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Review

A Bibliometric Review of Nature-Based Solutions on Urban Stormwater Management

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Abstract: Urban stormwater management is a critical challenge facing cities globally, with natural-based solutions (NBS) emerging as a promising approach for mitigating the impacts of urban stormwater runoff. This bibliometric review examined the research trends and hot topics related to NBS for urban stormwater management. The study utilized a combination of qualitative and quantitative methods to analyze 176 articles from the Web of Science database, covering the period from 2016 to 2022. Results showed that NBS is a widely researched topic with a growing trend in publications in recent years, led by the United States, China, and several European countries. The majority of NBS articles were research papers (82%) with a focus on environmental performance rather than social and economic dimensions. Quantitative methods were more frequently used in research articles, particularly statistical analysis/modeling. Interviews and discussions were the most common qualitative method used. The review identified the most relevant countries, affiliations, authors, and journals in the field. Furthermore, hot topics in NBS research were highlighted, including ecosystem services, climate change, and sustainability. The study also emphasized that future research perspective should focus on interdisciplinary and collaborative research, scaling up and mainstreaming NBS, and exploring new ways of integrating different disciplines and stakeholders in the research process. The findings of this review provided insights into the current state of NBS research and offer valuable information for researchers, policymakers, and practitioners in the field of urban stormwater management.

Keywords: nature-based solution; urban stormwater management; bibliometric; VOSviewer; urban flooding; green infrastructure

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1. Introduction

Urban flooding is a critical issue caused by heavy rainfall intensities over a brief period of time in a small area, resulting in significant surface runoff and flooding, which harms human well-being and damages local economies [1]. The vulnerability of urban areas to pluvial floods is increasing due to the high percentage of impervious surfaces, flat land cover, and low-lying regions [2,3]. As rainfall events are becoming more frequent due to global climate change, cities must enhance their resilience and capacity to deal with urban flood hazards [4,5].

Urban stormwater management (USM) is a growing area of concern due to the impacts of climate change, over-urbanization, faulty urban planning, and weak public awareness of environmental protection. The concept of Nature-Based Solutions (NBS) has emerged as a means of addressing climate change adaptation and mitigation while promoting policy objectives such as ecosystem-based adaptation, ecosystem services, and low-impact

development [6]. According to Maes and Jacobs [7], NBS refers to "any transition to a use of ecosystem services with decreased input of non-renewable natural capital and increased investment in renewable natural processes". Bertilsson et al. [8] distinguish NBS from conventional engineering approaches by highlighting their multifunctionality, contribution to the stock of natural capital, and ability to increase the resilience of landscapes. The effectiveness of NBS in flood mitigation depends on the scale of implementation and their hybrid combination with grey infrastructure [9]. To enhance the resilience of urban areas and reduce the impacts of flooding, it is important to test the impacts of NBS and grey infrastructure combinations in different scales [10]. NBS can provide a means of addressing climate change and disaster risk reduction while conserving biodiversity and promoting a green economy [11]. Policymakers have adopted NBS as an innovative means of promoting economic development and human well-being [12,13], and NBS has been incorporated into the European Commission's Horizon 2020 Framework Programme [14]. Integrating NBS measures into USM can enhance urban resilience in the face of flooding and other hazards.

To date, several review studies have evaluated NBS for effectively managing urban stormwater from different perspectives. For instance, Keeler et al. [15] integrated a framework comprising social, ecological and technological factors to identify efficient NBS, while Venkataramanan et al. [16] systematically reviewed green infrastructure for flood management using four criteria (knowledge, attitude, intention to implement and behaviour) for adopting new solutions. However, comprehensive reviews using bibliometric approaches in this domain remain scarce. Bibliometrics, a subset of scientometrics, is widely applied for quantitative assessments in various research fields, and bibliometric reviews can provide valuable insights into the landscape of a specific research area.

Hence, this paper aims to offer a systematic and bibliometric literature review of NBS for USM. Previous bibliometric reviews, such as those by Liu et al. [17] on green roofs and Caparrós-Martínez et al. [18] on green infrastructure, have demonstrated the value of this approach in identifying research trends and "hot topics." By combining a traditional overview with bibliometric analysis, our review facilitates a better understanding of the NBS research structure and future trends.

