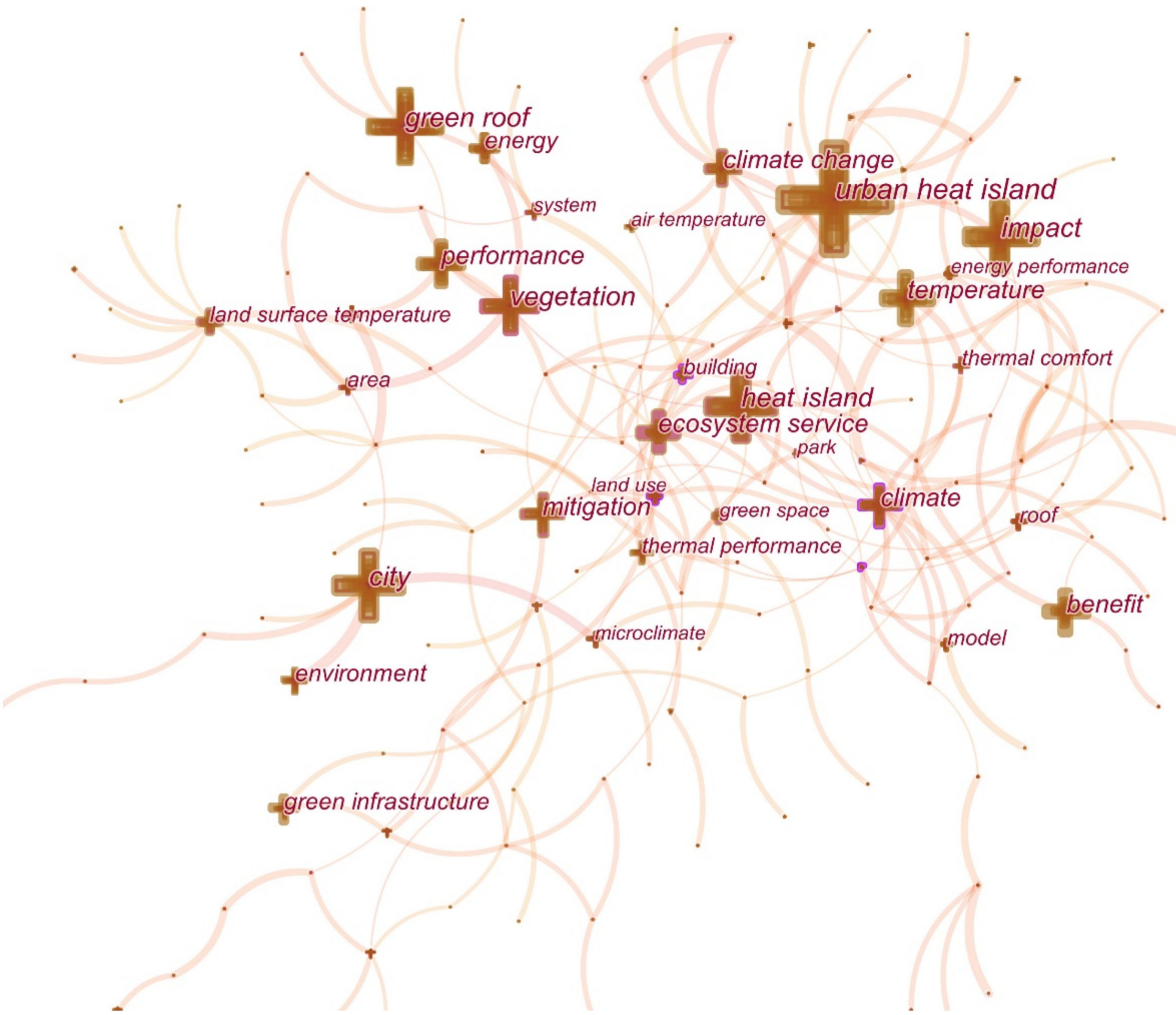

Figure 3. Distribution of the top 30 keywords.

Table 1 lists the top 15 most frequently used keywords from different GI types from 1990 to 2021. Among the top three keywords for all the different GI types, the most commonly appearing ones are "impact" and "urban heat island", followed by "heat island", "city", and "vegetation", as shown in Figure 3. This shows that these keywords were the most important and more frequently used in this research field than any other keywords.

We then counted and sorted the top 15 keywords of all the different GI types, yielding the following ranking: "urban heat island/heat island", "climate/climate change/microclimate", "temperature/land surface temperature/air temperature", "city/urban", "impact", "performance/thermal performance/thermal comfort", "vegetation", and "ecosystem service". These top 15 keywords indicate that the primary terms are more focused on the UHI concept and phenomenon, methods and indicators, performance and impact on urban areas/cities, and ecosystem service with vegetation. Among the keywords for GI, the top three keywords are green infrastructure, ecosystem service, and heat island, and the keywords "green infrastructure/infrastructure" only appeared in this research area. In keywords of UPS and UFS the top one keywords is city, "park", and "green space" only appeared among the keywords of UPS. Furthermore, the keywords "forest/urban forest" appeared among the keywords of UFS. Similarly, "street/street canyon" among the keyword of UTS, but for this type, the keyword "microclimate" also appeared. "Green roof/roof" appeared in the keywords for GR and GW, and for the latter "facade/living wall/green wall" appeared as well. Urban heat island/heat island, impact, temperature, climate/climate change appeared in all different GI types of research, which means that these keywords are more frequently used than others. Vegetation only appeared in GI, UPS, UFS, GR, GW research, and ecosystem service only appeared in GI, UPS, UFS, and UTS research, etc.

Timeline of Keywords

The timeline of keywords is a time series of clusters of keywords that can show the relationships between the clusters of keywords sets and historical spans. As shown in Figure 4, the larger the cross symbol on each horizontal axis, the higher the frequency of keywords, allowing a determination of the research hotspots in a given period. The words with "# number" on the right are a type of keyword cluster in which the number is arranged from large to small. There were 11 clusters in Figure 4: *urban park system*, *ecological restoration*, *Zillow neighborhood*, *truck circumference*, *street greenery*, *green roof*, *near-ground air*, *spatial resolution*, *unshaded condition*, *spatial structure*, and *blue daze*. Among these clusters, #5 *green roof* lasted the longest, and "energy", "urban heat island", "green roof", and "vegetation" were the four highest-frequency keywords used. The cluster #10 *blue daze* lasted the shortest, and "energy consumption", "plant", and "vegetated roof" were the three highest-frequency keywords used. By analyzing and summarizing the keywords of each cluster, it can be seen that they are more focused on the methods of UHI, functions, and benefits of GI types, the data source and study scale, indicators, and patterns.

