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Deciphering Urban Heat Island Mitigation: A Comprehensive Analysis of Application Categories and Research Trends

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ABSTRACT

This review investigates research on Urban Heat Island Mitigation (UHIM), examining 2906 publications from 1980 to 2022 for the first time. The current study uncovers an upward trend in UHIM research, with the number of publications peaking in 2022 at 494. Collaboration and global interest are rising, with 2049 authors, 779 institutions, and 68 countries contributing to the research in 2022. The application topics of UHIM were categorized into eight main categories and 32 sub categories. Nature-based solutions, urban planning strategies, and modifications to the built environment draw the most research interest. Green Roofs and Walls, a subcategory of Vegetation and Shade, tops the list with 705 publications, indicating the recognition of the cooling effect and aesthetic value of green spaces. Land Use and Zoning, within Urban Planning and Design, comes next with 575 articles, signifying researchers' interest in how urban planning impacts UHIM. Similarly, Permeable Pavement (Cool Roof and Pavement Technologies) and Natural Ventilation (Energy Efficiency) hold considerable interest. Overall, the interdisciplinary nature of UHIM research is evident, pointing towards the need for a holistic, integrated approach to address urban heat islands. Although Sustainable Transportation is the least explored category, it might represent an opportunity for further research.

1. Introduction

The issue of reducing Urban Heat Island (UHI) has become increasingly urgent in light of the growing urbanization and climate change (Rogelj et al., 2018; Zhong et al., 2017). In research conducted in Hong Kong (Lin et al., 2017), the peak warmth is noted from June to September, where temperatures typically lie between 25.8°C and 31.4°C and the average humidity is approximately 80%. The findings indicate that enhancing the floor area ratio, building density, and tree canopy in urban settings can decrease daytime UHI effects without intensifying early evening UHI effects. This highlights the significance of shade in subtropical zones.

Cities worldwide have seen natural terrains replaced by man-made structures due to swift urbanization, leading to unfavorable thermal consequences. The influence of this urban expansion on local climates, particularly outdoor temperatures, is deeply concerning, as evidenced by multiple studies (Asimakopoulos, 2001; Givoni, 1998; Oke, 2002). These urban developments modify the radiative, thermal, moisture, and aerodynamic qualities of their surroundings (McGregor & Nieuwolt, 1998). As a result, urban areas tend to accumulate heat, a phenomenon termed UHI. The peak of heat effect could reach a height equivalent to three to five times the average height of buildings in an area (Givoni, 1998). The precise magnitude of UHI is variable, influenced by meteorological factors, location, and specific urban attributes (Emmanuel, 1997).

UHI effect has been linked to a variety of undesirable outcomes, such as higher energy consumption (Li et al., 2014), worse air quality (Li et al., 2004), and detrimental impacts on human health and well-being (Heaviside et al., 2017).

UHI effect, a direct consequence of rapid urbanization, poses a considerable threat to cities' comfort, health, and overall liveability. Research by Yang et al. (2015) highlighted its role in fostering several environmental challenges in urban settings. Grimmond (2007) further elucidated how the intensified warming associated with urbanization

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detrimentally affects health, human comfort, and the local atmospheric conditions. Digging deeper into the multifaceted repercussions of UHI, studies by Ichinose et al. (2008), Synnefa et al. (2011), Yang et al. (2015), and (Mohajerani et al., 2017) spotlighted a range of consequences. These encompass a surge in cooling energy consumption and its consequent costs, a notable rise in peak energy demand, and the creation of extensive smog and air pollutants, which deteriorate air quality. Moreover, there is pronounced thermal stress exerted on inhabitants, considerable disruption to urban ecosystems, and a palpable degradation in the living environment. Notably, the heat exacerbates health vulnerabilities, resulting in an escalated risk and occurrence of heat-related illnesses (Mohajerani et al., 2017).

Given the significance of this issue, it is essential to comprehend the current state of research in UHI mitigation and to identify trends, gaps, and prospects in the field. In this context, a bibliometric analysis of the current literature on Urban Heat Island Mitigation (UHIM) is crucial for providing an overview of the intellectual environment and guiding future research efforts.

Bibliometric analysis is a quantitative method for evaluating the scientific output on a particular topic by analyzing the publications and their citations (Zyoud & Fuchs-Hanusch, 2017). By evaluating the published literature on UHIM, it is possible to get insight into research trends, significant authors, institutions, nations, and the most influential works and the evolution of key concepts through time. In addition, bibliometric analysis can aid in identifying potential cooperation networks and interdisciplinary research opportunities that could drive innovation and progress in the field (Sweileh et al., 2017).

UHIM strategies aim to reduce the effects of the UHI effect by employing techniques such as increasing urban green spaces, utilizing cool roofs and pavements (Rawat & Singh, 2022; Rosati et al., 2021), enhancing building designs (Taleghani et al., 2016), and promoting sustainable urban planning (Coseo & Larsen, 2014). The growing body of UHIM research encompasses environmental science, engineering, architecture, urban planning, and social sciences. The interdisciplinary nature of the subject highlights the need for a comprehensive literature review that incorporates multiple perspectives and approaches to addressing UHI challenges.

UHI phenomenon has been studied from various perspectives. For example, Lee et al. (2016) investigated the cooling effects of trees and grasslands in reducing human heat stress in a residential neighborhood in Freiburg, Germany. The researchers employed the physiologically equivalent temperature measure to evaluate the impact of vegetation. Results indicated that trees were more effective than grasses in reducing heat stress, emphasizing the importance of incorporating urban greenery, especially trees, in UHI mitigation strategies. In another study, Deilami et al. (2018) conducted a comprehensive analysis of spatio-temporal elements, data, techniques, and mitigation strategies related to UHI. The authors analyzed 213 publications between 2009 and 2019 and identified major patterns and topics in UHI research. The study revealed a growing interest in UHI research, emphasizing remote sensing and GIS techniques, as well as the significance of integrating local climate conditions and urban morphologies into UHI mitigation efforts.

Urban Green Infrastructure has been shown to reduce summer temperatures in European cities significantly. Marando et al. (2022) examined UHI impacts in 601 European functional metropolitan areas and found that urban green infrastructure can cool cities by an average of 1.07°C and up to 2.90°C. However, the study also revealed that a minimum tree cover of 16% is necessary to decrease urban temperatures by 1°C. The cooling effect is primarily determined by the amount of vegetation in a city, as well as transpiration and canopy evaporation. The research also highlighted that nearly 40% of the population in many countries does not benefit from the microclimate regulation provided by urban greenery. To improve the health and sustainability of urban environments, the study emphasized the need to prioritize and target urban green infrastructure efforts, particularly in dry areas and cities with insufficient tree cover.

Study shows green spaces and green-mark commercial buildings' impact on reducing UHI in Singapore. Teo et al. (2022) investigated the impact of green areas and green-mark commercial buildings on Singapore's temperature distribution and their efficacy in reducing UHI impacts. Using ArcGIS software and cloud mapping, the research examines Singapore's temperature data, energy use, and green areas. The data suggest that business areas with a high concentration of green spaces and Green Label buildings had the lowest percentage of temperature change (1.6%). The study reveals a substantial relationship between the percentage change in temperature and the urban concentration of green areas. Adding green spaces, such as gardens and skyscraper greenery, may assist in decreasing urban heat, particularly in residential areas. The research indicates that combining green-mark buildings with green areas might reduce UHI and environmental deterioration in tropical cities such as Singapore. The suggested technique may apply to more relevant nations.

Anthropogenic heat emission is one of the most crucial drivers of UHIs. Chen et al. (2022) investigated the influence of anthropogenic heat emission on UHI impacts in five high-AHE blocks in Xi'an, China. At 33 urban locations, microclimatic indices such as air temperature and relative humidity were monitored, while urban morphological indicators were estimated in buffer zones of 20m and 50m. Green cover ratio, impervious surface area ratio, sky view factor, and reflectivity strongly affected microclimate, accounting for up to 35% and 31% of variations in air temperature and relative humidity, respectively, according to the research. To keep the maximum air temperature below 37°C (high-temperature orange alert), the ratio of impervious surface area to the impervious surface area should be maintained between 44% and 21.5%. The study underlines the significance of the green cover ratio in affecting building blocks with high anthropogenic heat emission and gives insights into the development of UHIM measures and climate-appropriate design in urban renewal projects.

UHI provides issues in terms of risk and resiliency, energy needs, and pollution mitigation techniques. Gonzalez-Trevizo et al. (2021) reviewed 171 papers related to UHI to reveal the knowledge gaps and trends in environmental degradation and energy research. The majority of studies were done in North America, Europe, and Asia, with an inherent bias toward microscale household applications. Urban environmental quality deterioration (95%) and energy demand and efficiency (25%), with repercussions for material science, urban design, and planning, were the key issues of attention. The study stresses the necessity for multiscale investigations, health vulnerability prevention strategies, and increasing energy safety for urban resilience. They reported that future studies should concentrate on the relationship between urban overheating and heatwaves in high-emission scenarios, energy cooling demand, and scale-specific analytical accuracy.

In light of ongoing urbanization and the impacts of climate change expected in the coming decades (Nations, 2018), adopting effective strategies for UHIM becomes paramount in ensuring the sustainability, resilience, and livability of urban areas. Research related to UHI phenomena and mitigation strategies is evolving continuously. Carpio et al. (2020) analyzed the progression of pavement research about UHI from 1990 to 2019, finding an increasing focus on UHI mitigation and residential energy efficiency. They noted a shift from field to laboratory experiments after 2008, with the majority of publications originating from the European Union. The study underscored the growing importance of understanding pavement's impact on UHI and the need for further research. Similarly, He et al. (2023) conducted a bibliometric analysis of urban heat mitigation and adaptation research from 1989 to 2021. They identified the field as expanding and interdisciplinary, encompassing environmental, technological, health, economic, and social aspects. Four research clusters were identified: UHI effect assessment, microclimate control, climate-related health implications, and urban heat mitigation techniques. The study highlighted geographical distribution disparities, gradual evolution, and knowledge isolation as challenges in the field.