To further examine NBS research on USM, this study employs bibliometrics to provide a quantitative analysis. The objectives of this paper are to (1) analyze the status and development trends in NBS; (2) illustrate qualitative and quantitative approaches to NBS; (3) summarize scientific bibliometric statistics on NBS for urban stormwater runoff management; and (4) suggest future directions for applying existing research. Overall, this review seeks to elaborate on the current development of NBS from multiple perspectives and provide recommendations and strategies for NBS implementation. This review could be valuable to a wide range of stakeholders, including urban planners, policymakers, researchers, and practitioners working in the fields of sustainable urban development, water management, and environmental engineering.

2. Materials and Methods

2.1. Data Source

In the field of bibliometric studies, both Web of Science (WoS) and Scopus are commonly used databases, each having its own advantages and limitations. WoS is recognized for its rigorous selection process, which ensures the inclusion of high-quality and impactful research publications from well-established, peer-reviewed journals. Moreover, the WoS database provides a comprehensive coverage of the Citation Index, an essential component for conducting a reliable bibliometric analysis [19]. On the other hand, although Scopus is known for its extensive database, it may include a wider range of sources, which may not always meet the same stringent quality criteria as that of WoS [20]. In the context of this review focusing on NBS for USM, the choice of the WoS database was made to prioritize the inclusion of research publications from high-quality, peer-reviewed journals in the field of environmental science and sustainability. This decision was guided by the objective of ensuring a robust and reliable analysis of the research landscape in this domain.

The literature search was conducted in January 2023 using keywords and Boolean operators in the "Topic" (TS) area of the WoS database. The authors opted for this approach because the TS area search encompasses not only the titles, abstracts, and author keywords but also additional indexed keywords and terms within the full record of each publication. By searching in the TS area, the authors were able to include a wider range of relevant publications, ensuring a more comprehensive and thorough analysis of the research landscape in NBS for USM. The search strings were the following: TS = ("urban flood*" OR "stormwater manage" OR "urban hydrology") AND TS = ("nature-based solution") AND TS = ("green infrastructure" OR "blue infrastructure" OR "nature infrastructure" OR "ecosystem-based management" OR "ecosystem-based mitigation" OR "ecosystem-based adaptation" OR "ecosystem disaster risks reduction" OR "low impact development"). The decision to employ "stormwater manage" in the search query aimed to concentrate on articles emphasizing the management aspect of stormwater. This choice refines the scope of the analysis, ensuring that only articles specifically addressing stormwater management through NBS are captured. Utilizing "stormwater manage*" might result in a broader pool of articles but could also introduce noise by including publications that only peripherally address management or lack primary focus on it. Regarding the last part of the query (AND TS = (green (...))), this was included to concentrate specifically on NBS for stormwater management. This portion of the query ensured that only articles focusing on NBS (e.g., green infrastructure, green roofs) were considered in this review. It is important to acknowledge that some potentially relevant terms may have been overlooked, and certain pertinent papers might have been missed.

A total of 195 raw journal articles were retrieved, from 2015 to 2022, and articles classified as research papers and reviews were considered. The authors manually removed irrelevant, unavailable and non-English files. For example, an article on urban heat mitigation was excluded because it did not fit our research area. Unavailable articles were those not accessible due to copyright restrictions or unavailability through our institutional subscriptions. After manual removal, the final result set consisted of 176 papers. Although there were only a few publications on the integration of NBS and USM before 2018, the authors still included all relevant publications to provide sufficient background for our analysis. Figure 1 outlines the literature search process.