Keywords Bursts

Keyword bursts can reflect the changes in the keywords used in a research field, which could indicate the research topics and hotspots, which is a very important aspect to be analyzed and summarized. Figure 5 shows the top 30 keywords with the strongest citation bursts from 1990 to 2021 based on the WOS database. The earliest keyword bursts are "vegetation", "green roof", "city", and "microclimate" (beginning in 2010), and the latest keyword burst is "shade tree" (beginning in 2019 and ending in 2019). The longest keyword burst is for "design" (beginning in 2013 and ending in 2017), while the shortest bursts are for "albedo", "climate change adaptation", "air temperature", "spatial pattern", "island", "energy performance", "cool", and "shade tree." "Reduction" is the only keyword whose burst continues to the present; it began in 2018. The top four keywords with the strongest bursts are "design", "vegetation", "quality", and "reduction". These are research hotspots related to vegetation planning, methods, functions, and benefits. In addition, they show that the research topics can change rapidly and that more specific research branches developed fast.

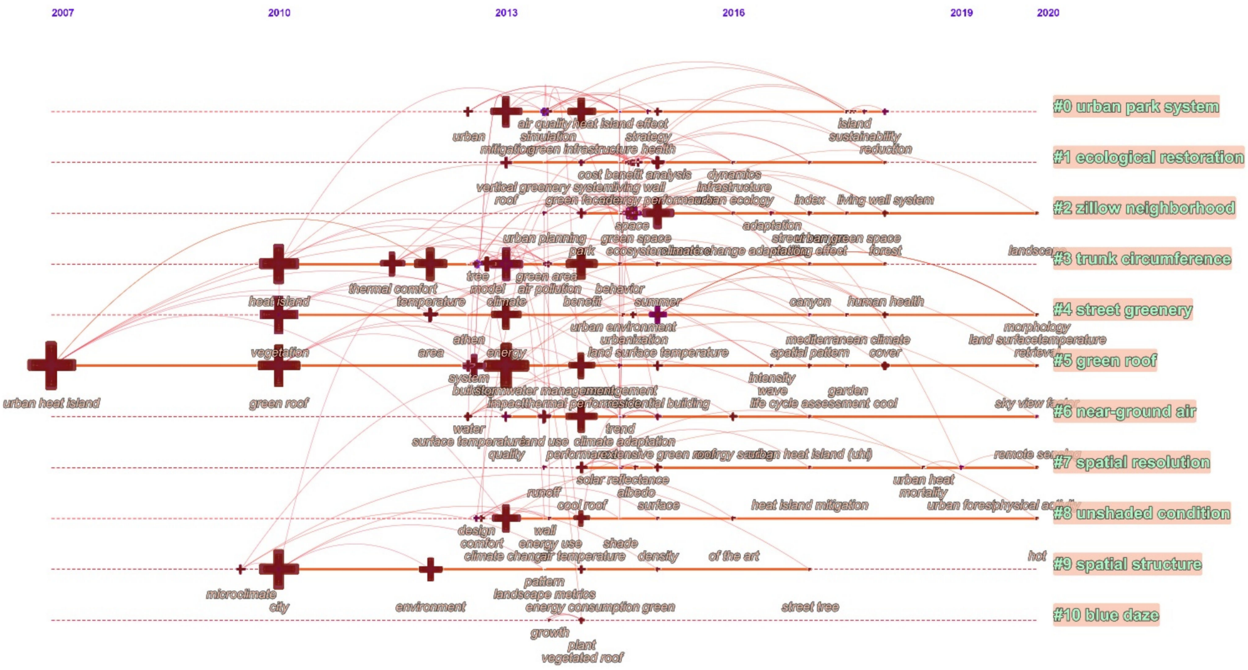

Figure 4. Keyword timeline in the literature on different GI types to mitigate UHIs from WOS.

Top 30 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	1996 - 2021
vegetation	1996	4.5815	**2010**	2013	
green roof	1996	2.2785	**2010**	2011	
city	1996	2.2445	**2010**	2012	
microclimate	1996	2.4382	**2010**	2012	
design	1996	3.6016	**2013**	2017	
water	1996	3.2433	**2013**	2015	
quality	1996	5.6744	**2013**	2016	
runoff	1996	2.3476	**2014**	2016	
urban planning	1996	3.5267	**2014**	2016	
green facade	1996	2.9537	**2014**	2015	
energy use	1996	3.0202	**2014**	2015	
green area	1996	3.5253	**2014**	2015	
albedo	1996	2.3178	**2015**	2015	
behavior	1996	2.2691	**2015**	2016	
biodiversity	1996	3.18	**2015**	2016	
ndvi	1996	2.2691	**2015**	2016	
management	1996	3.18	**2015**	2016	
climate change adaptation	1996	2.3303	**2016**	2016	
climate	1996	2.4803	**2016**	2017	
air temperature	1996	2.666	**2017**	2017	
adaptation	1996	2.4434	**2017**	2018	
spatial pattern	1996	2.2793	**2017**	2017	
green wall	1996	2.687	**2017**	2018	
island	1996	2.6591	**2018**	2018	
energy performance	1996	2.6204	**2018**	2018	
cool	1996	4.1507	**2018**	2018	
strategy	1996	2.6232	**2018**	2019	
reduction	1996	2.4173	**2018**	2021	
sustainability	1996	2.9173	**2018**	2019	
shade tree	1996	2.6655	**2019**	2019	

Figure 5. Timeline of keywords.