Considering the UHI without mitigation approaches, a few recent studies investigated the trend of the research. Huang and Lu (2018) investigated UHI research from 1991 to 2015. The results showed steady growth in UHI-related publications. The study encompasses scientific output, citations, topic categories, important journals, keywords, prominent nations, institutions, authors, and research partnerships. The most prevalent topic areas are meteorology, environmental sciences, and building construction technology. The United States and China are the leaders in UHI research, providing about half of all papers. Authors (Huang & Lu, 2018) found four significant categories of keywords: research techniques and indicators, generation factors, environmental consequences, and mitigation and adaptation options. The study forecasts that modeling will continue to be the dominant research technique, that remote sensing will gain popularity, and that UHI effects and mitigation techniques will get more attention in the future (Huang & Lu, 2018).

In a more updated research considering UHI, Wu and Ren et al. (2019) analyzed the development of UHI research from 1990 to 2017 using scientometrics to identify trends, major disciplines, and patterns of cooperation. It emphasizes the rise in UHI-related publications but acknowledges the need for a comprehensive understanding of research trends. The report proposes two relevant research directions: the adverse effects of UHI on public health and mitigation and adaptation measures. This exhaustive analysis intends to stimulate future research on UHI by providing insights into its evolution and new research areas.

The current research delivers an in-depth evaluation of the UHIM literature, using advanced bibliometric techniques to examine publication patterns and research trajectories. The objective of the review is to provide a holistic view of the existing UHIM literature landscape. Central to the investigation is identifying pivotal publications, leading institutions, and forefront nations in this arena. Of paramount importance, the research explores the application categories and their respective subcategories within UHIM. By closely examining the trajectories within these categories, one gains essential insights into the dynamic nature of UHIM research. Moreover, the study evaluates the spread of publications among distinct application categories and sheds light on the primary areas of concentration for the top-contributing countries.

2. Methodology

2.1. Urban Heat Island Mitigation

UHI mitigation commonly employs a range of globally recognized techniques. These include designing urban morphology (Tan et al., 2016), integrating phase-changing materials (Kuznik et al., 2011), using cool (reflective) pavements (Santamouris, 2013), and promoting green infrastructure (Matthews et al., 2015). Central to these approaches is to alter the energy balance on constructed surfaces. For example, urban green spaces can shift more energy towards the latent heat of vaporization (Wang et al., 2013), while pavements with higher albedo properties can reflect greater solar radiation. However, the efficacy of these UHI mitigation methods is influenced by factors like surface characteristics, geographical features, and local climate (Aflaki et al., 2017).

2.2. Research scope

The present scientific investigation aims to conduct a comprehensive scientometric analysis of the topic of UHIM. To achieve this objective, a search was conducted on the Web of Science (WoS) database using a specific search string, ((TS=("urban*")) AND TS=("heat* island*")) AND TS=("mitigat*"), limited to the timeframe of 1980 to 2022. The first search term, (TS=("urban*")), is a title search that retrieves records containing the word "urban" or any word beginning with "urban" in the title. The second search term, TS=("heat* island*"), is also a title search that retrieves records containing the words "heat," "island," or any word beginning with "heat" or "island" in the title. Finally, the third search term, TS=("mitigat*"), retrieves records containing the word "mitigation" or any word beginning with "mitigat" in the title. This search strategy is commonly used in scientometric research to yield a comprehensive set of records related to the topic.

Upon obtaining the raw text codes from WoS, a meticulous data analysis process was initiated via Python coding and manual interventions (Appendix A). In the realm of keyword analysis, it is crucial to recognize that a single concept can be expressed in multiple ways due to the application of the stemming method (Singh & Gupta, 2017). For instance, the concept of "Cool roof" could also be expressed as "Cool--roof", "Cool roof", "Cool roofs", or "Cool roofing". Although these variations exist, they fundamentally share the same idea and should be unified under a single keyword. To achieve this, an initial step was taken to transform all keywords to their root form, which served as the standard keyword. For example, "cool roof" was chosen as the root form, encompassing all variations of the keyword. For more details about the data analysis procedure, see Appendix B.

The goal of this study is to conduct a comprehensive analysis of productivity, influence, and collaboration trends within a specific set of articles. To achieve this, several parameters are evaluated, including the total number of publications, distribution of publication types, total number of authors, number of associated institutions, number of represented countries, and citation count of the articles. This study examines various variables to assess the productivity, impact, and collaboration patterns within a specific subset of articles. These variables include total publications (TP), which represents the overall number of publications in the dataset, and the percentage of total publications, indicating the proportion of a specific publication type in the dataset as a percentage. Other variables considered are the total number of authors (AU) contributing to the dataset, the number of associated institutions (Inst), and the number of countries (Count) represented by the authors.

Citation-based variables are also analyzed, such as the total citation count (TC) of articles in the dataset and the average number of citations per publication (TC/TP). The average number of authors per publication (AU/TP) is also examined. The H-index (HI) is used as a measure of productivity and influence, taking into account the number of publications and citations. The study further investigates the number of publications with the same first author (AU1) and corresponding author (AUC), as well as the distinction between independent (Indep) and collaborative (Collab) publications. The ratio of collaborative publications to the total number of publications (Collab/TP) is calculated to determine the extent of collaboration. The impact factor (IF) is also used to assess the average annual citation count for journal articles and evaluate the significance of journals within their respective fields.

Furthermore, this research scrutinizes various metrics to gain insights into the productivity and influence of the articles. These metrics include the average citation count per publication, the average number of authors per publication, and the H-index, which measures productivity and influence based on publication and citation counts. The study also investigates the number of publications by the same first or corresponding author, as well as the proportion of independent and collaborative publications. In addition to productivity and influence, the impact factor is also considered. The impact factor serves as a metric to assess the average annual citation count for journal articles, providing insights into the relevance and impact of the journals within their respective fields. Moreover, this study identifies and classifies the different types of application categories and sub categories for UHIM utilized in the articles. The focus then shifts to analyzing the geographical locations and the number of studies conducted for each application type. Additionally, trends for each application type over time are explored, allowing for a comprehensive understanding of the evolving landscape within the field.

3. Data overview

The search yielded 3292 relevant records in the field, of which 139 were excluded as they were associated with the year 2023 to ensure the completeness of the data set. Consequently, 3153 records were included in the study, which was filtered to include only articles, proceedings papers, and article/proceedings paper hybrid publications, as these are original research publications. This filtering process resulted in a final set of 2906 records in the analysis. The findings of this study will provide valuable insights into the trends and patterns of UHIM strategies and their effectiveness in mitigating the impacts of urban heat islands. The analysis will contribute to the development of evidence-based policies and practices for urban planning and management, aiding in mitigating the impacts of urban heat islands. Furthermore, this study will serve as a foundation for further research on this crucial topic, advancing knowledge and understanding. The link to the data is available here (Mendeley, 2023) (https://dx.doi.org/10.17632/mwvf5vdj8b.1).

Fig. 1a summarizes the distribution of publication categories on the subject of UHIM. The five document types analyzed in this study include "Article," "Proceedings Paper," "Review," "Article; Proceedings Paper," and "Other." The results show that "Articles" accounted for the majority of publications (2575), followed by "Proceedings Papers" (279), "Reviews" (192), and "Article; Proceedings Paper" (52). The "Other" category included various publication types, such as "Article; Book Chapter," "Editorial Material," "Book Review," "Correction," "Editorial Material; Book Chapter," "Review; Book Chapter," "Article; Data Paper," "Meeting Abstract," "Book," and "Proceedings Paper; Retracted Publication," totaling 55 publications. More details about publication types can be found on the WoS web page (Web-of-Science, 2023)

A total of 2906 publications are distributed across twelve languages (Fig. 1b). The majority of publications (2872) were published in English, constituting 98.8% of all publications. Spanish ranked as the second most prevalent language, with 17 publications making up 0.6% of the total. French, Korean, Italian, and German contributed two to five publications each, representing 0.2% of the total; the remaining languages are insignificant. https://technoscience.icu/data/UHIM/

4. Results and discussions

4.1. Annual analysis

Table 1 summarizes key characteristics of published records in the field of interest from 1991 to 2022, revealing several patterns and trends. One of the most notable trends is a general upward trend in TP, with a peak of 494 articles in 2022, indicating a growing interest in the field and increased research activity. The proportion of total publications (TP%) has also increased, with 2022 accounting for 17% of all publications, suggesting a surge in significant contributions to the corpus of literature in recent years. The number of authors, AU, contributing to publications has steadily grown, with 2022 recording the highest number of writers (2049), indicating an increasing trend of collaboration and attracting more scholars to the discipline.

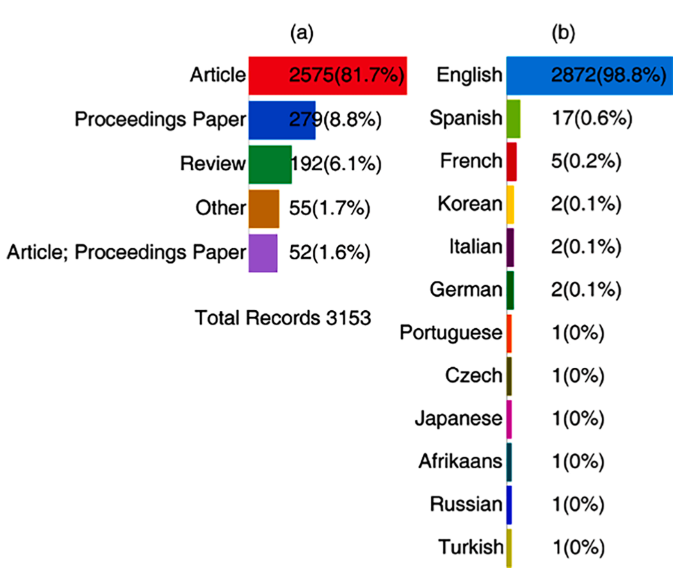

Fig. 1. Categories of publications. (a) Details of 3153 publication records related to UHIM, (b) Languages of the publications include 2906 records.