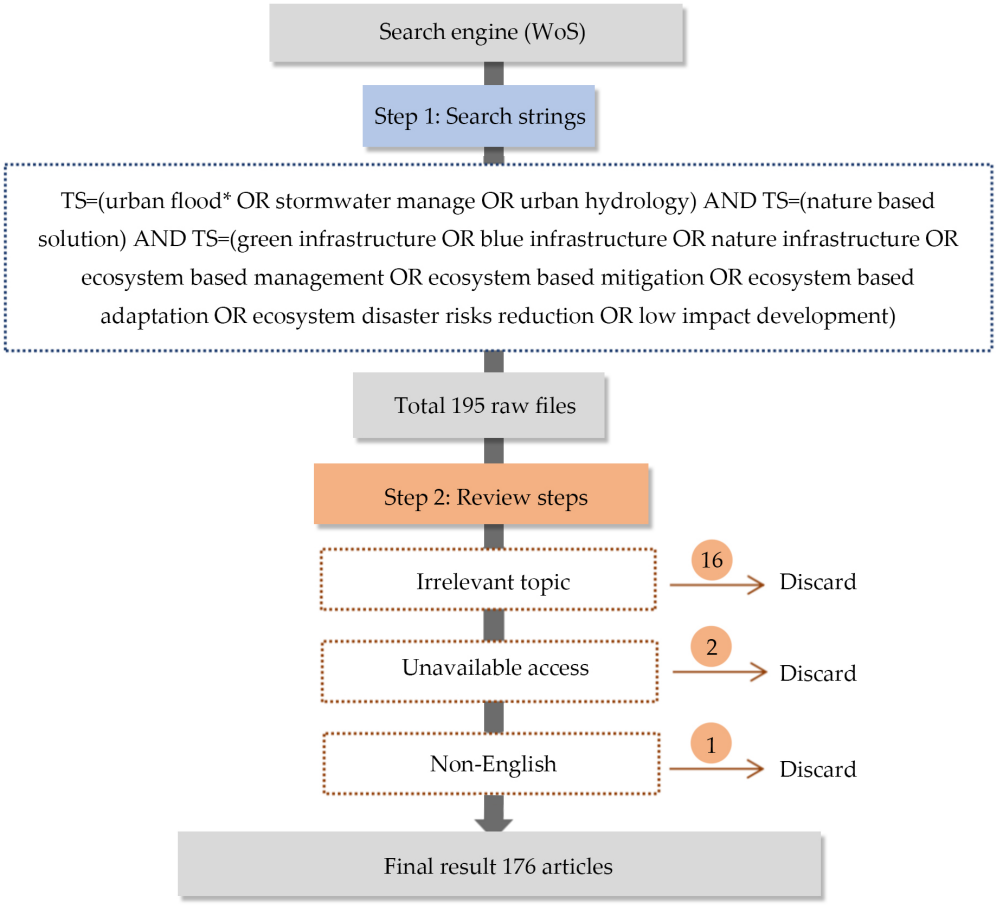


Figure 1. The literature search procedure for final results of total articles. Note: The asterisk (*) serves as a wildcard, which can be used to replace one or more characters, thereby broadening the search scope.

2.2. Qualitative/Quantitative Classification

To obtain more specific information about the research papers, the authors further subdivided them into more specific subgroups based on primarily qualitative and quantitative methodologies which were based on more detailed research approaches (Figure 2). The classifications and subsequent analysis were conducted using Microsoft Excel. The primarily qualitative subgroup (QLT) consists of 7 criteria (i.e., Descriptive case study, Participatory planning, Interview/discussion, Stakeholder engagements, Observations, Questionnaire survey/field survey, and Frame/toolkit/definition/guide), while the quantitative subgroup (QNT) comprises a total of 8 criteria (i.e., Spatial analysis/mapping, Scenario simulation, Cost analysis/benefits, Performance/evaluation, Statistical analysis/modeling, Multi-Criteria Analysis (MCA), Experiments, and Environmental sampling) [21]. For those articles in which multiple methods were used, the authors only identify the most prominent ones [22].