3.1.3. Geographic Patterns

Distribution of Publications by Country

The distribution and number of publications by country in a certain period can reflect the degree of the country's contribution to this research field, which also can implicate the research hotspots concerned by researchers and the environmental issue in this country. Table 2 summarizes the top 10 countries in the number of publications for different GI types from 1990 to 2021, which is also shown in Figure 6. From the listed countries in each column of GI types in Table 2, it is reflected that in different countries the important research topic with these five different GI types are different, and it also indicates that the more publications of a GI type research in one country, the more preferred to study this topic than other countries. Among the top three countries of all the different GI types, the most published country was the People's Republic of China (PRC), followed by the USA, Australia, Germany, and Italy. It shows that these countries thus occupy a dominant position in this field, and place more focus on the GI to mitigate UHI research than any other countries.

Table 2. Top 10 countries by publications on different GI types, 1990–2021.

No.	Countries of GI	Countries of UPS	Countries of UFS	Countries of UTS	Countries of GR	Countries of GW
1	USA	PRC	PRC	PRC	USA	Australia
2	PRC	USA	USA	USA	Italy	Italy
3	England	Germany	Germany	Australia	PRC	PRC
4	Australia	Australia	Australia	Italy	Australia	Malaysia
5	Germany	Italy	Canada	Germany	England	Portugal
6	Italy	Japan	England	Singapore	Spain	USA
7	Netherlands	England	Italy	South Korea	Australia	Singapore
8	Canada	Spain	India	Greece	Germany	Germany
9	Japan	Brazil	Turkey	Canada	Japan	Ireland
10	Spain	Greece	Japan	Malaysia	Netherlands	Qatar

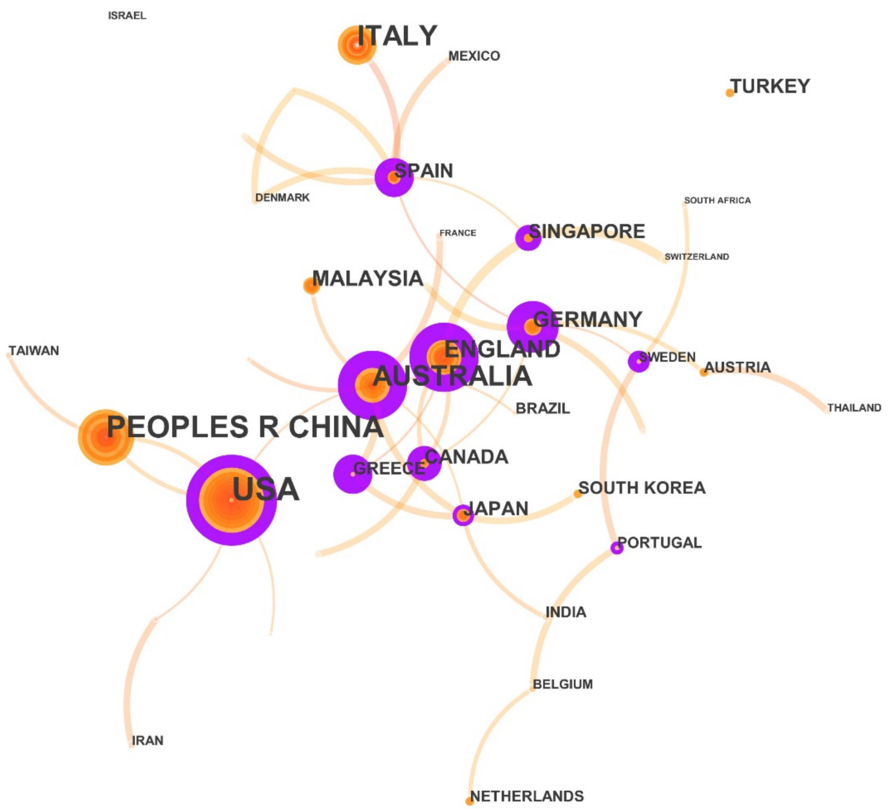

Figure 6. Distribution of main countries.

For different GI types, in GI research, the USA has the most publications than other countries, and then followed by PRC and England, Australia, etc. Also in GR research, the USA is the top one. The PRC and USA were the top two most published countries in UPS, UFS, and UTS, then followed by Germany, Australia, etc. In GW research, Australia ranks first, followed by Italy and the PRC. For different countries, in the USA, it ranked in publications, and ranks second in UPS, UFS, and UTS, but in GW research it ranks sixth. Additionally, Australia ranked third in UTS and fourth in GI, UPS, and UFS. The PRC is ranked first in UPS, UFS, and UTS, second in GI, and third in GR and GW. Other Asian countries such as Malaysia, Singapore, South Korea, and Japan also play significant roles in the research field of GW, UTS, and UPS. European countries such as England, the Netherlands, Spain, and Portugal play important roles in the research fields of GI, UPS, and GR.

Distribution of Publications by Institution

The distribution and numbers of publications by institution can implicate the contribution and degree of cooperation of each institution in this research field, which can show the cross-regional development of the field and the status quo of the cooperation network between different institutions, allowing researchers to quickly identify the leading research institutions. Table 3 shows the top 10 institutions by number of publications for different GI types from 1990 to 2021. The same information is presented in Figure 7, where the more lines there are in the network, the greater the cooperation with other institutions, and the larger the words, the greater the contribution. Table 3 clearly shows the ranking of the research importance of these different GI types in different institutions, and also indicates that the more publications of a GI type research in one institution, the more preferred to study this topic or more cooperation than other institutions.

Table 3. Top 10 institutions by publications in different GI types, 1990–2021.