Table 1
Features of annually released records in UHIM

Year	TP	TP%	AU	Inst	Count	TC	TC/TP	AU/TP
1991	1	0	1	1	1	15	15	1
1994	1	0	5	1	1	0	0	5
1995	1	0	7	1	1	303	303	7
1996	3	0.1	9	3	2	234	78	3
1998	4	0.1	11	4	3	228	57	3
1999	1	0	3	2	1	378	378	3
2000	2	0.1	8	3	2	558	279	4
2001	3	0.1	10	3	2	1188	396	3
2003	1	0	1	1	1	1	1	1
2004	3	0.1	10	4	2	154	51.3	3
2005	5	0.2	13	4	3	816	163.2	3
2006	9	0.3	32	13	5	1521	169	4
2007	29	1	75	31	11	3300	113.8	3
2008	18	0.6	71	35	11	1405	78.1	4
2009	30	1	106	46	17	1435	47.8	4
2010	38	1.3	133	52	15	3030	79.7	4
2011	49	1.7	177	70	22	5482	111.9	4
2012	71	2.4	241	105	24	5798	81.7	3
2013	65	2.2	225	100	22	3757	57.8	3
2014	118	4.1	411	186	35	9311	78.9	3
2015	151	5.2	527	208	34	6285	41.6	3
2016	213	7.3	708	311	47	9653	45.3	3
2017	225	7.7	805	355	50	8535	37.9	4
2018	253	8.7	951	418	55	7816	30.9	4
2019	291	10	1116	456	60	7265	25	4
2020	417	14.3	1544	630	64	7038	16.9	4
2021	410	14.1	1668	700	67	3696	9	4
2022	494	17	2049	779	68	1537	3.1	4

The number of institutions and countries involved in publications has also risen, with 779 institutions and 68 nations participating in 2022. These results suggest that research in the field is becoming more globally and diversely represented, with contributions from numerous institutions and nations. Furthermore, TC has fluctuated over the years but shows an overall upward trend, with 2014 recording a high of 9311 citations. The TC/TP measure indicates the average impact of publications, reaching its peak in 2001, with an average of 396 citations per article. Finally, AU/TP measure have remained relatively steady throughout the years, with small teams of researchers collaborating on publications.

The number of institutions and countries involved in publications reached their highest levels in 2022, with 779 institutions and 68 nations participating, indicating a more diverse and global representation of research in the field. TC has shown an overall upward trend, with a peak of 9311 citations recorded in 2014, indicating the influence and acceptance of the research within the academic community. TC/TP measure peaked in 2001 with an average of 396 citations per article, highlighting the significant impact of studies published in that year. AU/TP measure has remained relatively steady, with an average of 3 or 4 authors per publication, indicating that the general organization of research collaborations has not significantly changed.

4.2. Countries/Institutes contribution analysis

UHIM has received citations in at least 90 countries, while publications related to UHIM have been identified in 93 countries. The study presented the strengths and weaknesses of each country's academic performance in Table 2, along with the corresponding impact on their research ecosystems.

China displayed an impressive research output, topping the list with 847 TP and 29.1% TP%, indicating a significant quantity of publications. Although China had a lower TC/TP ratio than the United States, England, and Greece, the country's large number of publications still resulted in a substantial total citation count of 25,693. China's research efforts also focused more on independent research, with 528 publications compared to 319 collaborative articles, which accounted for 37.7% of their TP. The country's research prowess was highlighted by its excellent AU1 AUC and H-index scores, second only to the United States.

In terms of TP and TP%, the United States ranked second with 567 and 19.5%, respectively, but outperformed China with a higher total citation count of 29,189 and TC/TP ratio of 51.5, indicating a greater impact per publication. The United States demonstrated a more balanced distribution of collaborative and independent publications, with a Collab/TP ratio of 49.4%. Its AU1 and AUC scores also highlighted its research excellence, with the highest HI among the analyzed nations.

Italy's academic scene displayed a high TP (327) and TP% (11.3%), yet its TC/TP ratio (27.9) was lower than both China and the United States. Despite its relatively modest number of joint publications (99), Italy maintained a fair balance between cooperation and independence, with a 30.3% Collab/TP ratio. Its research prowess was underscored by its impressive AU1, AUC, and HI scores.

Australia ranks fourth for TP (196) and TP% (6.7). It has a higher TC (6,593) and TC/TP (33,6) than Italy, indicating a better effect per article. Australia places a considerable emphasis on collaborative research (64.3% Collab/TP), publishing 126 collaboration works and 70 solo works. Its AU1 (117) and AUC (119) are lower than the top three nations; however, its HI (46) is extremely competitive.

The TP and TP% numbers for Japan, England, and Germany are comparable, ranging from 5.1% to 6.2%. While their TC/TP ratios differ, all three nations exhibit a preference for collaborative research, with Collab/TP ratios above 40%. England (40) and Germany (36) have higher HI ratings than Japan (37), but Japan's HI is the lowest (37). The AU1 and AUC values for these countries are comparable, with England having the lowest AU1 (85) and Japan having the highest AUC (132).

According to the survey, 2,250 institutions have received at least one citation in the field of UHIM, while 2,469 institutions have published at least one paper on the topic. Table 3 provides a comprehensive overview of the academic publishing landscape among various institutions. The Chinese Academy of Sciences (CAS) stands out with 177 publications, constituting 6.1% of the total. While this number of publications is significant, CAS has a lower TC/TP ratio of 31.5 than certain other universities, such as Arizona State University and the University of Athens. Nevertheless, CAS has many citations (5,580), indicating its strong overall impact.

On the other hand, Arizona State University (ASU) has a high TC/TP ratio of 63.4 and a significant number of publications (86), accounting for 3% of the total. ASU's research influence is strong, with a total of 5,450 citations, making it the second leading institution in terms of TP. It also has a more substantial effect per article than the leading institution, CAS.

The University of Chinese Academy of Sciences (UCAS) and the University of Perugia both have identical TP and TP% levels, with UCAS having 79 articles (2.7% TP%) and a lower TC/TP ratio of 24.6, while the University of Perugia has 78 publications (2.7% TP%) and a higher TC/TP ratio of 31.8. Nonetheless, both universities display a robust research output, with UCAS getting 1,941 citations and the University of Perugia obtaining 2,483.

The University of New South Wales (UNSW) and the National University of Singapore (NUS) have both exhibited high impact per publication, with TC/TP ratios of 43.5 and 55.3, respectively. UNSW's 62 publications make up 2.1% of the total, while NUS's 54 publications constitute 1.9%. Both institutions have a significant research impact, with UNSW earning 2,696 citations and NUS receiving 2,986.

Wuhan University, Peking University, and the University of Hong Kong each have TP values ranging from 39 to 43 and TP% values between 1.3 and 1.5. Among these universities, Wuhan University has the lowest TC/TP ratio (23.6), while Peking University has the highest (64.5). The University of Hong Kong has a TC/TP ratio of 37.4, placing it in the center. As indicated by their total citations, all three universities maintain a significant research influence.

The University of Athens is distinguished for its remarkably high TC/TP ratio of 118.6 (1.2), despite having a relatively lower TP (34) and TP % (TP%). Though less in amount, the institution's research output has a remarkable influence, as evidenced by its 4,034 total citations.

China leads with 12 universities, including the Chinese Academy of Sciences, University of Chinese Academy of Sciences, Wuhan University, Peking University, University of Hong Kong, Beijing Normal University, Tongji University, Nanjing University of Information Science & Technology, Chinese University of Hong Kong, Tianjin University, Hong Kong Polytechnic University, Nanjing University, and Sun Yat-sen University. Meanwhile, the United States, Italy, Australia, Singapore, Greece, Japan, and Canada each have one university included in the survey.

Table 2
Top twenty countries in terms of Total publications in UHIM

Country	TP	TP(%)	TC	TC/TP	Collab	Indep	Collab/TP(%)	AU1	AUC	HI
China	847	29.1	25693	30.3	319	528	37.7	773	749	78
USA	567	19.5	29189	51.5	280	287	49.4	360	365	88
Italy	327	11.3	9125	27.9	99	228	30.3	284	279	50
Australia	196	6.7	6593	33.6	126	70	64.3	117	119	46
Japan	180	6.2	5534	30.7	76	104	42.2	131	132	37
England	151	5.2	6231	41.3	107	44	70.9	85	78	40
Germany	147	5.1	4248	28.9	88	59	59.9	88	82	36
Canada	100	3.4	4517	45.2	61	39	61	57	51	36
India	91	3.1	1774	19.5	34	57	37.4	80	79	23
Greece	90	3.1	6407	71.2	43	47	47.8	64	65	39
Singapore	85	2.9	3888	45.7	58	27	68.2	49	47	33
South Korea	84	2.9	1129	13.4	27	57	32.1	69	74	18
Spain	81	2.8	2218	27.4	43	38	53.1	54	53	23
France	74	2.5	2028	27.4	34	40	45.9	55	51	23
Netherlands	65	2.2	2992	46	46	19	70.8	39	37	27
Switzerland	57	2	1652	29	39	18	68.4	37	33	22
Malaysia	56	1.9	1342	24	29	27	51.8	44	45	17
Iran	43	1.5	1077	25	20	23	46.5	36	32	17
Turkey	37	1.3	223	6	6	31	16.2	36	34	10
Brazil	36	1.2	668	18.6	13	23	36.1	33	31	15

Table 3
Statical analysis of the top 20 institutes in UHIM in terms of total publications

Institution	TP	TP (%)	TC	TC/TP	Collab	Indep	Collab/TP(%)	AU1	AUC	HI
Chinese Acad Sci	177	6.1	5580	31.5	63	114	35.6	101	94	37
Arizona State Univ	86	3	5450	63.4	26	60	30.2	51	54	38
Univ Chinese Acad Sci	79	2.7	1941	24.6	26	53	32.9	50	2	25
Univ Perugia	78	2.7	2483	31.8	26	52	33.3	58	55	30
Univ New South Wales	62	2.1	2696	43.5	46	16	74.2	32	28	27
Natl Univ Singapore	54	1.9	2986	55.3	33	21	61.1	27	27	27
Wuhan Univ	43	1.5	1013	23.6	8	35	18.6	27	29	18
Peking Univ	41	1.4	2646	64.5	18	23	43.9	27	25	21
Univ Hong Kong	39	1.3	1459	37.4	19	20	48.7	20	17	20
Univ Athens	34	1.2	4034	118.6	16	18	47.1	22	18	27
Beijing Normal Univ	33	1.1	1409	42.7	12	21	36.4	23	22	20
Tongji Univ	32	1.1	822	25.7	10	22	31.3	27	21	16
Nanjing Univ Informat Sci & Technol	31	1.1	1422	45.9	17	14	54.8	18	9	15
Univ Tsukuba	30	1	1469	49	23	7	76.7	18	18	18
Chinese Univ Hong Kong	29	1	1863	64.2	14	15	48.3	21	17	18
Tianjin Univ	29	1	349	12	9	20	31	14	15	10
Hong Kong Polytech Univ	28	1	778	27.8	17	11	60.7	13	15	12
Nanjing Univ	28	1	891	31.8	13	15	46.4	18	16	15
Sun Yat Sen Univ	26	0.9	717	27.6	18	8	69.2	10	11	14
Concordia Univ	26	0.9	2248	86.5	15	11	57.7	19	12	20

Table 3 indicates that 12 out of 20 universities included in the UHIM subject are based in China, highlighting their significant contribution to UHIM research output. This observation suggests that Chinese institutions are placing considerable emphasis on research and innovation in the field of urban heat island abatement, likely driven by the challenges associated with rapid urbanization and its associated impacts, including rising heat island effects.

