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Review

Research Progress and Hotspot Analysis of Urban Heat Island Effects Based on Cite Space Analysis

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Abstract: The urban heat island (UHI) effect has become a hot topic in the global urban ecological environment. Research on the UHI effect is of great significance for alleviating urban environmental problems. Therefore, it has attracted the extensive attention of a large number of researchers in the field of urban environmental issues, such as urban ecologists, urban climatologists, urban planners, geographers, relevant policy makers, etc. However, systematic reviews are lacking on UHI research in the context of rapid urbanization and global change in recent years. In this study, we used Cite Space software to analyze the development process and current situation of UHI research from multiple perspectives during 2008–2021, aiming to reveal research hotspots and predict future trends. We found that UHI has gradually become a multidisciplinary field, and has existed in a flourishing period since 2008 with the rapid development of a number of publications. A large amount of research has been carried out by relevant institutions and scholars in 85 countries from 2008 to 2021. The hotspot research frontier focuses on the influencing factors, mitigation measures, and quantitative analysis of the UHI effect. Based on these trends and the status of the field, we proposed further research directions to promote interdisciplinary integration, optimize quantitative monitoring methods, strengthen the impact of three-dimensional urban landscape and vegetation landscape patterns, and expand the study of the urban agglomeration scale. Our results provide a valuable reference and potential frontier for future research in the field of the UHI effect.

Keywords: urban heat island effect; cite space; influencing factors; mitigation measures; bibliometric analysis

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1. Introduction

With the rapid development of the population and economy, urbanization has become an inevitable trend in human society [1]. However, in the context of the continuous development of urbanization and the gradual warming of the global climate, rapid urbanization has greatly changed the underlying surfaces of cities. This has had a serious impact on the urban thermal environment, leading to a serious increase in urban heat island (UHI) effects [2,3].

Since the concept and phenomenon of UHI was first proposed by Howard in 1833 [4], the study of UHI has attracted more attention from scholars in recent decades. At present, the UHI has become a multidisciplinary cross-fusion issue, including meteorology, environmental science, ecology, resource application, building science, remote sensing, etc. Furthermore, due to the continuous advancement of urbanization and the enhancement of ecological protection awareness [5], sustainable urban development has become a vital goal of human society in the new era, and the UHI, as an important and serious urban environmental problem, has attracted more concern from relevant scholars and decision makers [6]. Previous studies have been conducted on the land surface temperature (LST) inversion algorithm [7–9], spatio-temporal variation [10,11], influence factors, and mitigation strategies of UHI [12,13], as well as the relationship between daytime LST and 2D/3D urban form [14], urban microclimate [15–17], etc. The relevant research has confirmed that the expansion of the influence range of the global UHI effects could not only cause an abnormal rise of the urban climate and prominent urban ecological problems [18], but also threaten the health and welfare of urban residents [19,20]. Therefore, it is necessary to synthesize the current research status to reveal the evolutionary trends and future potential directions in this field, so as to promote more scientific and in-depth research on the UHI effect and to provide references to mitigate effectively the urban environmental problems which it brings about.

In the present study, we analyzed the research on the UHI effect using data from a literature search of the Web of Science (WOS) core collection and the China National Knowledge Infrastructure (CNKI) databases from January 1980 to December 2021. We emphatically reviewed the academic achievements and progress in this field during the rapid development period (2008–2021). The bibliometric method and scientific knowledge graph method, made possible by the Cite Space 5.8.3 software, were used to study the evolution of the number of studies, as well as to assess research cooperation networks, subject categories, and frequently cited literature so as to analyze the overall progress in this field. Meanwhile, the research hotspots and frontiers were identified by keyword co-occurrence and emergent analysis, and the future potential research directions were proposed according to the synthetic analysis of the trend of studies in this field. The aim of this study is to provide a clear picture of the current situation, evolution process, hotspot topics, and future research directions in the field of the UHI effect, which will be helpful in improving the theoretical research on urban heat islands and provide references for new research directions and perspectives regarding them.

2. Materials and Methods

2.1. Database and Screening

The China National Knowledge Infrastructure (CNKI) is the largest Chinese database in the world, with a powerful full-text retrieval system in its network database, providing an essential way to retrieve Chinese data. Web of Science (WOS) is the world's largest comprehensive academic information resource, covering the most disciplines and containing more than 10,000 of the world's most influential high-quality core journals in multiple research fields [21]. In view of this, to increase the representativeness and accessibility of the data, the CNKI database and the WOS database were selected as the data acquisition sources using the data collected on 17 August 2022. Based on the CNKI database, SU% = 'urban heat environment' + 'urban heat island' + 'urban heat effect' + 'urban surface temperature' AND KY = 'urban heat island' + 'urban surface temperature' was used as the search statement to select all of the journals for professional search. The time span of the literature search was from 1 January 1980 to 31 December 2021. Based on the WOS database, the TI = (urban thermal environment OR urban heat island OR urban thermal effect OR urban land surface temperature) was used as the search statement, and the article type was selected for the advanced search, spanning from 1 January 2008 to 31 December 2021. A total of 4223 articles were retrieved from the two databases, including 1769 WOS articles and 2454 CNKI articles (1912 published from 2008 to 2021), which were used as the basic data for this study.

2.2. Analytical Methods

Due to the large data volume of this paper, it was difficult to extract their information manually, and data analysis needed to be carried out with the help of software. Therefore, Cite Space 5.8.3 software, jointly developed by Dr. Chen Chaomei and WISE Laboratory of Dalian University of Technology, was used in this study for data visualization analysis [22,23]. Cite Space Bibliometry tools combine the bibliometry method, the information visualization method, and the data mining method, and can explore the key paths and knowledge turning points of research hotspots and trend evolution in different disciplines [24]. Meanwhile, compared with other visualization software, CiteSpace has the advantages of simple operation, multiple mapping, high information content, automatic recognition mapping, and easy interpretation [15–17]. Therefore, the powerful visualization tool of this software was used to meet our research goals.

First of all, we used the traditional bibliometric method based on the Excel software of the two databases, the distribution of national published literature, journal distribution, high-frequency literature, and high-yield authors to create the corresponding charts so as to analyze the CNKI and WOS databases and assess the basic situation of urban heat island-related papers. Subsequently, Cite Space 5.8.3 software was used to explore the keyword co-occurrence network and discover the research hotspots in the field of urban heat islands in the two databases, CNKI and WOS. We accomplished this by setting the node type in the Cite Space 5.8.3 software to "key word", the time period to 2008–2021, and the other settings to default. In addition, by choosing the temporal axis view of the software (time zone map) and emergent analysis (emergent map), it became possible to visualize the trend evolution of the subjects in this field. Firstly, the relevant charts from the two databases were interpreted and analyzed. Then, the differences between CNKI and WOS from 2008 to 2021 were compared and analyzed in terms of publication trend, journal distribution, subject categories, research hotspots, etc (Figure 1).