No.	Institutions of GI	Institutions of UPS	Institutions of UFS	Institutions of UTS	Institutions of GR	Institutions of GW
1	Arizona State Univ	Chinese Acad Sci	Chinese Acad Sci	Monash Univ	Arizona State Univ	Natl Univ Singapore
2	Univ Melbourne	Chinese Acad Sci	Univ Chinese Acad Sci	Univ Melbourne	Natl Univ Singapore	Univ Lisbon
3	Tech Univ Munich	Arizona State Univ	US Forest Serv	Natl Univ Singapore	Chinese Acad Sci	Univ Hong Kong
4	Univ Exeter	Griffith Univ	Arizona State Univ	Swiss Fed Inst Technol	Univ Lisbon	Univ Coll Dublin
5	Univ New South western	Beijing Forestry Univ	Tech Univ Munich	Tech Univ Munich	Univ Hong Kong	Chinese Univ Hong Kong
6	Univ Hong Kong	Nanjing Forestry Univ	Univ Hong Kong	Wageningen Univ	Chinese Univ Hong Kong	Hamad Bin Khalifa Univ
7	Tongji Univ	Univ Hong Kong	Univ Wisconsin	Nature Conservancy	Univ New South western	Univ Technol Sydney
8	Chinese Univ Hong Kong	Univ Freiburg	Nanjing Univ Informat Sci & Technol	Univ Putra Malaysia	Columbia Univ	
9	Swiss Fed Inst Technol	Univ Politecn Madrid	Univ Salzburg	Chinese Acad Sci	Univ Catania	
10	Humboldt Univ	Educ Univ Hong Kong	Rudn Univ	Univ Florence	Univ Coll Dublin	

Based on Table 3, among the top three institutions of these different GI types, the most published institutions were the Chinese Academy of Sciences, Arizona State University, the National University of Singapore, the University of the Chinese Academy of Sciences, and the University of Melbourne. As also shown in Figure 7, these institutions have obvious networks of cooperation through which they play an important role in this field. In short, Arizona State University ranked first in GI and GW, and the Chinese Academy of Sciences ranked first in UPS and UFS. In GW research, the National University of Singapore ranked first, while Monash University ranked first in UTS. In the research fields of GW and GR, the National University of Singapore plays a dominant position. In UPS and UFS, the Chinese Academy of Sciences and University of the Chinese Academy of Sciences contribute the most, while in GI and UTS, Arizona State University does so.

Figure 7. Distribution of institutions.

3.1.4. Journal Analysis

Journal analysis is very important for research scholars by helping academic researchers quickly identify the most suitable and authoritative journals in a field. Table 4 shows the top 10 journals by the number of publications from 1990 to 2021 on different GI types, and each column shows the different journals sorted by the number of publications, and also indicates the most popular journals in different GI types research. Based on Table 4, among the top three journals for the different GI types, the journals with the most publications were *Landscape and Urban Planning*, *Building and Environment*, *Energy and Buildings*, and *Urban Forest and Urban Greening*. This means these journals play a professional and significant role in these fields and they make an important contribution by accepting the submissions, and also that these journals are more popular and published than any others. *Landscape and Urban Planning* is the top publications journal in GI, UPS, UFS, and UTS, and ranked third in GR and GW. For GR and GW, *Building and Environment* and *Energy and Buildings* are the most published journals. *Science of the Total Environment*, *Solar Energy*, and *Environmental Pollution* are also important journals. For different types of GI published journals, there is also a little difference. For example, authors in UFS may choose *Remote Sensing of the Environment*, *International Journal of Remote Sensing*, and *Remote Sensing*, while those in GR and GW may choose *Building and Environment*, *Energy and Buildings*, *Solar Energy*, and *Ecological Engineering*.

3.2. Green Infrastructure for UHI Studies

In the second step, we finally chose and downloaded a total of 221 related articles (review papers, widely cited papers, and other selected papers) from the Web of Science, as shown in Table 5 below. We then read these papers more carefully, and subjected them to both quantitative statistical and qualitative content analysis, whose results are shown in Figure 8 below.

Table 4. Top 10 journals by publications on different GI types, 1990–2021.

No.	Journals of GI	Journals of UPS	Journals of UFS	Journals of UTS	Journals of GR	Journals of GW
1	*Landscape and Urban Planning*	*Landscape and Urban Planning*	*Landscape and Urban Planning*	*Landscape and Urban Planning*	*Building and Environment*	*Building and Environment*
2	*Urban Forest and Urban Greening*	*Building and Environment*	*Remote Sensing of the Environment*	*Building and Environment*	*Energy and Buildings*	*Energy and Buildings*
3	*Building and Environment*	*Energy and Buildings*	*Urban Forest and Urban Greening*	*Energy and Buildings*	*Landscape and Urban Planning*	*Landscape and Urban Planning*
4	*Energy and Buildings*	*Urban Forest and Urban Greening*	*Science of the Total Environment*	*Urban Forest and Urban Greening*	*Solar Energy*	*Urban Forest and Urban Greening*
5	*Science of the Total Environment*	*International Journal of Biometeorology*	*International Journal of Remote Sensing*	*Solar Energy*	*Urban Forest and Urban Greening*	*Applied Energy*
6	*Journal of Environmental Management*	*International Journal of Climatology*	*Remote Sensing*	*International Journal of Climatology*	*Ecological Engineering*	*Solar Energy*
7	*Environmental Pollution*	*Solar Energy*	*Building and Environment*	*International Journal of Biometeorology*	*Renewable & Sustainable Energy Reviews*	*Ecological Engineering*
8	*Solar Energy*	*Theoretical and Applied Climatology*	*Energy and Buildings*	*Theoretical and Applied Climatology*	*Applied Energy*	*Renewable & Sustainable Energy Reviews*
9	*Sustainable Cities and Society*	*Science of the total environment*	*Environmental Pollution*	*Urban Climate*	*Environmental Pollution*	*Environmental Pollution*
10	*sustainability*	*Remote Sensing of the Environment*	*Science*	*Sustainable Cities and Society*	*Atmospheric Environment*	*Atmospheric Environment*

Table 5. The 221 related articles downloaded from the Web of Science.