4.3. Journals Analysis

In this study, 2906 articles associated with UHIM were identified, and 685 journals with at least one publication on the topic were found. Table 4 analyses the top twenty journals related to UHIM in terms of their TP, TP%, total citations, and H-index. Sustainable Cities and Society, Building and Environment, and Energy and Buildings are the three journals with the most publications and highest TP% related to urban development, built environments, and energy efficiency. These areas are critical components of reducing urban heat island effects, and the high publishing volumes and percentages of these journals highlight their significance in the field. Energies, which has a stronger emphasis on energy-related topics such as renewable energy and energy systems, has the fewest articles and lowest TP% among the top twenty journals, indicating that UHIM research makes up a small portion of its content. Building and Environment has the most overall citations, followed by Energy and Buildings and Sustainable Cities and Society, indicating that research published in these journals has had a significant impact in the field of UHIM. Land, which focuses on land use planning and management, has the lowest total citations among the top twenty journals, likely due to its more specialized readership.

Table. 4
Top 20 journals in UHIM with most publications

Journal name	TP	TP (%)	TC	HI
Sustainable Cities and Society	182	6.3	5664	41
Building And Environment	153	5.3	8144	49
Energy And Buildings	151	5.2	7484	49
Sustainability	145	5	2096	27
Urban Climate	132	4.5	2926	30
Science of the Total Environment	96	3.3	4424	36
Remote Sensing	88	3	1453	20
Urban Forestry & Urban Greening	69	2.4	3094	33
Solar Energy	58	2	5580	29
Landscape and Urban Planning	50	1.7	5227	34
Atmosphere	43	1.5	309	9
Environmental Research Letters	39	1.3	1700	21
Journal of Cleaner Production	33	1.1	1138	20
International Journal of Environmental Research... Health	33	1.1	338	10
Theoretical and Applied Climatology	28	1	769	14
Climate	27	0.9	385	12
Journal of Applied Meteorology and Climatology	22	0.8	1476	16
Land	21	0.7	106	5
Journal of Geophysical Research-Atmospheres	19	0.7	586	10
Energies	19	0.7	343	8

Fig. 2 depicts the publication trends of the top five journals in the field of urban health and its impact on the environment from 2010 to 2022. The selected journals are Sustainable Cities and Society, Building and Environment, Energy and Buildings, Sustainability, and Urban Climate.

Sustainable Cities and Society has experienced remarkable growth in publications since its inception, with no publications in 2010 and steadily increasing its output to a peak of 39 publications in 2022. This upward trend can be attributed to the journal's focus on sustainable urban development and the increasing recognition of UHIM as a vital component of sustainability. This development indicates that Sustainable Cities and Society has become a significant venue for scholars and practitioners interested in urban heat island abatement.

Building and Environment, with the most publications overall, started with four publications in 2010, declined to a minimum of two in 2013, and then showed an upward trend, peaking at 42 publications in 2022. This increasing trend demonstrates significant interest in the impact of the built environment on urban heat islands and highlights the journal's role as a prominent forum for research in this field. The decline in publications in 2013 may be attributed to several factors, such as editorial policies, research funding, or research priorities.

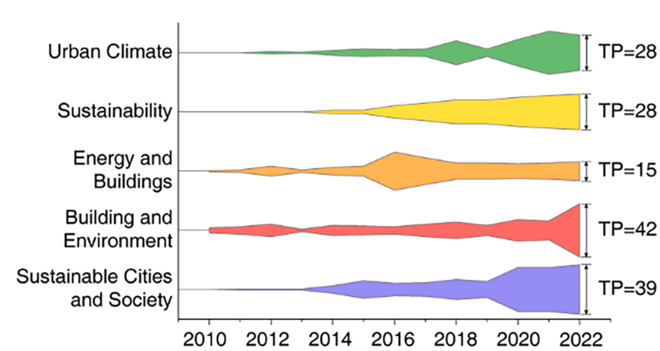

Fig. 2. Publications of top five journals over time in UHIM

Energy and Buildings began with a single publication in 2010 and experienced a substantial increase to 30 articles in 2016. Following this peak, the publishing trend of the journal has remained relatively consistent, with a minor decline in subsequent years, reaching 15 publications in 2022. This trend may reflect the significance of energy-efficient building design and construction in addressing urban heat island challenges, in addition to the journal's focus on energy-related topics.

Sustainability, a journal with a wider scope on sustainable development, did not have any publications in 2010 but has shown consistent growth in the number of articles published, with a peak of 28 in 2022. This steady rise in publications may be attributed to an increasing recognition of the interconnectedness between sustainable development and mitigating urban heat island effects. Scholars and practitioners are focusing more on sustainable practices to address urban heat island issues, thus contributing to the growth of articles in this journal.

Despite not having any publications in 2010, Urban Climate has observed a substantial increase in the number of articles over time, with a maximum of 34 in 2021. This trend indicates a growing interest in understanding the microclimatic conditions and the impacts of urban heat islands in cities. The journal is increasingly becoming an essential platform for disseminating research on mitigating heat island effects and adapting to urban climate change, as evidenced by the rise in publications.

The current research investigates the journals that are most actively publishing on distinct UHIM topics. This is particularly beneficial for institutions and librarians. With this information, they can make informed decisions on which journal subscriptions to prioritize, ensuring their library resources are optimally aligned with the most relevant and cutting-edge research in the UHIM field.

4.4. Keywords analysis and UHIM trending

Fig. 3a presents a keyword cloud map that depicts the top 25 most significant and frequently used keywords in the field of UHIM. The size of each keyword in the cloud map reflects its frequency or significance in the literature, with more prominent keywords indicating greater frequency or significance. Among the prominently featured keywords in the UHIM keyword cloud map are urban heat island, land surface temperature, climate change, green roof, urban planning, and remote sensing. These keywords demonstrate the interrelated themes and subtopics that are the research focus in UHIM-related studies.

4.4.1. Keywords distribution

Fig. 3b presents the top twenty keywords in UHIM, highlighting their significance and impact in the field. The keyword with the highest TP and TP% is "Urban Heat Island," which appears in 1033 publications, accounting for 35.5% of the total. This underscores the central role of urban heat islands in the UHIM research domain and their importance as a critical issue in urban planning and sustainability. "Urban Heat Island"