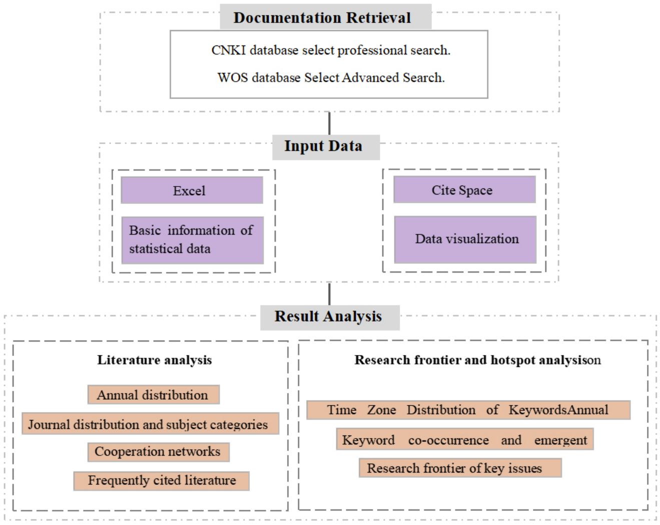

Figure 1. Technological roadmap. The implementation process of the research method is demonstrated.

3. Results

3.1. Annual Distribution

The amount of annual literature in both CNKI and WOS displayed obvious stages (Figure 2). For the literature in CNKI, the relevant research on UHI emerged in the 1980s. The development process can be divided into three stages, namely, (1) the embryonic stage (1980–2001), during which the annual number of publications was less than 25; (2) the rapid growth stage (2001–2008), during which the number of annual publications increased year by year at the maximum growth rate; and (3) the fluctuating growth stage (2008–2021), during which the annual number of publications fluctuated between 115 and 170—however, the growth rate decreased overall in this stage (Figure 2a). Previous studies reported that the literature on UHI published in WOS emerged in 1990, and the research process experienced two stages of preliminary development, with fewer publications from 1990 to 2008 and rapid development from 2008 to 2021 [25]. In this study, we analyzed the annual publications in WOS between 2008 and 2021. This indicated that the annual number of publications increased continuously during 2008–2021 in WOS, and the publication trend in this period could be subdivided into two stages, namely, a slight growth phase from 2008 to 2016 and a faster growth phase from 2016 to 2021 (Figure 2b). On the whole, the annual number of publications both in CNKI and WOS from 2008 to 2021 increased obviously;

however, the quantity of annual research published in WOS was greater than that in CNKI beginning in 2016 (Figure 2c).

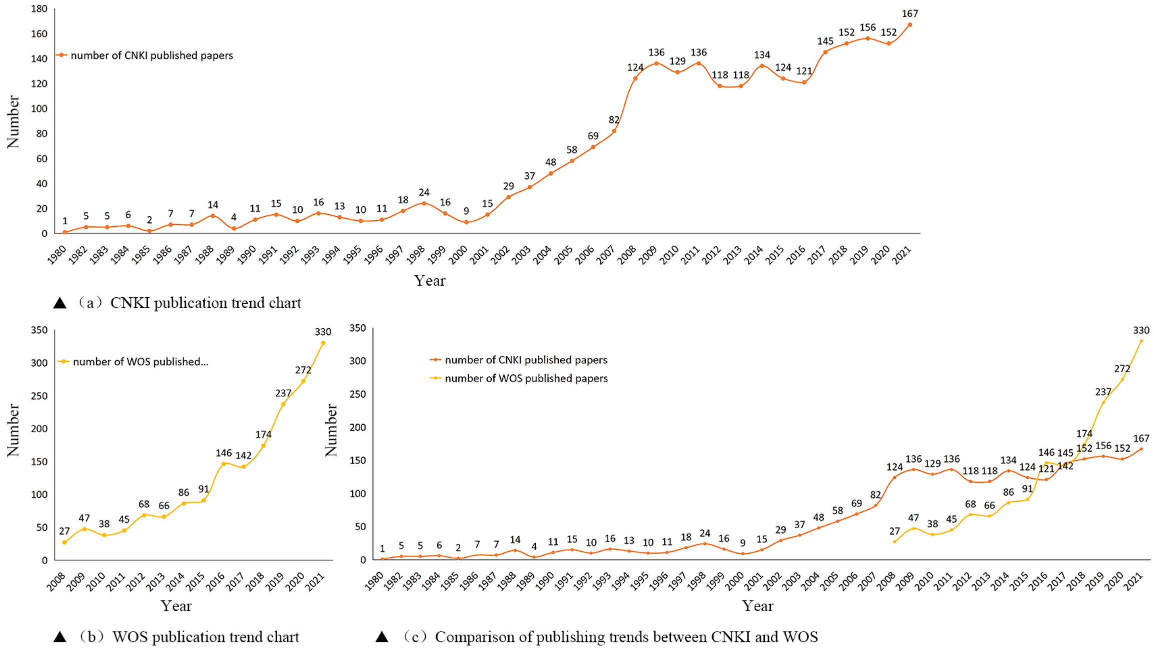

Figure 2. Changes in the number of urban heat island publications in the WOS and CNKI databases from 1980 to 2021. The WOS database included articles published from 2008 to 2021. Data from the CNKI database included articles published from 1980 to 2021.

3.2. Journal Distribution and Subject Categories

There were 20 journals which primarily published the literature on UHI in CNKI. Among them were *Acta Ecologica Sinica*, with the largest number of publications (56 articles), followed by *Ecology and Environmental Sciences* (47 article) and *Remote Sensing Technology and Application* (33 articles) (Table 1). However, the 1769 articles in WOS were distributed across 283 journals. *Sustainable Cities and Society* was the journal with the largest number of published documents (129 articles), followed by *Remote Sensing* (103 articles) and *Urban Climate* (96 articles). The number of articles published in these three journals accounted for 18.5% of the total articles in WOS. However, the average annual number of papers cited in WOS was greater in *Sustainable Cities and Society* (349.29), *Science of the Total Environment* (310.71), *Building and Environment* (251), and *Energy and Buildings* (219.79) than in other journals, which indicated that the relevant research in these four journals received greater attention in the field of UHI (Table 2).

Table 1. Distribution of top 10 journals on UHI in the CNKI database from 2008 to 2021.

No.	Journal	Total Articles	Proportion (%)	Journal Type	Compound Influence Factor	Comprehensive Impact Factor
1	*Acta Ecologica Sinica*	56	11.27	CSSCI	4.733	3.444
2	*Ecology and Environmental Sciences*	47	9.46	CSSCI	2.667	2.002
3	*Remote Sensing Technology and Application*	33	6.64	CSSCI	2.105	1.535
4	*Chinese Journal of Ecology*	27	5.43	CSSCI	2.997	2.182
5	*Journal of Geo-information Science*	27	5.43	CSSCI	3.455	2.428
6	*Journal of Anhui Agricultural Sciences*	27	5.43	CA\JST	0.716	0.494
7	*Geomatics & Spatial Information Technology*	24	4.83	JST	0.81	0.576
8	*Resources and Environment in the Yangtze Basin*	23	4.63	CSSCI	4.145	3.009
9	*Scientia Geographica Sinica*	21	4.23	CSSCI	5.987	4.293
10	*Chinese Journal of Applied Ecology*	21	4.23	CSSCI	3.893	2.851

Table 2. Distribution of major journals on UHI in WOS database from 2008 to 2021.