Types	Review Papers (*N*)	High-Cited Papers (*N*)	Research Papers (*N*)
UPS-related articles	16	10	10
UFS-related articles	12	6	10
UTS-related articles	10	10	10
GR-related articles	38	16	10
GW-related articles	16	6	10
GI-related articles	11	10	10

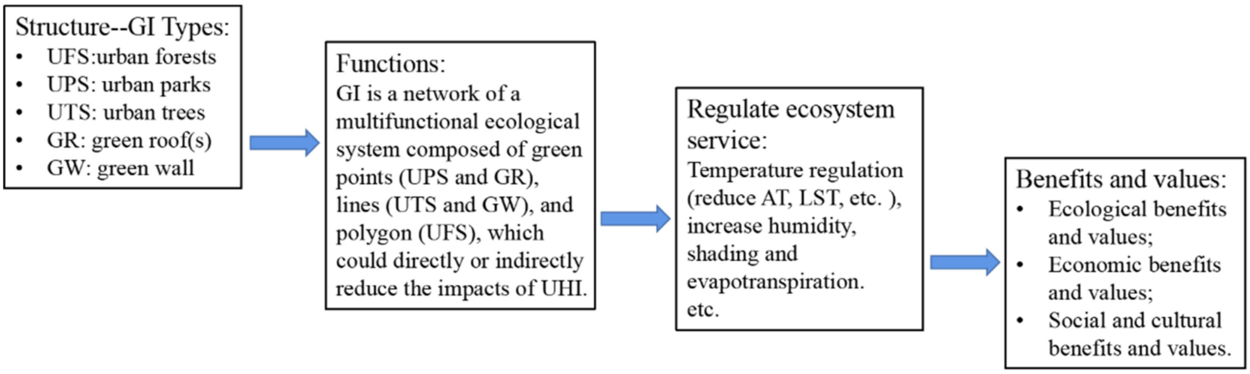

Figure 8. Conceptual framework describing GI analysis used in this study.

3.2.1. The Function of GI Types

Green infrastructure as a UHI mitigation and adaptation strategy has a comprehensive function. Different types of GI of different sizes, shapes, and so on, could be seen as the ecosystem hardware for different structures in the city to provide ecological benefits for human beings, such as (1) reducing the land surface temperature (LST) and mitigating surface urban heat islands (SUHIs) by providing protection and shading effects from vegetation (trees, shrubs, grasses), reducing and absorbing solar radiation, and irrigation; (2) cooling surfaces and the environment through evaporation, transpiration from vegetation (the leaves of trees, etc.), and its thermal and optical properties, and in addition some solitary large parks could offer minimal boundary-layer cooling; (3) reducing building energy needs and greenhouse gas-related emissions; (4) improving thermal comfort and human health (physical and psychological), reducing thermal stress, and improving the quality of life of residents; and (5) reducing the morbidity, mortality, number, and severity of climate-related disasters associated with urban heat islands, as summed up in Table 6 below.

Table 6. The functions and regulative ecosystem services, benefits, and values of GI.

GI	UPS, UFS, UTS, GR, GW	Reference
Functions	(1) Reducing the land surface temperature (LST) and mitigating surface urban heat island (SUHI); (2) Cooling surfaces and environment; (3) Reducing building energy needs and greenhouse-gas-related emission; (4) Improving thermal comfort and human health (physical and psychological), reducing thermal stress, and improving the quality of life of residents; (5) Reducing morbidity, mortality, number, and severity of climate-related disasters associated with urban heat islands.	[42–55]
Regulative Ecosystem Service	(1) Temperature regulation and shading are the primary ways GI regulates UHI. GI could reduce air temperature and thermal temperature by shading, and also reduce air temperature and land surface temperature by reflecting and absorbing solar radiation, preventing or reducing the absorption of short-wave radiation by the underlying surface. (2) Shading and evapotranspiration have the most effective cooling effects and climate regulation Different types of GI, especially UFS, UPS, and UTS, could, through photosynthesis, transpiration, and evapotranspiration of vegetation, change air movement and heat exchange to reduce/lower temperature (such as canopy temperature, ambient air temperature) and increase humidity (such as micro-ambient air humidity), effectively alleviating UHIs	[34,44,47,55–63]
Benefits and Values	(1) Ecological benefits and values: could reduce the heat storage, solar radiation absorption, urban energy consumption, and carbon footprints linked to food, increase thermal comfort, etc. (2) Economic benefits and values: could lower the air temperature and thus reduce the use of air conditioners, in turn saving energy, lessen micro-climate heat to reduce air and land surface temperatures to reduce irrigation, and increase the ability of cities to adapt to climate change to save money. (3) Social and cultural benefits and values could provide shading to reduce air heat stress, as well as a refuge and green leisure area during times of intense heat, which could add thermal comfort, and could be good for human health and well-being, as well as significantly reduce morbidity and mortality.	[42,44–46,52–56,58,60,61,63–69]

In an urban ecosystem, green infrastructure is a network of a multifunctional ecological system composed of green points (UPS and GR), lines (UTS and GW), and polygons (UFS) that could directly or indirectly reduce the impacts of UHI.

For UFS, in 2022, Carrillo-Niquete et al. used a Landsat image series to analyze annual deforestation (from 2000 to 2018) in Mérida (a tropical city in the Yucatan), comparing the land surface temperature before and after deforestation, which showed that the land surface temperature had increased significantly after deforestation, and urban heat islands mainly occurred in the deforested areas [42]. In 2021, Lin et al. studied the relationship between the spatial structure and thermal comfort of a bamboo forest with four distinct seasons at the micro-scale level in Dujiangyan City, China, using Rayman software to calculate the physiological equivalent temperature, which showed that modifying the forest structure (cover plant ratio, canopy diameter width, degree of facing the sun's trajectory vertically, etc.) could improve the thermal comfort on the micro-scale [43].

Regarding UPS, in 2020, Motazedian et al. analyzed the climatic interactions between a small inner-city park (1.5 Ha) and its surrounding urban environment in Melbourne, Australia, from the summer of 2013 to 2014, showing that the urban park areas were cooler than the surrounding built-up areaa at all times and in all weather conditions [44]. In 2014, Skoulika et al. studied a medium-sized (60,000 m^2) urban park in Greece, finding an important temperature inhomogeneity during both the day and the night resulting in an obvious cooling effect [45]. The sky view factor has a positive impact on park cooling intensity, reduces air temperature, and improves thermal comfort [46], as does high tree cover [47]. Similarly, Yang et al. used ENVI-met to simulate the thermal environment of a park in Shanghai, finding the park to have useful microclimatic mitigative effects [48].

For GR, Knaus and Haase (2020) studied the thermal effects of intensive green roof implementation in Berlin, Germany, using the ENVI-met model on a neighborhood scale, and reported that green roofs can significantly improve daytime thermal comfort at the roof level, especially as the physiological equivalent temperature showed a decrease [49]. Sanchez and Reames showed that green roofs could alleviate UHIs by raising surface albedo and increasing evaporative cooling [50], which could play an important role in mitigating UHI effects and promoting climate change adaptations in the city, making citizens willing to build green roofs to attenuate heat stress.