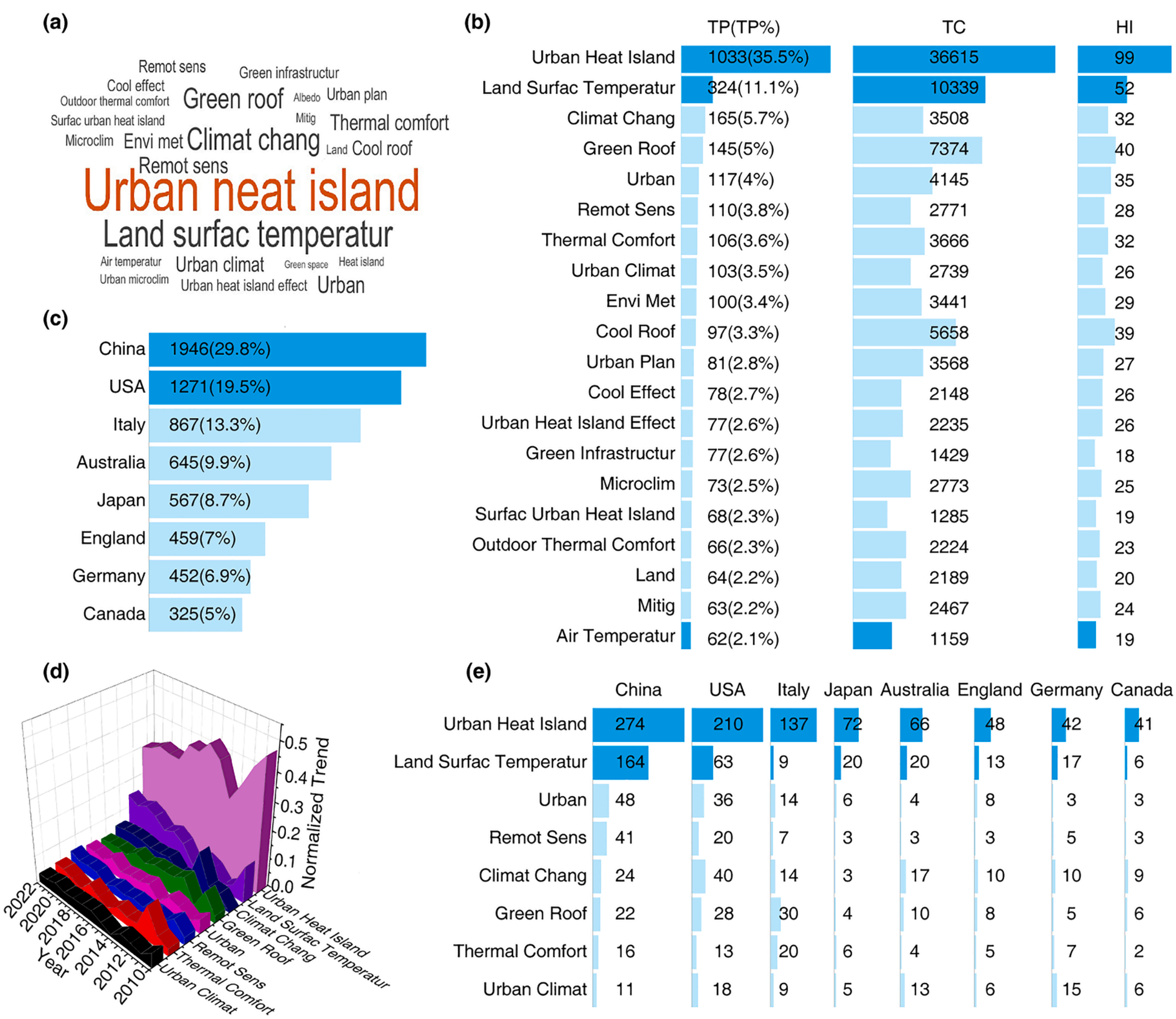

Fig. 3. Keywords on UHIM: (a) Keyword root cloud map for the top 25 keywords, (b) Top twenty keywords in UHIM, (c) Top eight Countries with involved keywords in UHIM, (d) Top eight keywords trending over time in UHIM, (e) Bar chart of eight keywords for the top eight productive countries in UHIM.

also tops the list in terms of TC and HI, with 36,615 citations and an H-index of 99, respectively. These metrics reflect the high impact of this keyword on UHIM research and its broad recognition among scholars and practitioners. Given its significance in the field, the urban heat island term is expected to have a profound impact. As anticipated, “Urban Heat Island” emerged as the leading keyword in this investigation. “Land Surface Temperature” (LST) was identified as the second most prevalent keyword in terms of total publications TP=324 (11.1%), total citations TC=36615, and HI =52.

The keyword “Climate Change” ranked third in TP and fifth in TC, underscoring the growing apprehension regarding the influence of urban heat islands on the global climate system. “Green Roof”, ranking fourth in TP and third in TC, attests to the efficacy of this mitigation strategy in alleviating the urban heat island effect. The term “Urban”, ranking fifth in TP and fourth in TC, accentuates the significance of urban planning and design in the management of urban heat islands. “Remote Sensing”, ranking sixth in TP and ninth in TC, underscores the escalating importance of remote sensing techniques in studying and monitoring the urban heat island phenomenon and its impacts on urban environments.

In stark contrast to its significance in comprehending the thermal dynamics of urban landscapes and their interplay with urban heat islands, “Air Temperature” appears at the bottom of keyword list in the literature, accounting for a mere 2.1% of the total publications, amounting to a mere 62 articles (Fig. 3b). One might naturally assume that air temperature, being paramount in unraveling the complexities of urban environments, would find itself perched at the zenith of the keywords list. However, to our bewilderment, it languishes at the bottom of the top 20 keywords enlisted in the articles. Puzzled by this enigma, we hypothesize that the challenges inherent in accurately measuring air temperature in urban settings could be a contributing factor, albeit we remain uncertain as to the precise reasons behind its underrepresentation in the published works.

4.4.2. Keywords used in articles published in different countries

Fig.3c provides an overview of the top eight nations actively involved in UHIM research. China leads the pack, contributing 1,946 keywords to urban heat island research. This substantial contribution reflects China’s rapid urbanization and recognition of the importance of controlling urban heat islands. The country is committed to finding effective solutions to mitigate the negative effects of UHIM on cities, the environment, and public health, as demonstrated by its strong involvement in the sector. The United States is the second most active country in UHIM research, with 1,271 involved terms. This highlights the importance of urban heat island issues in the US and the country’s ongoing efforts to develop innovative solutions and legislation to mitigate UHIM. Italy, Australia, Japan, England, Germany, and Canada also make significant contributions to UHIM research, with involved keyword counts ranging from 325 to 867. These nations recognize the importance of addressing urban heat island issues and actively engage in research, policy development, and technology innovation to reduce their impact.

4.4.3. Top eight keywords over time

The usage trends of the top eight keywords in UHIM from 2010 to 2022 are depicted in Fig. 3d. This visualization provides insights into the evolving research focus over time, highlighting usage patterns for each keyword. Urban Heat Island has consistently remained a popular keyword throughout the years, underscoring its significance as a primary focus of UHIM research. Land Surface Temperature usage has steadily increased, reaching its peak in 2022, signifying growing recognition of its importance in understanding and mitigating UHI impacts. On the other hand, the usage of Climate Change has fluctuated, indicating researchers’ recurrent concerns about UHI effects on the climate system and the need for adaptive solutions. The fluctuating usage patterns of Green Roof as a keyword are notable, with a peak occurrence in 2011, followed by a decline and resurgence in 2018. This suggests continued interest and effectiveness of green roofs as a solution to UHIM, contributing to sustainable urban development. Conversely, using Urban as a keyword has shown variations over time, with 2015 witnessing the highest occurrences. This underscores the importance of urban planning and design in addressing Urban Heat Island challenges and promoting sustainable urban living, possibly reflecting shifts in focus or introducing new concepts in urban planning.

The analysis reveals significant insights into the prominence of various keywords. Remote Sensing was most commonly used in 2011, and its usage has shown an overall upward trend from 2012 to 2022, indicating the growing recognition and importance of remote sensing techniques in Urban Heat Island research. Thermal Comfort’s popularity has fluctuated over time, with its peak in 2012, highlighting its significance in UHI research concerning human well-being in urban areas. Urban Climate has consistently maintained popularity over the years, with a slight increase recently, emphasizing the importance of considering the broader urban climate context in UHIM studies. The enduring usage of this term indicates sustained interest in exploring the urban climate’s role in UHI research.

4.4.4. UHIM-related research keywords across eight nations

An examination of Fig. 3e unveils the distribution of UHIM research keywords across eight nations, namely China, the USA, Italy, Australia, Japan, England, Germany, and Canada, illuminating distinct geographical interests. China stands out with high output in Urban Heat Island (274), Land Surface Temperature (164), and Remote Sensing (41), while the USA’s research prominence is evident in Urban Heat Island (210), Land Surface Temperature (63), and Urban Climatology (20). Italy’s research heavily emphasizes Urban Heat Island (137), mirroring a similar interest shared with Canada. Australia and Japan register major interest in Urban Heat Island, alongside secondary foci on Climate Change (17) and Land Surface Temperature (20). In England, research efforts revolve around Urban Heat Island (48), Land Surface Temperature (13), and Urban Climatology (6).

Germany’s research diversely spans multiple UHIM aspects, whereas Canada’s interest is predominantly confined to Urban Heat Island studies. Parallel research patterns in Italy and Canada underscore their comparability in UHIM research orientations. Country-specific pursuits, such as China’s engagement with Land Surface Temperature, illustrate efforts to decode urban heat island dynamics. Italian and Australian researchers’ commitment to Urban Heat Island and Green Roof studies highlights sustainable UHIM methods such as green roofs, while Germany’s interest in Urban Climate and Climate Change underscores the global impact of urban heat islands, offering insights into their interaction with broader climate systems. Such knowledge has far-reaching implications for policy and urban planning decisions, instrumental in promoting sustainable urban living.

4.5. In-depth application categories analysis and trending

A comprehensive overview of the distribution of 2906 original articles found that on UHIM across eight main categories and their respective subcategories. It shows a diverse range of explored strategies, from nature-based solutions and urban planning strategies to modifications of the built environment and energy efficiency measures. Fig. 4a serves as a visual representation that condenses the application categories and subcategories found in Fig. 4b. This graphical format has been incorporated to provide a more accessible and illustrative presentation. Using Fig. 4, readers can quickly grasp the key elements and relationships between categories and subcategories. Below, each of the eight application categories and its relationship with UHIM has been established.

4.5.1. Vegetation and Shade

The "Vegetation and Shade" category within the context of UHIM encompasses strategies that utilize natural or constructed elements to