Number	Journal	Total Articles	Proportion (%)	Journal Impact Factor	Average Number of Citations of Journal Papers per Year
1	*Sustainable Cities and Society*	*129*	7.292	10.696	349.29
2	*Remote Sensing*	*103*	5.822	13.85	196.93
3	*Urban Climate*	*96*	5.427	6.663	122.79
4	*Sustainability*	*81*	4.579	3.889	91.07
5	*Building and environment*	*73*	4.127	7.093	251.00
6	*Science of the total Environment*	*71*	4.014	10.753	310.71
7	*Theoretical and applied climatology*	*58*	3.279	3.409	133.5
8	*Energy and buildings*	*45*	2.544	7.201	219.79
9	*Journal of Applied Meteorology and Climatology*	*43*	2.431	3.557	161.71
10	*International journal of Remote Sensing*	*31*	1.752	3.531	67.93

The subjects of the publications displayed an obvious discipline aggregation. The relevant research in CNKI was mainly focused on the fields of meteorology, environmental science and resource utilization, and building science and engineering. However, although the academic categories of the studies on UHI in WOS numbered more than 1000, the environmental sciences, meteorology atmospheric sciences, and remote sensing were the three dominant disciplines with the most extensive coverage and distribution.

3.3. Cooperation Networks

The network of cooperation of countries and institutions based on the nationality of authors displayed the key countries and institutions that have a strong influence in the field of UHI. A total of 85 countries have participated in studies on UHI, among which 10 countries have produced the majority of the literature, accounting for 99.32% of the total literature in WOS. China (665 articles) and the United States (380 articles) were the dominant countries, which reflected the significant research volume and output of scholars in these 2 countries in the field of UHI. They were followed by the United Kingdom (117 articles), India (109 articles), Japan (104 articles), Germany (91 articles), Italy (90 articles), Australia (86 articles), Canada (59 articles), and Greece (56 articles). Although Greece was ranked tenth of the publications in these 10 countries, its average number of citations per paper was the highest, with a value of 82.79, followed by Canada (62.63), the United States (56.7), and the United Kingdom (47.99), indicating that the scientific research results produced by these countries has greater influence and higher citation value (Figure 3).

In line with the countries with higher quantities of published literature, the institutions with larger numbers of publications were mainly distributed in China and the United States (Figure 3). In CNKI database, the Nanjing University of Information Science & Technology contributed the most publications, with the total number of publications, 96, accounting for 11.47% of the articles in CNKI, followed by Nanjing University (68 publications) and Beijing Normal University (53 publications). Professor Xu Hanqiu from Fuzhou University is author with the most publications in the CNKI database, with 21 publications. In contrast, the top 10 institutions with the most publications in WOS database were distributed within China (7), the United States (2), and India (1), among which 4 institutions (i.e., Chinese Academy of Sciences, University of Chinese Academy of Sciences, the Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences, Nanjing University) were the largest contributors to the field of UHI in the world, accounting for one-fifth (20.18%) of the total publications in WOS. In addition, the total publications of the Arizona State University (47 publications) and Arizona State University Tempe (44 publications) in the United States were relatively fewer than those of the above 4 institutions in China; however, the average numbers of citations per paper of these 2 institutions (71.26% and 75.68%, respectively) were obviously greater than those of other institutions (Figure 4).

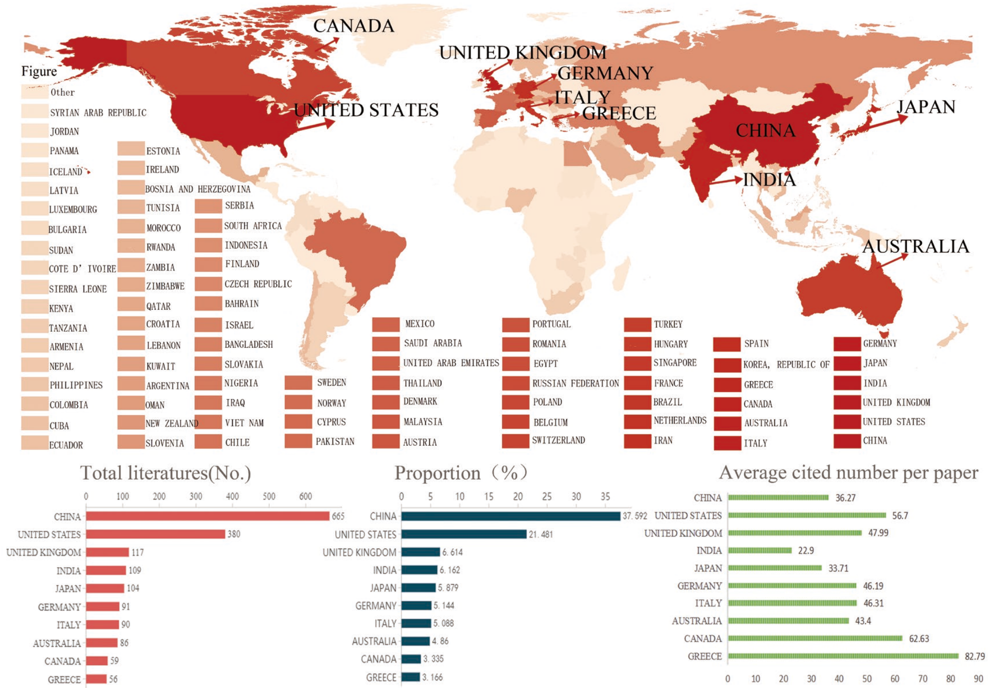

Figure 3. Distribution of high-publication-yield countries regarding UHI from 2008 to 2021. The chart highlights the top ten countries with the greatest number of published articles in the field of urban heat island research.