For UTS, cooling and shading are the most important functions, and it can thus constitute a long-term investment in terms of microclimate regulation. In 2020, Langenheim et al. first used pedestrian access modeling, tree-scape shade modeling, and shade optimization in Melbourne, Australia, obtaining the results that planting the right tree in the right place at the right time could provide a more effective shading function and significantly reduce solar radiation flux, thereby improving thermal comfort [51]. Finally, Cheung et al. (2020) studied five sites with different SVFs in a golf course in Hong Kong, China (a humid subtropical climate area), finding that the cooling magnitude of trees would be influenced by seasonal and meteorological effects, and UTS could reduce solar radiation and provide shading to exert cooling effects [52].

For GW, Rupasinghe and Halwatura present findings of a field study of existing green walls in Sri Lanka (a tropical country), showing that they reduce thermal performance, and the different plant species had different effects in reducing UHIs [53]. Peng et al. studied the cooling effects of a block-scale green wall, indicating that the large-scale structure also noticeably reduces the building surface temperature and cooling loads in summer [54]. It could also reduce energy usage, and the plant choice would influence the cooling properties [55].

3.2.2. Regulate Ecosystem Service

Temperature regulation and shading are the primary ways GI regulates UHI effects. GI could reduce air temperature and thermal temperature by shading, and also reduce air temperature and land surface temperature by reflecting and absorbing solar radiation, preventing and lowering the absorption of short-wave radiation by the underlying surface. Different types of GI, especially for UFS, UPS, and UTS, could change air movements and heat exchange through photosynthesis, transpiration, and evapotranspiration of vegetation to lower the temperature (such as canopy temperature and ambient air temperature) and increase humidity (such as micro-ambient air humidity), which would be an effective way to alleviate UHIs. Moreover, shading and evapotranspiration have the strongest effects in cooling and climate regulation, as summarized in Table 6 below.

In the urban ecosystem, different types of green infrastructure provide regulative ecosystem services to mitigate UHIs.

For UFS, in 2020, Richards et al. demonstrated the cooling benefits of secondary forest (mainly on former agricultural land) in densely-populated urban areas, showing that it facilitated effective temperature regulation [56]. Rathmann et al. demonstrated the potential positive effects of urban forests on bioclimatic conditions by regulating temperatures so as to reduce the maximum air temperatures during summer [57]. Moss et al. (2019) showed that urban forests promoted climate regulation and reduced UHI effects as evapotranspiration from trees reduced the air temperature in the urban microclimate by converting sensible heat to latent heat [58].

For UPS, in 2020, Motazedian et al. showed that urban parks could regulate the temperature on a micro-scale and decrease air temperatures by providing shading and evapotranspiration that reduces heat stress, especially during the peak daytime hours, in sunny conditions, and under higher wind speeds [44]. Cheung and Jim also reported that UPS could regulate temperature, based on an analysis of the landscape parameters significantly associated with air temperature and estimates of their cooling potentials [47]. Wang et al. (2019) studied the microclimate regulation and energy-saving potential of UPS, revealing that urban parks could regulate the hot and cold environment in adjacent urban zones, resulting in improvements in thermal comfort and 3D energy savings [34].

GR is a natural-based solution used in buildings to increase ecosystem services with positive effects on energy consumption, urban heat island impacts, and greenhouse gas generation in urban areas. In 2016, Razzaghmanesh et al. reported that green roofs are effective in mitigating UHI by replacing low albedo materials (asphalt, metal, etc.) and increasing natural vegetation, reducing the surrounding micro-climate temperature and energy consumption [59]. In 2017, Sergio et al. studied green roofs as a supplement to the green spaces in the city, showing that they could buffer the negative effects of the increase of the maximum temperatures, mitigate UHI, and regulate temperature [60].

For UTS, in 2018, Morakinyo et al. studied Hong Kong's common UTS for outdoor temperature regulation, which showed that it significantly reduced maximum temperature, physiological equivalent temperature, and energy usage [61]. Similarly, in 2016, Gülten et al. compared effects of areas with/without trees on urban heat island potential in the highest urban density area of Elazig, Turkey, showing that increased trees could significantly reduce air temperatures and heat islands by decreasing the ratio of surface temperatures and exerting a cooling effect on surfaces [62].

For GW, in 2017 Perini et al. studied the contributions of the green wall system to urban heat island mitigation in the city of Genoa, Italy, with a Mediterranean climate, demonstrating that a green wall can mitigate outdoor and surface temperatures, improve conform conditions, and reduce building surface warming [55]. Also in 2013, Cameron et al. reported that green walls could reduce the thermal load on buildings and energy consumption, thereby serving to mitigate urban heat islands, and regardless of whether they were covered with shrubs or climbing plants, they effectively reduced air and surface temperatures more than brick walls; they also reported that different species varied in their cooling capacity because of different evapotranspiration and shade cooling effects, which were also influenced by plant physiology and leaf area/morphology [63].

3.2.3. Benefits and Values

Green infrastructure is a system of human-modified landscapes that includes different types of green space that have been specifically designed and used for social and economic benefits. GI could provide the following multiple benefits and values: (1) ecological benefits and values by reducing heat storage, solar radiation absorption, urban energy consumption, and carbon footprints linked to the food, as well as by increasing thermal comfort, which could promote smart/sustainable urban growth and exert long-term effective impacts on climate change and mitigate UHI effects on the micro/local/meso scale in the short term. (2) Among economic benefits and values, it could lower the air temperature and thereby reduce the use of air conditioners, which in turn saves energy, lessens micro-climate heat to reduce air and land surface temperatures to reduce irrigation, and increases the ability of cities to adapt to climate change to save money. (3) Among their social and cultural benefits and values, they could provide shading to reduce air heat stress and provide a refuge and green leisure area during times of intense heat, which could enhance thermal comfort and benefit human health and well-being, as well as significantly reduce morbidity and mortality, as summarized in Table 6 below.

In the urban ecosystem, different types of green infrastructure provide a variety of ecological, social, cultural, and economic benefits and values, through multi-functional regulative ecosystem services to mitigate UHIs.