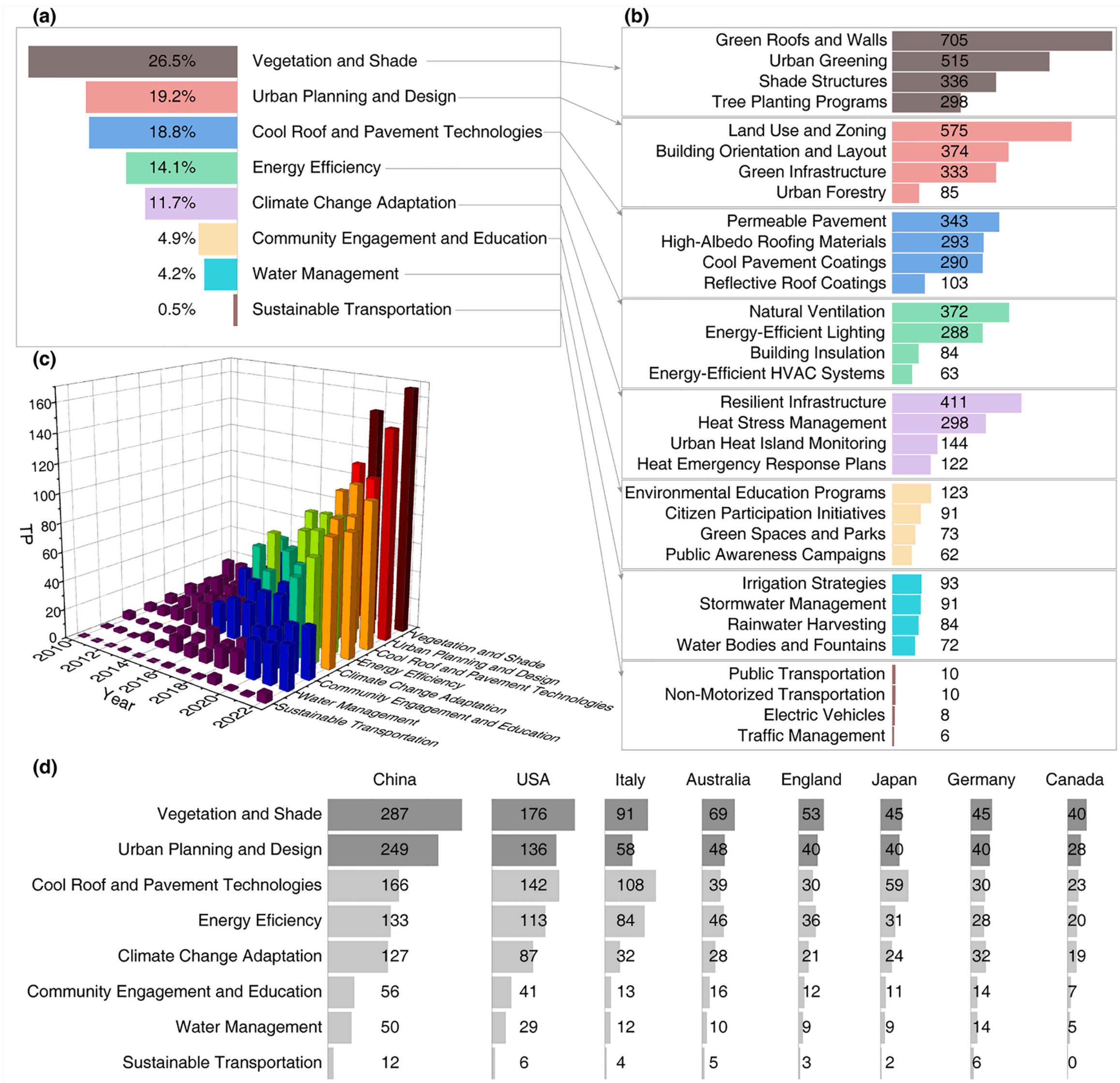

Fig. 4. UHIM-related publication categories analysis and trending. (a) Distribution of published articles, (b) Application categories and subcategories in the UHIM, (c) UHIM application categories trending over time, (d) UHIM-related maps of eight application categories for the top eight productive countries.

provide shade and reduce urban temperatures. Firstly, "Green Roofs and Walls" involve the incorporation of vegetation on building exteriors, either on the rooftop or vertical surfaces. These installations not only absorb sunlight but also insulate buildings, reducing energy consumption and heat radiation. "Urban Greening" is a broader initiative, involving the transformation of urban spaces into green, vegetative areas. This could be through parks, gardens, or even roadside plantations. By increasing green cover, cities can effectively reduce surface temperatures. "Shade Structures" are man-made installations designed specifically to provide shade in public areas, reducing direct sunlight exposure on surfaces. Lastly, "Tree Planting Programs" focus on increasing urban tree cover. Trees, with their broad canopies, provide shade, absorb pollutants, and release moisture, thereby cooling the surrounding environment. Together, these elements play a critical role in mitigating the effects of urban heat islands.

4.5.2. Urban Planning and Design

The "Urban Planning and Design" category in the context of UHIM integrates thoughtful urban layout and architectural strategies to combat rising temperatures in built-up areas. "Land Use and Zoning" refers to regulatory measures that guide the city's distribution of functions and activities. Cities can prevent heat accumulation by allocating specific zones for green spaces or using mixed-use development. "Building Orientation and Layout" pertains to the design and placement of buildings to maximize natural shading and promote airflow, thereby reducing the need for cooling and minimizing heat retention. "Green Infrastructure" introduces eco-friendly components like permeable pavements, rain gardens, and bioswales, which reduce surface heat and manage stormwater. "Urban Forestry" emphasizes the integration of trees within city planning, considering their invaluable role in providing shade, improving air quality, and cooling urban environments. Collectively, these urban planning and design strategies aim to shape resilient and sustainable cities in the face of rising temperatures.

4.5.3. Cool Roof and Pavement Technologies

The "Cool Roof and Pavement Technologies" category, within the broader topic of UHIM, centers on innovative solutions that focus on reducing heat absorption and radiation from urban surfaces, which are often major contributors to elevated temperatures in urban areas. "Permeable Pavement" is a technology that allows water to seep through, aiding in cooling while also managing stormwater runoff. "High-Albedo Roofing Materials" are specially designed to reflect a more significant portion of sunlight, thereby preventing buildings from absorbing excessive heat. Similarly, "Cool Pavement Coatings" are surface treatments that reduce the temperature of pavements by reflecting sunlight and emitting absorbed heat. "Reflective Roof Coatings" are applied to existing roof surfaces, turning them into high-albedo surfaces that reflect more solar radiation. Together, these technologies aim to diminish the heat retention properties of urban materials, offering cooler urban environments and reducing the strain on energy resources used for cooling.

4.5.4. Energy Efficiency

The "Energy Efficiency" category, in the realm of UHIM, addresses the reduction of excess heat produced from buildings and urban infrastructures by optimizing energy use and decreasing waste. "Natural Ventilation" leverages architectural design to facilitate outdoor airflow into buildings, reducing the reliance on mechanical cooling systems and thereby reducing the heat emitted into the environment. "Energy-Efficient Lighting" pertains to lighting systems that consume less power and produce less heat than traditional systems. "Building Insulation" involves materials and techniques that prevent heat transfer between the interior and exterior of structures, ensuring cool interiors in hot conditions and reducing the need for air conditioning. Lastly, "Energy-Efficient HVAC Systems" are designed to provide heating, cooling, and ventilation with minimal energy consumption, emitting less heat into urban spaces. Together, these measures not only mitigate urban heat islands but also significantly reduce energy costs and greenhouse gas emissions.

4.5.5. Climate Change Adaptation

The "Climate Change Adaptation" category, when discussing UHIM, revolves around strategies designed not only to counteract the immediate effects of urban heat islands but also to prepare urban areas for the broader impacts of climate change. "Resilient Infrastructure" refers to constructing and retrofitting urban structures and systems to withstand extreme weather events and rising temperatures. This can include flood defenses, shade structures, and more. "Heat Stress Management" focuses on public health initiatives that aim to reduce heat-related illnesses and fatalities, educating the public on the dangers of extreme heat. "Urban Heat Island Monitoring" involves systematically observing and tracking temperature variations within urban spaces to detect heat hotspots and measure mitigation efforts' effectiveness. Lastly, "Heat Emergency Response Plans" encompass comprehensive strategies that cities enact during heat waves, including opening cooling centers, public information campaigns, and medical responses. Collectively, these efforts aim to safeguard urban populations and infrastructures from the escalating challenges of a warming climate.

4.5.6. Community Engagement and Education

The "Community Engagement and Education" category under UHIM underscores the imperative role of involving citizens and raising awareness about the urban heat island effect and its mitigation measures. "Environmental Education Programs" serve as foundational initiatives to instruct individuals about the science of urban heat, its impacts, and potential solutions, thereby fostering a more informed public. "Citizen Participation Initiatives" actively involve residents in mitigation activities, such as tree planting or community garden establishment, instilling a sense of ownership and hands-on contribution to urban cooling efforts. "Green Spaces and Parks" not only provide direct cooling effects but also serve as tactile, educational sites where community members can experience the benefits of urban greening firsthand. "Public Awareness Campaigns" utilize various media to disseminate crucial information, tips, and calls to action regarding urban heat mitigation. Together, these strategies aim to cultivate a proactive community, recognizing that collective action is key to addressing the challenges of urban heat islands.

4.5.7. Water Management

The "Water Management" category, in the context of UHIM, highlights the importance of water as both a cooling agent and a valuable resource in urban settings. "Irrigation Strategies" involve the deliberate application of water to landscapes, aiding in vegetation health, which in turn cools surrounding areas through shade and evapotranspiration. "Stormwater Management" pertains to the controlled collection and utilization or safe disposal of rainwater runoff, preventing urban flooding while also facilitating the use of this water for cooling and greening purposes. "Rainwater Harvesting" captures, stores, and reuses rainwater, reducing the demand for municipal supplies and allowing for localized cooling through landscape irrigation. "Water Bodies and Fountains" play a dual role; they not only serve as aesthetic features but also introduce cooling through water evaporation, creating microclimates that can significantly lower surrounding temperatures. These water-centric strategies collectively aim to optimize urban water use for resource conservation and heat mitigation.

4.5.8. Sustainable Transportation

The "Sustainable Transportation" category within UHIM emphasizes the role of transportation choices and systems in reducing the heat generated from urban mobility. "Public Transportation" focuses on buses, trams, and metros, reducing the number of individual vehicles on roads thereby cutting down heat emissions and pollutants. "Non-Motorized Transportation" encompasses modes such as cycling and walking, which produce zero emissions, help in decongesting cities, and reduce the heat generated by vehicle engines and road friction. "Electric Vehicles (EVs)" are a game-changer as they produce minimal heat and no exhaust emissions compared to their gasoline counterparts. Their increased adoption can significantly reduce urban heat contributions from transportation. "Traffic Management" strategies aim to optimize traffic flow, reducing congestion and idling vehicles, diminishing the heat and pollutants released. Collectively, these sustainable transportation measures not only counteract the heat but also promote a cleaner, more efficient urban mobility paradigm.

4.5.9. Distribution of published articles

Fig. 4a provides a comprehensive overview of the distribution of articles across the primary categories of UHIM research, expressed as a percentage of the total number of articles. It offers valuable insights into the relative emphasis placed on each category within the UHIM literature. Notably, the "Vegetation and Shade" category takes precedence, comprising 26.5% of the articles. This substantial percentage suggests a significant focus on nature-based solutions, encompassing green roofs and walls, urban greening, shade structures, and tree planting programs. Such strategies are deemed vital in mitigating urban heat islands, given their myriad benefits, including cooling effects, biodiversity enhancement, improved air quality, and aesthetic value.