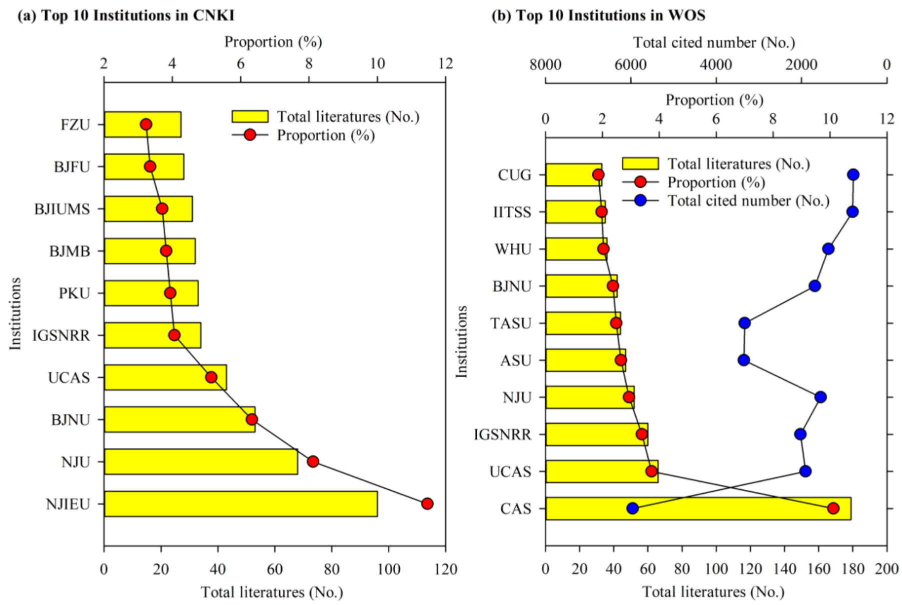

Figure 4. Analysis of the cooperation network of issuing urban heat island institutions. The ten institutions with the most publications in the two databases, WOS and CNKI, are summarized. Notes: FZU: "Fuzhou University "; BJFU: "Beijing Forestry University"; BJIUMS: "Beijing Institute of Urban Meteorological Science"; BJMB: "Beijing Meteorological Bureau"; PKU: "Peking University"; IGSNRR: "Institute of Geographic Sciences and Natural Resources Research, CAS"; UCAS: "University of Chinese Academy of Sciences"; BJNU: "Beijing Normal University"; NJU: "Nanjing university"; NJIEU: "Nanjing information engineering university"; CUG: "China University of Geosciences"; IITSS: "Indian Institute of Technology System"; WHU: "Wuhan University"; TASU: "Arizona State University at Tempe"; ASU: "Arizona State University"; IGSNRR: "Institute of Natural Resources, Chinese Academy of Sciences"; CAS: "Chinese Academy of Sciences".

3.4. Frequently Cited Literature

The articles with the top 10 highest citation frequencies in CNKI and WOS between 2008 and 2021 were sorted. We found that half of these articles in CNKI were published in Acta Ecologica Sinica. A review article published in Acta Ecologica Sinica by Chen et al. [26] had the highest citation frequency in CNKI (with 414 citations). This study comprehensively explored the impact of urbanization landscape pattern evolution on the UHI effect, and reviewed the research progress of the design of an urban ecological land and ecological security pattern. In addition, the remote sensing urban ecological index (RSEI) for assessing urban ecological effects, developed by Xu [27], and the relationship of the urban impervious surface with LST, conducted by Xu [28], had high citation frequencies, with 371 and 241 citations, respectively. Moreover, the frequently cited literature published in the CNKI database was focused on the impact factors (e.g., urban impervious surface, vegetation, water body, topography, land use structures, etc.) of the UHI effect [27–30], the spatial distribution of LST [31], and the theoretics of numerical simulation [32,33] (Table 3). As for the WOS database, 5 of the top 10 most often citated articles were contributed by Chinese scholars. In addition, the research issues were mainly concentrated on the mitigation measures and influence factors of UHI effects. For example, Imhoff et al. [34], in a research paper published in *Remote Sensing of Environment*, assessed the UHI skin temperature amplitude and its relationship to the development intensity, scale, and ecological environment setting for 38 cities in the United States (with 777 citations). Li et al. [35] revealed the influence of landscape composition and form on the heat island effect in the Shanghai metropolitan area. A research paper published by Zhao et al. [36] explored a possible method for the mitigation of UHI based on the temperature differences between urban and rural areas by using a climate model. A review article published by Santamouris et al. [37] in *Solar Energy*, the most frequently cited journal, with 858 citations in the WOS database from 2008–2021, systematically compared two measures (i.e., improving urban albedo and using vegetation on an urban scale to establish green roofs) to mitigate UHI (Table 4).

Table 3. Distribution of the most frequently cited CNKI articles on UHI from 2008 to 2021.

No.	Author	Year	Title	Journal	Total Citation Frequency
1	Chen Liding [26]	2013	Eco-environmental effects of urban landscape pattern changes: progresses, problems, and perspectives	*Acta Ecologica Sinica*	414
2	Xu Hanqiu [27]	2013	A remote sensing urban ecological index and its application	*Acta Ecologica Sinica*	371
3	Shou Yixuan [38]	2012	Recent advances in understanding urban heat island effects with some future prospects	*Journal of Meteorology*	261
4	Xu Hanqiu [28]	2009	Quantitative analysis on the relationship of urban impervious surface with other components of the urban ecosystem	*Acta Ecologica Sinica*	241
5	Bai Yang [39]	2013	Progress of urban heat island effect	*Journal of Meteorology and Environment*	240
6	Peng Baofa [30]	2013	The impacting mechanism and laws of function of urban heat islands' effect: A case study of Shanghai	*Acta Geographica Sinica*	230
7	Chen Songlin [33]	2009	Comparison Analyses of Equal Interval Method and Mean-standard Deviation Method Used to Delimitate Urban Heat Islands	*Journal of Geoinformation Science*	206
8	Xu Hanqiu [29]	2011	Analysis on urban heat island effects based on the dynamics of urban surface biophysical descriptors	*Acta Ecologica Sinica*	182
9	Su Yongxian [31]	2010	The cooling effect of Guangzhou City parks to surrounding environments	*Acta Ecologica Sinica*	173
10	Sun Jisong [32]	2008	Meso-β Scale Torrential Rain Affected by Topography and the Urban Circulation	*Atmospheric sciences*	155

Table 4. Distribution of the most frequently cited WOS articles on UHI from 2008 to 2021.

No.	Author	Year	Title	Journal	Total Citation Frequency
1	Santamouris, M [37]	2014	Cooling the cities–A review of reflective and green roof mitigation technologies to fight heat islands and improve comfort in urban environments	*Solar Energy*	858
2	Imhoff, ML [34]	2010	Remote sensing of the urban heat island effect across biomes in the continental USA	*Remote Sensing of Environment*	777
3	Li, JX [35]	2011	Impacts of landscape structure on surface urban heat islands: A case study of Shanghai, China	*Remote Sensing of Environment*	600
4	Peng, SS [40]	2012	Surface Urban Heat Island Across 419 Global Big Cities	*Environmental Science & Technology*	590
5	Zhao, L [36]	2014	Strong contributions of local background climate to urban heat islands	*Nature*	574
6	Tan, JG [41]	2010	The urban heat island and its impact on heat waves and human health in Shanghai	*International Journal of Biometeorology*	558
7	Santamouris, M [42]	2011	Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions	*Solar Energy*	536
8	Zhou, WQ [43]	2011	Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes	*Landscape and Urban Planning*	510
9	Buyantuyev, A [44]	2010	Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns	*Landscape Ecology*	456
10	Estoque, RC [45]	2017	Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia	*Science of the total Environment*	436

3.5. Time Zone Distribution of Keywords

The keywords (hot topics) during different stages of the research on UHI in CNKI and WOS were varied. In CNKI, early studies were mainly focused on the urban heat island effect and numerical simulation, temporal and spatial characteristics, heat island intensity, thermal environment, remote sensing, and surface temperature. After 2008, other new research hotspots, e.g., “urban landscape pattern”, “urban expansion”, “urban parks”, “spatio-temporal evolution”, “roof greening”, “cooling effect”, “sponge city”, “urban form”, and “spatio-temporal pattern”, emerged. Furthermore, the mitigation measures and influencing factors of the UHI effect were always hot topics in the CNKI database (Figure 5).