For UFS, in 2022, Carrillo-Niquete et al. noted that after a deforested area of 5413 ha in Mérida, Mexico, the land surface temperature increased by 2.36–3.94 °C and was significantly ($p < 0.05$) higher (0.90 °C) than in non-deforested sites [42]. Richards et al. (2020) showed that secondary forest was associated with the largest temperature reduction (−1.7 °C) [56], and in 2019, Joseph et al. showed that the urban forests in inner London provide a cooling benefit of 7.0–10.6 GWh, for savings equal to £1.23 million per year [58]. In 2019, Christopher et al. reported that planning urban forests to combine biophysical and socioeconomic factors could help curb negative environmental and human health impacts in a limited space [64]. Tran et al. (2017) showed citizens' willingness to pay $1.05–$1.22 million/year, or $5.24–$6.11 million over five years in Atlanta, to increase urban forests to mitigate climate change [65].

For UPS, in 2020, Motazedian et al. reported a park's mean maximum cooling effect to be up to 1.0 °C, with the magnitude of the difference in temperature between the park and its surroundings varying from 0.5 to 3 °C [44]. In 2019, Zhang et al. showed when the park sky view factor decreases from 0.9 to 0.1, air temperature could decrease by about 1.69 °C, and the mean radiant temperature decreased by 14.80 °C [46]. Skoulika et al. (2014) reported that the park cooling intensity varied between 3.3 and 3.8 K, while the temperature gradient along the traverse direction varies as a function of the thermal properties of the urban areas, but was between 0.2 and 1.4 K/100 m, and the climatic influence of the park extended up to 300 m beyond its borders [45].

For GR, in 2019, Yang and Bou-Zeida showed that when city centers retrofit 25% of their rooftops, though they can receive cooling up to 0.86 °C under certain favorable conditions, the monthly mean daytime temperature reduction is very limited (<0.3 °C for the largest-scale deployment); for a local plan (~1–10 km^2) of green roof deployment, the largest daily maximum cooling is 0.86 °C, while with regional plans (~500 km^2), the largest daily maximum cooling can be up to about 1.5 °C [66]. In 2017, Herrera-Gomez et al. reported that air temperature could be decreased by 1.5–6.5 °C when 740 ha of semi-intensive or intensive green roofs were built [60]. Peng and Jim (2015) showed that the annual UHI mitigation benefits of extensive and intensive green roofs in energy savings are 3.4 and 7.6 ($\times 10^7$ kWh), respectively, and the economic values are 3.99 and 8.92 ($\times 10^6$ USD) [67]. In 2019, Zhang et al. showed that citizens were willing to pay 148.58 Chinese yuan/year to build green roofs to mitigate heat island effects in Beijing, China [68].

For UTS, in 2021, Horvathov et al. studied the value of the shading provided by trees, to decrease the investments in urban green infrastructure, which showed the value of shading ranges between 4362 EUR and 9163 EUR over 20/40/50 years [69]. In 2020, Richards et al. showed that tree canopy over shrubs was associated with the largest temperature reduction (−0.9 °C), followed by a tree canopy (−0.6 °C) [56]. Similarly, Cheung et al. (2020) showed that the magnitudes of the annual mean ($\pm SD$) cooling were 0.9 ± 0.5, 2.5 ± 1.4, and 1.6 ± 0.8 °C in air temperature, and for every 1 MJ/m^2 increase in interception rate of incoming shortwave radiation in a day, the daily mean cooling magnitude increased by 0.03, 0.16, and 0.08 °C for air temperature, physiological equivalent temperature, and universal thermal climate index, respectively [52]. In 2018, Morakinyo et al. used ENVI-met to study UTS on a neighborhood scale (500×500 m^2), finding that a 7.2% greenery coverage ratio could reduce the temperature by 0.4 °C and the physiological equivalent temperature by 1.6 °C, and save 1500 kWh per typical summer day. With a 30% greenery coverage ratio, it could reduce by 0.5–1.0 °C, physiological equivalent temperature 0.5–1.0 °C, and save ~1900–3000 kWh of energy (equal to 200–450 US$) [61].

For GW, in 2020, Rupasinghe and Halwatura studied the benefits of a green wall in a tropical city, showing that thermal performance could be reduced by 10.16 °C, 3.31 °C, and 2.11 °C for the external wall surface, internal wall surface, and internal air temperature, respectively, with a maximum internal temperature reduction of 4.89 °C during the day [53]. In 2017, Perini et al. reported that greening walls (a volume of 7181 m^3) could reduce energy demand for air conditioning, with a theoretical energy-saving potential of 26% (1671.9 kWh) in summer [55]. Cameron et al. (2014) showed that the vegetated walls were 3 °C cooler than non-vegetated walls [63].

4. Discussion

4.1. The Current and Future Trajectory of Green Infrastructure to Mitigate UHIs

The areas of research on different types of GI to mitigate UHIs are gradually developing, with a significant potential to regulate temperature and adapt to climate change, as well as promote long-term urban sustainability. In this study, we analyze the publications from 1990 to 2021, as it is more data to make a comprehensive analysis, and the CiteSpace software has a good visualization function, which can analyze research status, research trends, research hotspots, and research directions based on the downloaded published to automated visual analysis in this field [4,39]. Furthermore, we analyzed and summarized more information on GI to UHI in functions, ecosystem services, benefits, and value than other literature review papers [4,11,16]. It provided a specific and accurate analysis, for a better understanding of these five different GI types of UHI. Future research should cooperate with other disciplines such as ecology, architecture, human health, and psychology, as well as assess ecosystem services, benefits, and values. Our results show that publication numbers have significantly increased from 2013; in 2020, the number of publications increased to 195, which indicates that more researchers are focused on, or are interested in, this field. Research should focus more on thermal comfort and human health to ensure human well-being and mitigate urban issues.