Following closely, "Urban Planning and Design" and "Cool Roof and Pavement Technologies" each account for 19.2% and 18.8% of the articles, respectively. These categories center on the built environment and its potential for modification or design to alleviate urban heat. The notable representation of these areas underscores their pivotal role as key strategies in UHIM research. Subsequently, "Energy Efficiency" represents 14.1% of the articles, highlighting a significant interest in reducing energy consumption and enhancing the energy performance of buildings as a means to combat urban heat islands. This category incorporates strategies like natural ventilation, energy-efficient lighting, building insulation, and energy-efficient HVAC systems.

A distinct focus on "Climate Change Adaptation" is evident, constituting 11.7% of the articles. This reflects an increasing acknowledgment of the necessity to adapt to climate change impacts, including those related to urban heat islands. Strategies such as resilient infrastructure, heat stress management, urban heat island monitoring, and heat emergency response plans fall within this category. Conversely, "Community Engagement and Education" and "Water Management' represent smaller portions, comprising 4.9% and 4.2% of the articles, respectively. While these areas are recognized as important in UHIM research, they may be less directly tied to urban heat mitigation than the other categories or perhaps more context-specific and less universally applicable. Lastly, "Sustainable Transportation" exhibits the smallest percentage of articles, standing at 0.5%. This relatively lower representation suggests that this area is currently less explored in UHIM research, possibly indicating a gap in the literature and an opportunity for further investigation.

4.5.10. Application categories and subcategories in the UHIM

Fig. 4b lists the subcategories within each of the eight primary fields of UHIM research, and certain patterns become evident. Notably, the "Vegetation and Shade" category encapsulates Green Roofs and Walls, Urban Greening, Shade Structures, and Tree Planting Programs, each showcasing nature's potential as a tool for urban heat mitigation. The Green Roofs and Walls subcategory alone accounts for 705 publications, pointing to its dual role in not just mitigating urban heat but also enriching urban biodiversity and aesthetics. Similarly, the "Urban Planning and Design" category, comprising Land Use and Zoning, Building Orientation and Layout, Green Infrastructure, and Urban Forestry, holds an impressive publication record, with the Land Use and Zoning subcategory leading at 575 publications. Such research concentration suggests a keen academic focus on the interplay between urban planning and urban heat islands.

In the "Cool Roof and Pavement Technologies" category, with 343 publications, Permeable Pavement illustrates a growing fascination with sustainable urban drainage systems. Here, permeable pavements become twofold tools, managing stormwater and reducing urban heat. The "Energy Efficiency" category, encompassing Natural Ventilation, Energy-Efficient Lighting, Building Insulation, and Energy-Efficient HVAC Systems, also displays considerable research activity, with Natural Ventilation leading with 372 publications, denoting the importance of passive cooling strategies in buildings. Concurrently, the "Climate Change Adaptation" category, housing Resilient Infrastructure, Heat Stress Management, Urban Heat Island Monitoring, and Heat Emergency Response Plans, spotlights Resilient Infrastructure boasts 411 publications, highlighting a shift towards urban resilience in climate change scenarios.

Moreover, the "Community Engagement and Education", "Water Management", and "Sustainable Transportation" categories, despite having fewer publications overall, each illuminates a key subcategory: Environmental Education Programs (123 articles) for community engagement, Irrigation Strategies (93 articles) for water management, and Public Transportation and Non-Motorized Transportation (10 articles each) for sustainable transportation. Although not as prolific as the other categories, these nonetheless represent growing facets of UHIM research. Interestingly, the total sum of publications across subcategories exceeds the overall publication count, underlining UHIM's inherently interdisciplinary research domain. This suggests the need for a holistic approach, marrying diverse strategies to yield effective UHIM. Furthermore, the lesser-researched categories, such as Sustainable Transportation, might signify untapped research potentials, begging for further exploration.

4.5.11. UHIM application categories trending over time

Our analysis, illustrated by Fig. 4c, provides a detailed, year-by-year overview of the volume of published works within the eight fields of UHIM research, encompassing the decade 2010 to 2022. This timeframe was selected as earlier data were less comprehensive. The data underscore an indisputable expansion of UHIM literature, showcasing the dynamic ebb and flow of research interest across the eight domains over this period. Strikingly, each category has witnessed a significant increase in publications throughout these twelve years, reflecting the escalating recognition of UHIM's significance.

Diving into specific fields, "Vegetation and Shade" consistently emerges as the forerunner, registering the highest yearly tally of publications, escalating from a modest 16 in 2010 to a notable 167 by 2022. This strong trend accentuates the continuing relevance of nature-based solutions in UHIM research and the diversification of explored strategies. It mirrors a greater appreciation for nature's role in mitigating urban heat islands and growing interest in ecologically sustainable countermeasures. Concurrently, the "Urban Planning and Design" category has seen a significant upward shift in the publication count, surging from a mere 7 in 2010 to an impressive 144 in 2022, underscoring the mounting interest in urban planning's role in mitigating urban heat islands.

An equally robust increase in publication count is observed in the "Cool Roof and Pavement Technologies" category, signaling a burgeoning interest in techniques that limit heat absorption by roofs and pavements, known contributors to urban heat islands. "Energy Efficiency" and "Climate Change Adaptation" have followed suit, demonstrating considerable growth in research interest. However, the "Community Engagement and Education", "Water Management", and "Sustainable Transportation" still lag in publication volume. Despite this, they have shown an uptrend, hinting at a gradually growing recognition in UHIM research. These observations offer an intriguing glimpse into the rapidly evolving landscape of UHIM research. By observing how the focus on application categories has evolved over time, a researcher can gain insights into emerging areas of interest, historical shifts, and potential future directions in UHI studies. This knowledge is invaluable for any UHI researcher aiming to align their work with global trends, identify gaps in current research, or collaborate internationally.

4.5.12. UHIM-related application categories for the top productive countries

Fig. 4d offers a comprehensive breakdown of the number of publications across eight categories of UHIM research for the top eight productive countries: China, the USA, Italy, Australia, Japan, England, Germany, and Canada. This detailed analysis provides a nuanced understanding of the specific focus areas within UHIM research for each of these nations.

China emerges as the frontrunner in terms of the total number of publications across all categories, reflecting its substantial investment in UHIM research. The category with the most publications in China is "Vegetation and Shade" with 286 articles, followed closely by "Urban Planning and Design" with 246 articles. This suggests that nature-based solutions and urban planning strategies are key focus areas in China's UHIM research. The USA also demonstrates a significant number of publications across all categories, with the most publications in "Vegetation and Shade" (174 articles) and "Cool Roof and Pavement Technologies" (142 articles). This indicates a robust interest in both nature-based solutions and technological modifications to the built environment within the USA's UHIM research.

While having fewer publications than China and the USA, Italy, Australia, Japan, England, Germany, and Canada also exhibit diverse interests across the categories. "Vegetation and Shade" emerges as the most popular category in all countries, reflecting global interest in nature-based solutions for UHIM. However, Italy and Japan stand out with a distinct focus on "Cool Roof and Pavement Technologies", underscoring their commitment to exploring and advancing technologies that modify the built environment for heat mitigation. "Urban Planning and Design" and "Cool Roof and Pavement Technologies" also emerge as popular categories in most countries, indicating a widespread recognition of the role of the built environment in UHIM.

As illustrated in Fig. 4, the present study offers a comprehensive overview of the UHIM landscape, specifically highlighting the contribution of various countries to different application categories. This allows researchers in the UHI domain to discern which countries are at the forefront of specific application categories, providing a clearer picture of global research trends and leadership.

4.6. Research focuses on high-cited papers

Table 5 showcases a selection of highly cited publications, each

Table 5
Publications that have received at least 500 citations

Ref.	Title	PY	TC
(Akbari et al., 2001)	"Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas"	2001	985
(Santamouris, 2014)	"Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments"	2014	923
(Li et al., 2011)	"Impacts of landscape structure on surface urban heat islands: A case study of Shanghai, China"	2011	664
(Peng et al., 2012)	"Surface Urban Heat Island Across 419 Global Big Cities"	2012	654
(Zhao et al., 2014)	"Strong contributions of local background climate to urban heat islands"	2014	647
(Harlan et al., 2006)	"Neighborhood microclimates and vulnerability to heat stress"	2006	614
(Santamouris et al., 2011)	"Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions"	2011	572
(Zhou et al., 2011)	"Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes"	2011	559
(Estoque et al., 2017)	"Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia"	2017	525
(Norton et al., 2015)	"Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes"	2015	524
(Ng et al., 2012)	"A study on the cooling effects of greening in a high-density city: An experience from Hong Kong"	2012	518
(Shashua-Bar & Hoffman, 2000)	"Vegetation as a climatic component in the design of an urban street - An empirical model for predicting the cooling effect of urban green areas with trees"	2000	500

having amassed at least 500 citations. These influential works span diverse domains, encompassing techniques (Akbari et al., 2001; Peng et al., 2012; Santamouris, 2014; Santamouris et al., 2011), landscape influences (Estoque et al., 2017; Li et al., 2011; Zhou et al., 2011), local climate and microclimate effects (Harlan et al., 2006; Zhao et al., 2014), and green infrastructure for urban cooling (Ng et al., 2012; Norton et al., 2015; Shashua-Bar & Hoffman, 2000). The remarkable citation records underscore the growing momentum and significance of UHIM techniques recently.

Central to UHIM endeavors is the commitment to mitigate the adverse impacts of urban heat islands. This pursuit entails a profound comprehension of their dynamics and the exploration of various mitigation strategies such as cool surfaces, shade trees, reflective materials, and green roofs. These measures aim to enhance air quality, curtail energy consumption, and elevate thermal comfort within urban landscapes.

The landscape influences on urban heat islands are of particular interest, where investigations delve into the intricate interplay between landscape structure, composition, and spatial configuration and their ramifications on urban heat patterns. In-depth analyses illuminate how distinct land cover patterns, landscape composition, and structural factors contribute to fluctuations in land surface temperature within urban areas.