In contrast, the relevant research in the WOS database at the early stages was mainly concentrated on the influencing factors of the UHI effect and numerical simulation. However, the interaction between UHI and the surrounding environment has become a hot topic tendency since 2008. Meanwhile, “urbanization”, “mitigation measures” and “the impact of UHI effect” were paid more attention in the field of UHI research, and have been continuously studied until now (Figure 6).

3.6. Keyword Co-Occurrence and Emergent Analysis

Keywords condensed the main research content of this paper, and a keyword co-occurrence atlas reflected the research hotspots in the field of UHI [20]. The high-frequency keywords for UHI in the CNKI and WOS databases had certain similarities, but also varied across different periods. For the CNKI database, the keywords “urban heat island”, “heat island effect”, and “surface temperature” appeared most frequently, with 468, 395, and 339 instances of co-occurrence, respectively. In addition, the keywords with higher frequencies of co-occurrence, i.e., more than 25, included “landscape pattern”, “remote sensing”, “heat island intensity”, “urban green space”, “numerical simulation”, “land use”, “impervious water surface”, “urban planning”, “NDVI”, “sponge city”, “single window algorithm”, etc., and these keywords were closely connected with each other (Figure 7). Furthermore, several keywords (i.e., “vegetation index”, “city”, “roof greening”, and “brightness temperature”) experienced a long duration (3–5 years), and “sponge city”, "spatio-temporal change", "landscape pattern", "spatio-temporal pattern", and "cooling effect" were continuous research hotspots in the field of UHI in recent years (Figure 8a). In contrast, "impact", "city", and "temperature" were the most frequently used keywords in the WOS database, with 637, 513, and 360, respectively. "Urbanization", "heat island", "model", "vegetation", "land surface temperature", "climate change", "pattern", "cover", "simulation", "intensity", and "mitigation" were the higher-frequency keywords with more than 100 instances of co-occurrence, and "energy balance" appeared in UHI research for the longest period of time (9 years) (Figure 9). Moreover, the change rate of emergent keywords in WOS was fast; the impact of the urban heat island effect and urban climate change were the research hotspots around 2008, while urban heat island mitigation measures were the continuous research hotspot from 2010 on (Figure 8b).

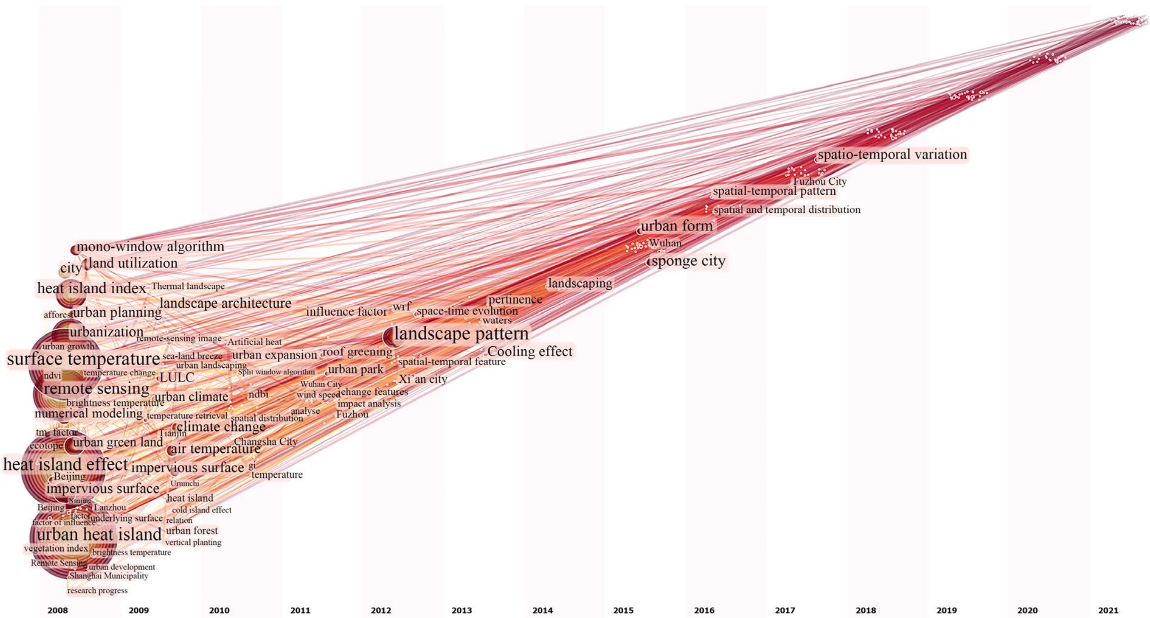

Figure 5. The evolution of urban heat island research objects (in CNKI). The trend began in 2008, and its evolution is shown through 2021, from left to right.

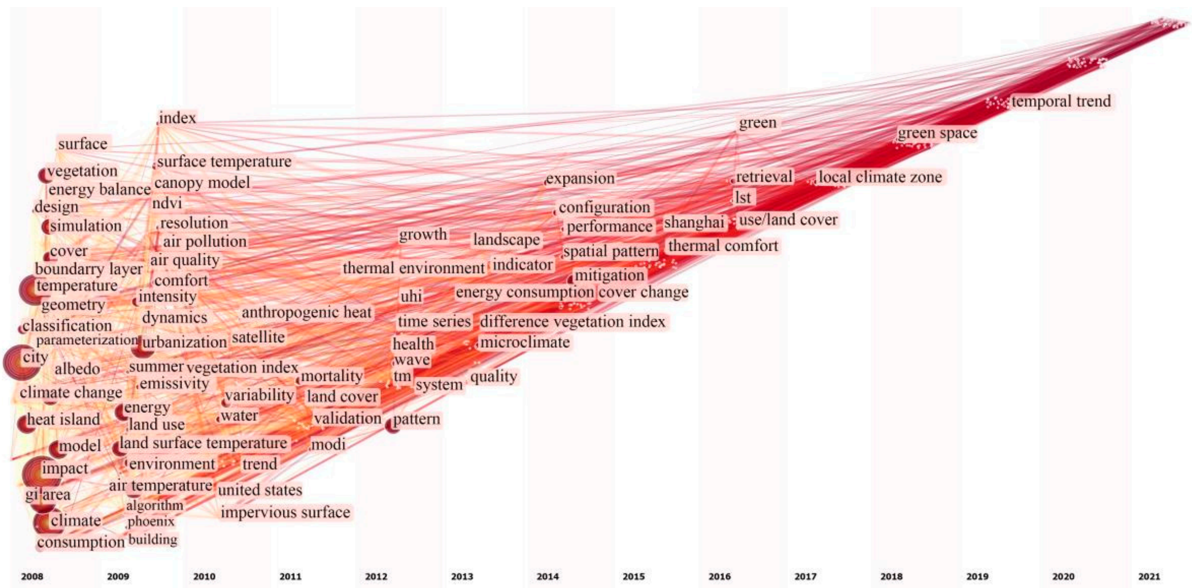

Figure 6. The evolution of urban heat island research objects (in WOS). The trend began in 2008, and its evolution is shown through 2021, from left to right.