From the analysis of the top 15 keywords, we found that researchers focus more on different types of ecosystem services in cities, climate and temperature regulation, reduction and impact of urban heat island, and benefits and values. The keywords of GI, UFS, and UPS are more focused on city/urban matters, which are the polygon and point elements in the urban ecosystem, so it is the meso/local/large scale of green space. The keyword timeline analysis reinforces this finding, showing that whether for the longest or shortest durations, the keywords of energy and vegetated/green roof, are frequent keywords. This indicates that these related topics need more research. The longest keyword bursts concern the structure of urban GI, the shortest keyword bursts relate to the function and ecosystem services of urban GI, and the strongest bursts relate to structure, function, ecosystem, benefits and values of urban GI systems. In addition, the identified bursts are associated with useful or important methods for different GI types to mitigate UHIs.

The analysis of the top 10 countries by publication indicates that the USA does more research on UPS, UFS and UTS, whereas Australia focuses more on GW, followed by UTS, GR, and so on. Germany does more research on UPS and UFS, but for China, every type of GI research seems of equal importance. This may be because urban issues such as UHI are more serious in China, and the GI types have the same importance and high potential for climate regulation. In research in the USA, Germany, and Australia on topics such as climatic conditions, the building style is more focused on the types that provide more functions and ecosystem services for their countries. The institutional analysis shows similar results to the country publication analysis, indicating the support of government and academic institutions. The analysis of the top 10 journals indicates that GI researchers are more inclined to choose Elsevier journals, focusing on urban planning, urban environment, energy-saving, and remote sensing. GI to mitigate UHI research has become increasingly multidisciplinary, including ecological and human health factors. Additionally, recent developments in engineering and technology have served to assess the functions, benefits, and values of different GI types. However, more practical and scientific methods are needed.

4.2. The Function, Regulative Effects, Benefits, and Values of GI Types

As an ecosystem in a city, GI plays an important role and affords a range of functions to mitigate UHI and adapt to climate change, provide the regulated ecosystem service, and create important benefits and values. Different types of GI have different shapes, sizes, locations, and functions, which as ecological elements are the points, lines, and planes in the ecological system, regulating, neutralizing, restoring, and optimizing the overall urban structure and function, serving to maintain sustainable urban development. The size and structure of GI in the city determine the ecological functions it provides and what functions are needed, which is useful when planning different GI types and structures (scale/size, etc.). Additionally, Yang et al. (2022) note that more landscape indicators and driving factors should be taken into consideration to more accurately predict the future surface temperature and explore the driving mechanism of the UHI [36].

At the same time, corresponding ecosystem services will be generated, just as GI could regulate the UHI, providing significant urban regulative ecosystem services. Moreover, based on knowing the function (shading, reducing solar radiation, etc.) of GI to UHI, it can be known what ecosystem services GI could provide (regulating the air temperature, etc.) and how it will provide them, as well as how ecosystem services are affected by climate change and this information can be used for climate change adaptation. This constitutes a major and valuable research topic in urban ecological ecosystems.

An important point is the ecological benefits and values, which allow us to have a more intuitive quantitative indicator or method to understand the significance and importance of GI in mitigating UHIs. Ecological benefits and values can not only demonstrate the role and value of GI in the city, but also provide an opportunity for all citizens, government decision makers, and urban planners to understand the role of GI more clearly. This will also provide more opportunities, funding, and support for the construction of GI. Furthermore, it can also be a good way for researchers to show the importance and value of different GI types. In particular, depending on the benefits and values that GI can generate, different types of GI of appropriate size/scale can be introduced where and when they are needed in the city to effectively perform useful functions [51]. This is of great significance for effectively and rationally building GI to achieve the greatest ecological effect in the city, which is also a very important key point for the sustainable development of urban ecology.

4.3. Limitations of This Study

This paper systematically analyzes publications about the effects of GI on urban heat islands from 1990 to 2021, and chooses five GI categories for retrieval and download. It improves the accuracy to a certain extent, but because these five different types of GI are not strictly distinguished in academic research fields, such as UPS and UTS, there will be some duplication in the downloaded publications, and it will be difficult to determine which GI-type database a paper might belong to, which can limit the historical review analysis and visualization. The same holds true regarding the second part of the analysis regarding function/regulate ecosystem service/benefits and values, having a similar impact on the analysis of the results. Because of the different backgrounds of experts, the recommended publications might also affect the results somewhat. If possible, it would be better to invite more experts in the field to recommend publications such as many important and impactful conference papers, etc. Furthermore, some policy and social documents from governments or institutions, editorial materials, and book reviews were not included in the database. Thus, in this review, the academic database based on the web of science and google scholar, a larger academic search database (such as Scopus, etc.) is needed with a more comprehensive collection of documents within the item list.

5. Conclusions

This study analyzes publications on the effects of GI in mitigating UHIs from the WOS database from 1990 to 2021. First, we used CiteSpace software to conduct a bibliometric analysis of these publications, analyze and visualize the historical review, and present the research status and trends, such as keywords, journals, and research hotspots. Second, we select the highly cited articles and review articles from UFS, UPS, UTS, GR, and GW databases, and added 10 publications from five important journals in each GI type. This study found that GI, within this 31-year timeframe, has experienced intense development and has a huge potential in the future.

GI plays an important role in urban ecosystems because the different types, such as UPS, UFS, UTS, GW, GR, and different structures (size, shape, location, etc.) enable it to perform multiple functions to mitigate UHIs and adapt to climate change. GI plays a role in regulating UHI, which we term its regulative ecosystem service, and it generates corresponding benefits and values. They make up a logically cascading system where structure determines function, the function provides and regulates ecosystem services, and ecosystem services generate benefits and values. The research topics of the publications reviewed in this study include ecological ecosystem services, and structure, function, benefits, and values. In short, no matter what research methods, research background, research location, and research scale are used, this research fundamentally concerns the structure, function, regulative ecosystem services, and benefits and values of various types of GI in cities, which is also the value of the research goals in this field. Therefore, researchers who analyze and study the research progress of GI to mitigate UHI can better adapt it to the sustainable development of cities, create a better ecological ecosystem, and increase human well-being. Based on this comprehensive review results, stakeholders, decision makers, and planners are encouraged when planning or constructing different types of green infrastructure in cities to be more sustainable in urban development and as an effective climate mitigation strategy. Future studies should expand the academic database to make more specific analysis results, and to focus on summarizing the methods of GI to mitigate UHI, and review the different scales of GI types in functions, ecosystem services, benefits, and value to UHI, etc.

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