The vital role of local climate and microclimate in shaping UHI precedes the scientific discourse. Researchers devote their efforts to exploring the influence of local background climate while delving into the intricacies of neighborhood microclimates and their vulnerability to heat stress. Such endeavors hold the potential to inform adaptive strategies for mitigating the detrimental consequences of urban heat.

As the pursuit of urban cooling strategies gains momentum, the spotlight shines on green infrastructure. Pioneering papers propose frameworks prioritizing green infrastructure interventions and investigating the cooling effects of vegetation, greening, and urban green spaces within high-density urban settings and street design. These insights carry profound implications for urban planning and sustainable urban development practices.

5. Conclusions

This comprehensive analysis of 2906 original articles on UHIM reveals eight major research categories. "Vegetation and Shade" leads with the highest number of publications, emphasizing the importance of nature-based solutions in urban heat reduction. "Urban Planning and Design" and "Cool Roof and Pavement Technologies" also have a significant number of publications, indicating a substantial research interest in these areas. However, "Community Engagement and Education," "Water Management," and "Sustainable Transportation" have fewer publications, suggesting potential areas for further research.

The study shows an increasing trend in UHIM-related publications from 2010 to 2022 across all categories. The most significant growth was observed in "Vegetation and Shade," "Urban Planning and Design," and "Cool Roof and Pavement Technologies." The top five journals publishing UHIM research are Sustainable Cities and Society, Building and Environment, Energy and Buildings, Sustainability, and Urban Climate.

The study also highlights the multidisciplinary nature of UHIM research, with Environmental Sciences & Ecology, Engineering, Construction & Building Technology, and Energy & Fuels being the top Web of Science subject areas. The analysis provides a comprehensive view of the various application categories for mitigating urban heat islands and could guide future research in the field.

Declaration of Competing Interest

The authors clarify that there is no conflict of interest for report.

Data availability

The data has been uploaded to the Mendeley data storage (Elsevier) at: https://dx.doi.org/10.17632/mwvf5vdj8b.1.

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Appendix A. Raw data sourced from WoS

Fig. A1 offers a glimpse into a sample of the raw data extracted from WoS, specifically relating to a segment of a record pertaining to UHIM. To transform this raw data into meaningful and statistically relevant reports, a custom Python code was developed. The Python code plays a pivotal role in extracting pertinent information from the raw data and processing it. However, it is noted that certain stages of the analysis require manual intervention and screening. Initially, filters are applied to the data based on specific criteria, such as publication types and years. Subsequently, the code organizes the data into a dictionary of various items, including keywords, institutes, countries, journal names, and more. Furthermore, evaluation indexes are computed for each item. These indexes serve as a basis for ranking the items and calculating connectivity matrices. Nevertheless, it is worth mentioning that inconsistencies in text format and author affiliations necessitate manual corrections at times. Similarly, standardizing abbreviations and resolving similar keywords often require human intervention. Furthermore, certain analyses, such as determining the type of UHIMs, cannot be automated and necessitate direct human analysis.

Title: The use of iron oxide in asphalt mixtures to reduce the effects of urban heat islands

Author(s): Porto, TR (Porto, Tassila Ramos); Lucena, AEDL (Lucena, Adriano Elisio de Figueiredo Lopes); Moraes, TMRPD (Moraes, Thalita Maria Ramos Porto de); Neto, ODM (Neto, Osires de Medeiros Melo); Costa, DB (Costa, Daniel Beserra); Carvalho, FDD (Carvalho, Flavia do Socorro de Sousa); Torres, PRB (Torres, Paulo Roberto Barreto)

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Abstract: Aiming to ensure greater well-being of the population, the aim is to mitigate the accumulation of heat in urban centers, which is intensified by the phenomenon known as Urban Heat Island (ICU), which is characterized by the increase in urban temperatures in comparison to rural areas, due to the dark color and the low reflectivity of the paved surfaces. To minimize such an impact, it is suggested to use materials that absorb less heat. This explains, the choice for incorporating iron oxide in asphalt mixtures, in red and yellow pigments, with the purpose of increasing the asphalt reflectivity and consequently reducing heat absorption. To meet these objectives, the following steps were taken: first, mechanical characterization of the mixtures with the incorporation of iron oxide (red and yellow pigment), to verify the resistance of these mixtures after the addition of the pigment, and second, to verify whether the addition of pigments significantly reduces tempera-ture and increases the reflectivity of the surface. The results indicated the technical feasibility of incorporating iron oxide into the mixture, allowing to increase in the useful life of these mixtures. Comparing conventional and colored mixtures, there was a reduction in the surface temperature of the coatings and an increase in solar reflectivity.

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Author Keywords: Asphalt mixtures; Urban heat island; Iron oxide; Mechanical characterization; Pavement coloring

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Fig. A1. Showcasing a sample of raw data sourced from WoS. The image displayed represents a portion of a single record's data, offering a glimpse into the nature of the information contained within WoS.

Appendix B. Analyzing scientometrics data

Analyzing scientometrics data from WoS involves several steps that enable researchers to gain insights into publication trends, author affiliations, and application categories. This process can be divided into six main steps: reading and cleaning data, extracting and filtering data, organizing data, processing data, conducting category analysis, and reporting data with visual representations. Fig. B1 shows a visual representation of these steps.

The first step is to read and clean the data obtained from WoS. This involves opening the raw data files, which typically come in structured formats, and reading the header tags to understand the organization of the data. The text data is then imported, and if multiple data files are available, they are merged to create a formatted raw data file. The next crucial task is inspecting and cleaning the raw data. This step involves identifying and correcting any mistakes, addressing missing data, and handling outliers that may affect the analysis.

Once the data is cleaned, the second step focuses on extracting the desired information and applying relevant filters. Items such as authors' names, affiliations, countries, titles, and publication years are extracted from the dataset. This data extraction process allows researchers to work with specific variables of interest. Filters are then applied to refine the dataset further, such as selecting specific publication types or limiting the dataset to a particular range of publication years. This step ensures that the analysis is focused on relevant data.

In the third step, the extracted and filtered data is organized for further analysis. A dictionary is created for each item, representing a publication or research record. This allows for convenient storage and retrieval of information associated with each item. Additionally, a rank table is generated based on important order criteria, such as the number of authors, countries, or institutions involved. This rank table provides valuable insights into the prominence and influence of authors, institutions, and countries within the dataset. Furthermore, keywords extracted from the dataset are transformed to their root format, facilitating better analysis and categorization.

With the data organized, the fourth step involves processing the data to uncover relationships and patterns. Cross-referencing is performed between the dictionaries of different items, establishing connections and links between related publications. This process helps identify collaborations, citations, and common themes within the dataset. Additionally, a connectivity matrix is created, visualizing the relationships between the item dictionaries and providing a comprehensive overview of the network of connections within the dataset.

The fifth step focuses on category analysis. Researchers determine application categories based on the content and focus of the publications. By categorizing publications into specific application categories, researchers can gain a deeper understanding of the research landscape within a particular field. This categorization aids in identifying emerging trends, prominent areas of research, and the distribution of publications across different application domains.

Finally, in the sixth step, the analyzed data is reported with appropriate visual representations. This includes reporting table data, presenting relevant information and statistics in a structured format. Supplementary materials, such as additional datasets or supporting documentation, may be included to provide further context or details. Moreover, graphical representations, such as charts or plots, are created to visually depict patterns, trends, or relationships within the analyzed data. These visualizations facilitate easier comprehension and enhance the communication of research findings.

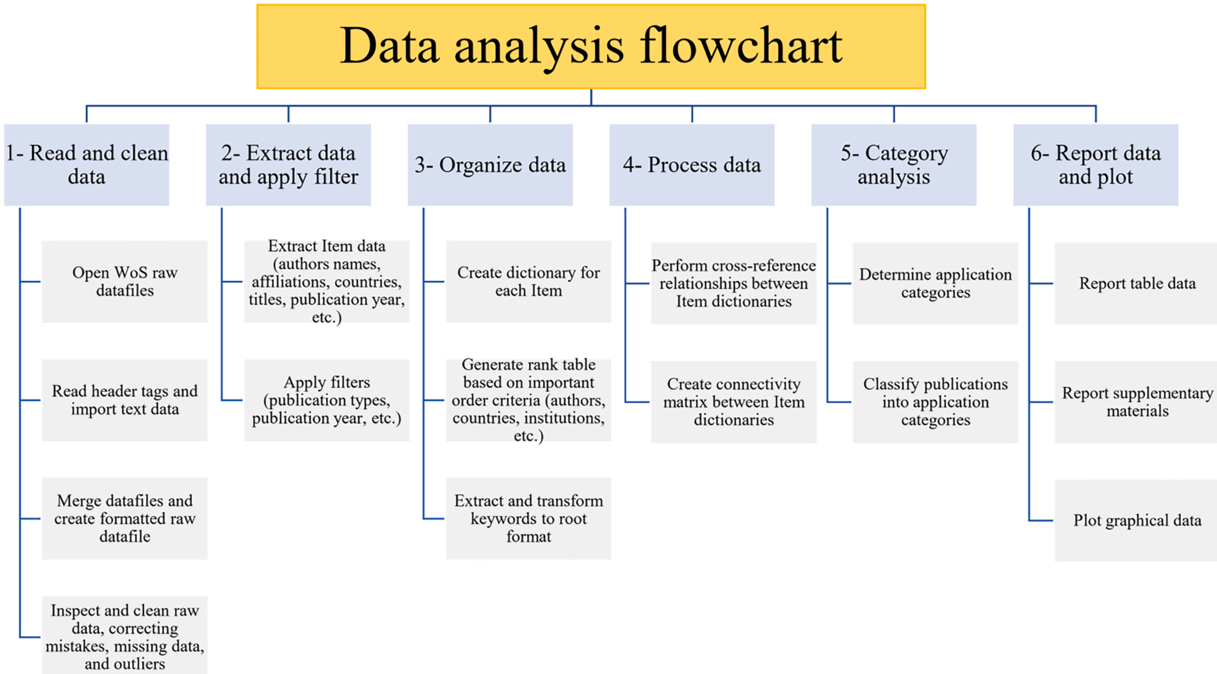

Fig. B1. A visual representation of steps involved in process of data

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