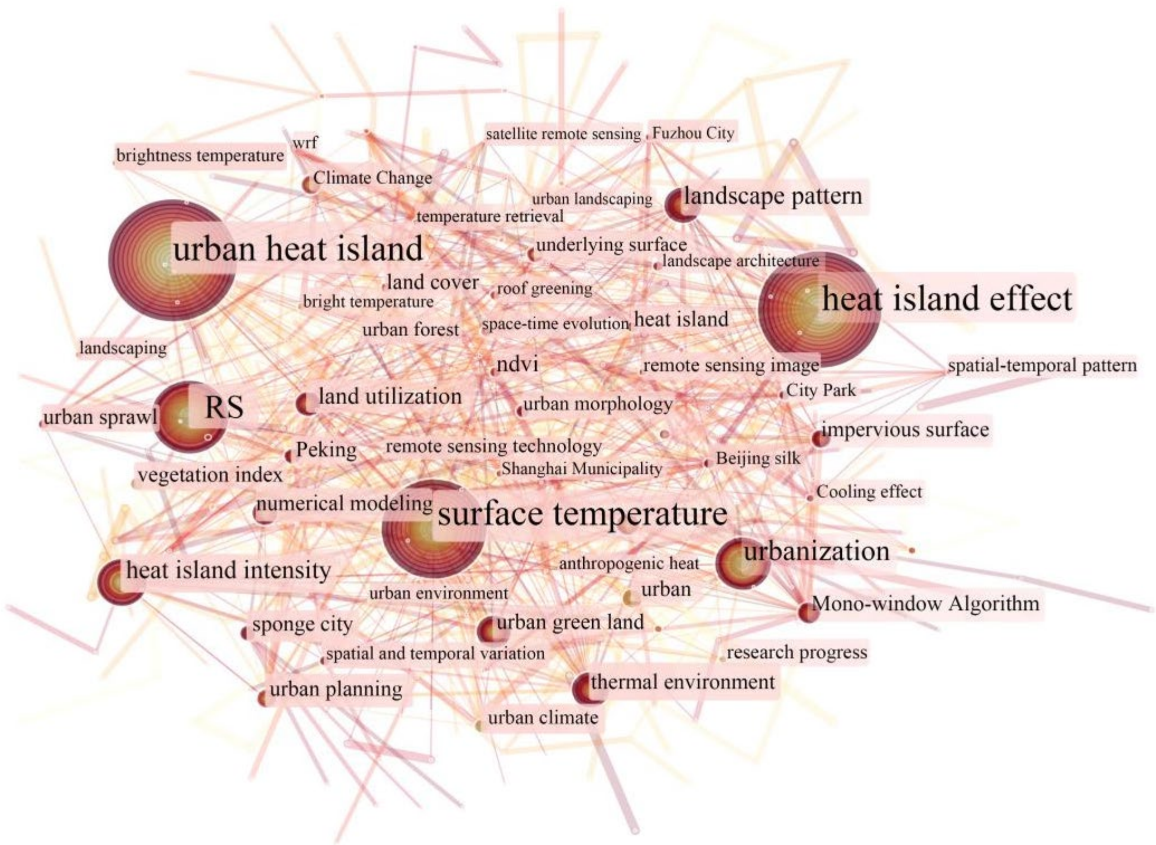

Figure 7. Co-occurrence network map of keywords in the CNKI urban heat island research literature.

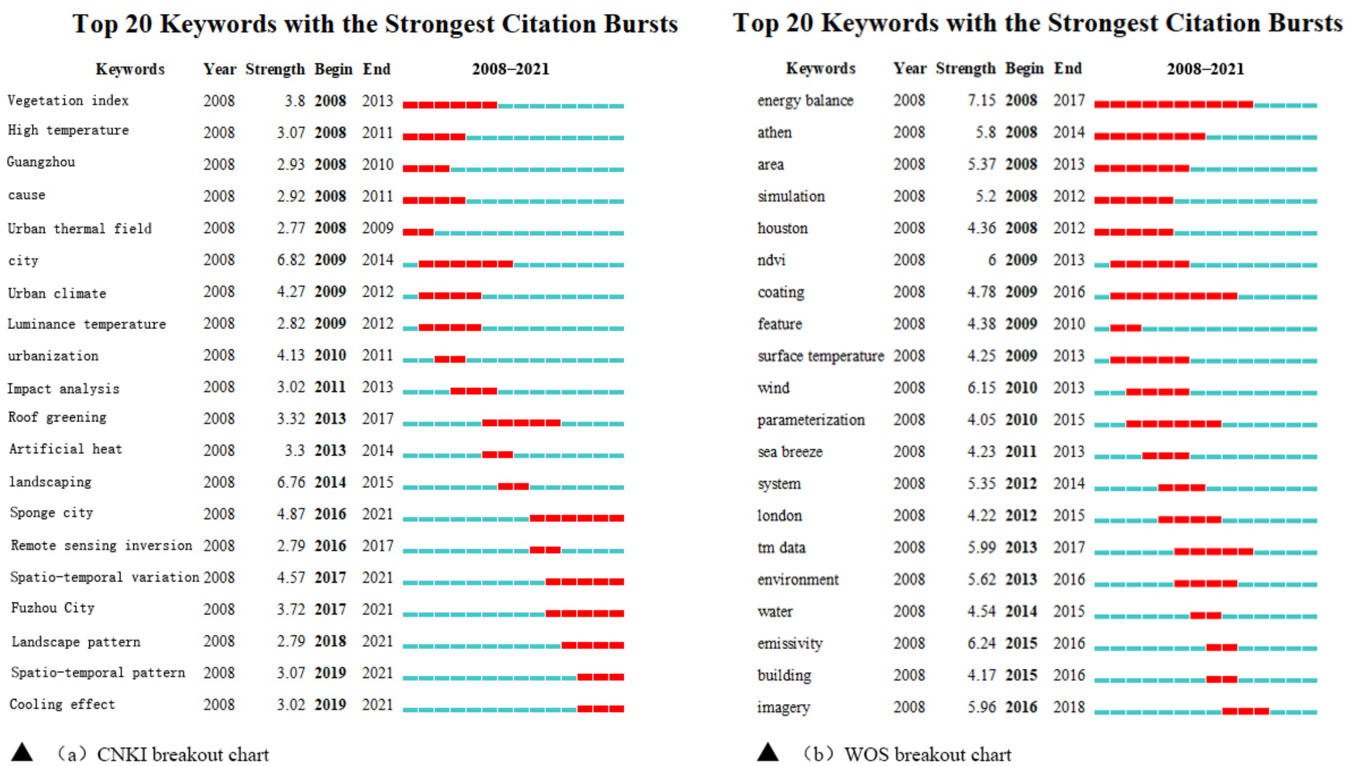

Figure 8. Emergence of keywords in WOS and CNKI urban heat island research literature. Note: red in the figure indicates the starting time and duration of hot keywords.

Figure 9. Co-occurrence network map of key words in the WOS urban heat island research literature.

3.7. Research Frontier of Key Issues

Based on the keyword co-occurrence and time zone distributions of the UHI studies in the WOS and CNKI databases, combined with the frequently cited literature analysis, the hot topics in UHI research between 2008 and 2021 were mainly focused on three key issues, i.e., influencing factors of urban heat islands, urban heat island mitigation measures, and urban heat island research methods.

3.7.1. Influencing Factors of Urban Heat Islands

UHIs are affected by various complex natural and human factors. Numerous studies have been conducted to reveal the influencing factors of UHI in different regions through various perspectives, and have noted that the impact factors included the urban underlying surface [46], man-made thermal emissions [47], urban green space scale [48], remote sensing spectral index [49], land use [50–52], urban form [53,54], etc. However, the UHI effect might be influenced not only by these conventional factors, but also by more complex factors. For example, Chen et al. [55] found that the night LSTs were closely related to socio-economic and topographic factors. Xiong and Zhang [56] pointed out that landscape pattern, urban construction intensity, and topography were the dominate factors affecting the spatial pattern of the urban thermal environment and identified that human factors have a greater role in promoting the UHI effect than natural factors do. Xiong et al. [57] found that the relationship between the soil brightness index (NDSI), normalized built-up index (NDBI), night illumination (NL), and the relative effect strength of UHI was significantly non-stationary in space. Gao et al. [58] confirmed that the impervious surface ratio (ISR) and building density (BD) rank of the urban form characterizes an enhanced UHI effect, while the green land rate (GR) was the key factor in the formation of cold islands in dense urban areas. Until now, the vast majority of studies on the influencing factors of UHI have mainly been focused on a single factor, especially for the impact of urban green space on the UHI effect. Meanwhile, in the current research on the influencing factors of the urban heat island effect, more attention is paid to factors related to the city itself, while the influences of some external factors are ignored, such as changes in policies, the influence of the surrounding environment, etc. [59].

3.7.2. Urban Heat Island Mitigation Measures

The UHI effect has a significant negative influence on the urban environment and its residents. In the context of unstoppable urbanization, mitigating the UHI effect has a vitally important role in sustainable urban development [60]. With the deterioration of the urban thermal environment, it is urgent to explore more effective UHI mitigation measures to alleviate its impact on the environment and city residents [61]. Several studies have explored mitigation strategies for UHI, such as reducing man-made heat emissions [62–64], increasing urban green space and green infrastructure [65], increasing the water area [66], improving underlying surface materials [67,68], building high-albedo roofs and roads [69,70], urban planning [71], building green ecological roofs [72,73], etc. For example, Bustami et al. [74] found that the continuous density and spread degree of urban development spaces were both key factors affecting the UHI effect, and maintained that urban continuity and more incongruous urban forms should be considered when designing mitigation strategies. Wu et al. [75] identified that urban blue infrastructure (UBI) could alleviate the UHI effect, and that the cooling effect of UBI is affected by its size and shape. Nuruzzaman [76] confirmed that green vegetation is the most effective measure. However, other studies have found that the number of green spaces was not the only standard to evaluate the temperature mitigation [77]; the spatial configuration of vegetation patches was also important for alleviating the UHI effect. For example, Kowe et al. [78] revealed that the cooling degree of clustered vegetation was more effective than that of scattered and broken vegetation patterns, and the variance in the complexity of the vegetation patch density, shape, and size led to different cooling effects. In general, the research on the mitigation measures for UHI was mainly focused on land use, water, green infrastructure, buildings, and energy [79]. However, although a large number of mitigation measures were developed to mitigate the UHI effect in various regions and on various scales, not every mitigation measure was universally applied to all scenarios. For example, improving the advantages of the cooling effects of urban landscapes (e.g., green spaces and water bodies) to mitigate UHI for some special regions might be a more suitable strategy than others, except for minimizing anthropogenic heat emissions [80]. In addition, the regulating effect of green spaces and water bodies on air temperature has a threshold, which means that the areas of green space and water bodies cannot be increased limitlessly. Only the landscape within the threshold range would exert the maximum regulating function for air temperature [81]. Therefore, there is a tendency for pay more attention to exploring the impact of the urban landscape pattern and vegetation patch spatial pattern on mitigating the UHI effect in future studies.

3.7.3. Urban Heat Island Research Methods

The traditional observation method, remote sensing monitoring, and boundary layer numerical model simulation were the three major methods for monitoring the UHI. Depending on different monitor conditions, the traditional observation method could be subdivided into three methods, i.e., the meteorological station method, the fixed point observation method, and the flow observation method [82]. In the early stage, the traditional meteorological station observation method, based on the distribution observation and the flow observation meteorological data of meteorological station data in urban and rural areas, was used to study the UHI effect through comparing the urban and rural air temperatures and surface temperatures [30]. Although this method is convenient to obtain data and can be used by meteorological stations or fixed stations over a long period of time, it was unable to reveal spatial distribution information on UHI or to deeply analyze the characteristics of UHI's layout and internal structure. This was due to either the limited locations and number of meteorological stations, or the restrictions on obtaining information from individual points [83]. Subsequently, with the development of computer technology, the boundary layer numerical model simulation method gradually matured. This method was able to obtain higher space resolution results to explore the spatial–temporal changes and the physical formation process involved in UHI, as well as to offset the inadequacy of traditional observation research at spatial locations [59,83,84]. To date, the most widely used boundary layer numerical models include MM5, WRF, and RAMS [85]. Several studies were conducted to simulate the UHI effect by adopting these models. For example, Diaz et al. [86] used the WRF model to explore its potential to provide a high-resolution vertical profile for thermal infrared remote sensing inversion of LST; Ilhamsyah [87] simulated the urban heat island effect in Jakarta, Indonesia, using the MM5 model; and Cantelli et al. [88] coupled a subgrid town energy budget (STEB) with the RAMS model to simulate the urban heat island over Rome, Italy.

Furthermore, due to the advantages of temperature field monitoring in a large area, including the wide coverage, low acquisition cost, and short time to acquire remote sensing technology [30], the remote sensing monitoring method has played an vital role in UHI research and has become a fundamental method for obtaining and analyzing UHI information [89]. Numerous scholars have adopted the remote sensing method and its data to assess the UHI effects around the world. For example, Ezimand et al. [90] analyzed the influence of two-dimensional and three-dimensional urban structures on LST changes in the Tatu region of Estonia by using remote sensing data. Moazzam et al. [91] used remote sensing data to explore the impact of urbanization on the land surface temperature and surface urban heat island in Jeju Island, Republic of Korea. Xue et al. [92] quantitatively studied the spatial patterns of urban heat islands and the associated cooling effect of blue-green landscapes with multi-source remote sensing data. In addition, according to different monitoring technologies, the remote sensing monitoring method could be subdivided into three heat island monitoring methods based on temperature, vegetation index, and thermal landscape, respectively. Among these, the temperature-based heat island monitoring method is the most intuitive [93]. In this context, several scholars have developed a variety of LST inversion algorithms based on satellite data, such as the atmospheric correction method, single-channel algorithm, split-window algorithm, and mono-window algorithm [7,94]. Wang et al. [95] used the atmospheric correction method to invert LST and identified the quantitative influence of configuration and morphological characteristics on the cooling effect of different urban park scales in Shanghai. Adeniran et al. [96] adopted the mono-window algorithm and split-window algorithm to conduct a comparative study of different LST images of different satellites in Hong Kong, China. Guha and Govil [97] applied the mono-window algorithm to invert the LST of Raipur City, India, and studied the relationship between LST and six remote sensing indices (i.e., MNDWI, NDBaI, NDBI, NDVI, NDWI, and NMDI). Although scholars have proposed many temperature inversion algorithms according to the characteristics of various thermal infrared remote sensing data, different inversion methods are suitable for different remote sensing data [98]. Some studies have shown that the surface radiation transfer model is suitable for surface temperature inversion of various thermal infrared remote sensing data, but its application is limited due to the large number of surface parameters required, and it is believed that the more universal inversion algorithms include the universal mono-window algorithm, split-window algorithm, multi-band regression method, etc. [99,100]. Although the aforementioned commonly used algorithms have been widely used both on land and at sea in different regions, and have become the basics of land surface temperature research, in general, the academic circle generally believes that the current land surface temperature inversion algorithm is more mature, and that the best applicability and inversion accuracy belong to the split-window algorithm [101]. For example, Yao et al. [101] compared the advantages and disadvantages of the different remote sensing inversion algorithms and pointed out that the split-window algorithm was a relatively mature algorithm for LST inversion due to its better applicability and inversion accuracy.

Some studies have indicated that the satellite remote sensing data commonly used in UHI research mainly include AVHRR, MODIS, TM/ETM+, ASTER, etc. [98]. AVHRR and TM/ETM+ were commonly used types of remote sensing data for UHI research before 2000. After 2000, with the launch of the TERRA/AQUA satellite, ASTER and MODIS data were increasingly used for their high spatial resolution, while TM/ETM+ data were still widely used for due to their free access and high resolution [100]. For example, Chen et al. [102] studied the differences in the UHIs and their driving factors between downtown and new urban areas of Wuhan from 2001 to 2018 based on MODIS data. Gu et al. [103] studied the temporal and spatial distribution characteristics of UHI in Nantong City based on TM/ETM + remote sensing images in 2001 and 2005. Wen et al. [104] studied the UHI problem of the Guangzhou metropolis in Guangdong Province of China based on ETM+/TM images. Yao et al. [105] studied the relationships among impervious water surface (ISA) dynamics; forest cover increases; and LST and SUHII changes in the Beijing plain area during 2009–2018 based on 8 scenes of Landsat 5 TM/7ETM/8OLI images, 920 scenes of EOS-Aqua-MODIS LST images, and other data/information collected by different approaches.

4. Discussion

The research on the UHI effect has always been a hot topic for urban ecological and environmental issues. With the increasing impact of population growth, rapid urbanization, and global climate change on the urban ecological environment, more and more scholars and policy makers have begun to pay attention to the issues related to UHI. At present, remarkable achievements have been made in the development of UHI research in terms of theory, method, content, and case studies. Based on our analysis, we propose the following directions for future research:

The defects of the existing traditional monitoring methods for quantitative inversion of LST include, e.g., the insufficient number of site observations, small application scope of fixed-point observation, inability of mobile observation to carry out temperature monitoring at the same time, low temporal resolution of remote sensing monitoring, and weather influence. More suitable and accurate monitoring methods should be developed to ensure objective and comprehensive analysis of the LST inversion results, and to reduce the mistakes and deficiency in the monitoring process based on different scales and purposes.

With the development of global urbanization, the UHI effect is no longer limited to influencing a single city; the interaction between cities has led UHI issues to become a common problem faced by all cities [106]. Some studies have been carried out regarding UHIs' effects on urban agglomeration, e.g., 218 cities in China [107], Fujian Triangle urban agglomeration [108], and Guangdong–Hong Kong–Macao Greater Bay Area [109]. Most of studies on UHI are still conducted on the small scale of a single city, or the local scale. Therefore, it is necessary to conduct and strengthen the comprehensive research on the UHI effect at a larger spatial scale (i.e., urban agglomeration scale) in the future.

The intensification of rapid urbanization has not only led to the continuous expansion of the urban form in the horizontal direction, but has also caused dramatical changes in the vertical direction. The architectural landscape could greatly affect the UHI in three-dimensional space by changing the energy flow between the surface, the building surface, and the lower atmosphere [110]. Research on UHI in the three-dimensional space has attracted widespread attention in recent years. However, the quantitative description of three-dimensional urban space and its relationship with UHI effect lacks systematic and in-depth exploration at present. Therefore, question of how to quantify three-dimensional urban spatial morphology and structure and its impact on the UHI effect might be a major research hotspot in future studies. Furthermore, apart from for the architectural landscape, the vegetation landscape has been confirmed to be an effective measure to mitigate the UHI effect. Its proper landscape composition, spatial configuration, and materials have a great impact on UHI at the local scale [111]. Therefore, more attention should be paid to the study of the mitigative effect of the vegetation landscape on UHI, especially regarding the vegetation landscape's structure and configuration pattern.

The UHI effect is a complex and severe urban ecological environment problem which involves many disciplines, such as meteorology, architecture, ecology, urban and rural planning, landscape architecture, environmental science, resource utilization, etc. Benefitted by the rapid development of research on the UHI effect in recent decades, such research has become a multidisciplinary comprehensive field. However, with the increasing attention being paid to human health and the urgent need for urban sustainable development and ecological civilization construction, the research on the UHI effect should pay more attention to the cross-research with other disciplines. This would strengthen the integration of theories and technologies inter-disciplinarily, especially in medicine, geography, and other disciplines, and would introduce the theories or methods of other disciplines (e.g., ant colony algorithm, recurrent neural network model, etc.) to promote in-depth development of the research on the UHI effect.

5. Conclusions

In this study, we analyzed a large number of publications in the field of UHI research from 1980 to 2021. We emphatically reviewed the academic achievements and progress in this field during the rapid development period (2008–2021) using Cite Space software, based on the WOS and CNKI databases. Through a comprehensive analysis of the literature to explore the current state of UHI research, and of the literature citations, cooperation networks, and hot topics, we identified that the research on UHI has existed in a flourishing period since 2008 with the rapidly rising number of publications. Relevant institutions and scholars from 85 countries have carried out UHI research, among which Chinese scholars and institutions are the major contributors in this field. Research has formed a tendency of interdisciplinary integration, involving environmental sciences, meteorology atmospheric sciences, remote sensing, resource utilization, building science and engineering, etc. The research mainly focused on the influencing factors, mitigation measures, and quantitative inversion of UHI. The present study represents a more comprehensive analysis of the development process of UHI research and reviews this hot topic's evolution and main progress, providing support for more scientific studies on the UHI effect and the research foundation in the field of UHI for scholars.

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