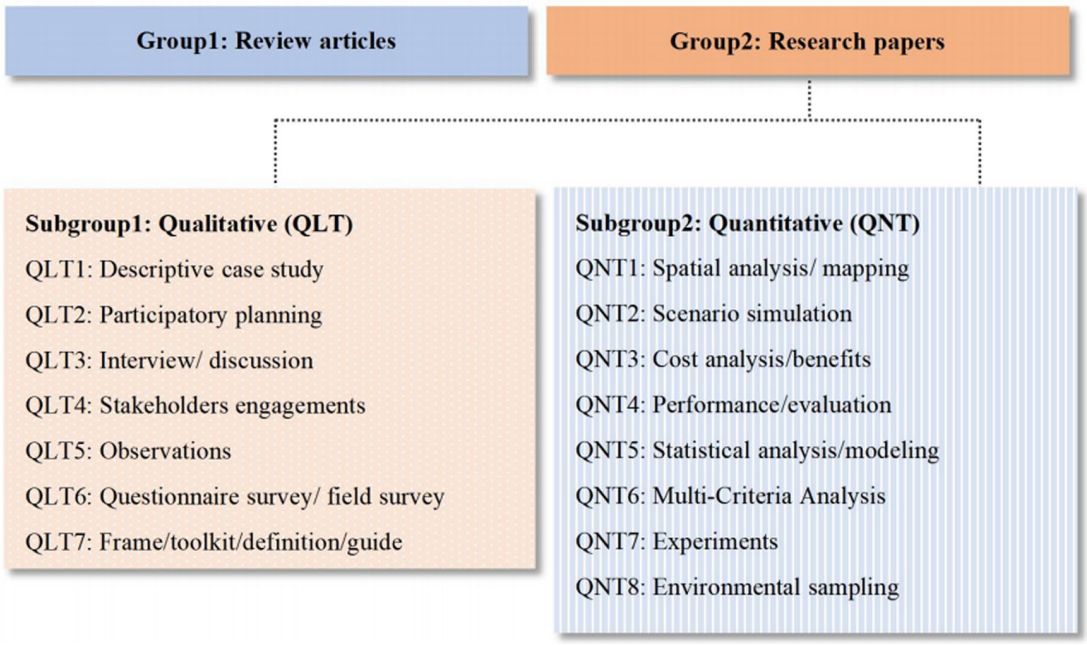


Figure 2. The classification of groups.

2.3. Biblometric Analysis

Bibliometric analysis involves a range of mathematical and statistical methods for analyzing bibliometric data [23]. In this review, the authors employed the "bibliometrix" R package and VOSviewer software for bibliometric analysis to explore the interrelationships among co-citation data and provide an overview of the current research topic. Both tools have been widely used in different disciplines for similar purposes. For instance, Chen et al. [24] utilized VOSviewer to map the research landscape and visualize collaboration networks in their study. Likewise, bibliometrix software has been employed by Aria and Cuccurullo [25] and Aksnes et al. [26] to analyze publication trends, citation patterns, and research themes in their respective fields. This review has identified and mapped the most relevant countries and organizations, affiliations, authors, sources and hot topics using the "bibliometrix" R package. The authors used VOSviewer to carry out clustering analysis. All source files used in this review were in ".txt" format, which is commonly used across multiple software platforms.

The "bibliometrix" package is a free open-source tool based on the R language for performing bibliometric analysis of papers [27]. The authors processed the details of each document using different mathematical functions implemented in R 4.2.1 (http://www.R-project.org, accessed on 20 January 2022) to improve keyword selection and identify future research trends. The raw materials were downloaded by the search strings, which contained document information such as year, number, types, authors, citations, etc. All data were computed and evaluated using "bibliometrix" version 4.0.2 (https://github.com/shivam11/bibliometrix/find/master (accessed on 20 January 2022)). The authors obtained results on the most relevant countries and organizations, affiliations, authors, sources and trend topics from R.

VOSviewer is a tool designed to help to create and visualize bibliometric maps [20]. The authors used it to obtain clustering maps that aid the analysis of the interrelationships between subject themes to understand how NBS (and related concepts such as green infrastructures, low impact development, etc.) and USM are linked. The authors used the free java-based software VOSviewer v.1.6.18 (https://www.vosviewer.com/download (accessed on 20 January 2022)) to extract keywords from the text for clear visualization. It can effectively organize information in the literature, identify similarities between selected parameters, and emphasize important themes among those parameters. Network

clustering analysis of keywords allows closely related words to be aggregated and grouped together graphically to form a cluster network. In the clustering map, the size of each circle represents the weight of each keyword, and the distance between two circles represents the affinity between them. If the affinity is stronger, the distance will be shorter, and if the affinity is weaker, the distance will be farther. The colors of the circles represent the respective cluster classes. The co-occurrence algorithm is used to count multiple information in the literature. This approach was chosen because of the challenges of manually handling the mapping of large numbers of articles in traditional literature reviews. Co-occurrence analysis is widely used as a useful knowledge mapping tool in theoretical and empirical research because of its ability to map the conceptual and thematic structure of a domain, representative of the cumulative knowledge of the target literature.

3. Results and Discussion

A bibliometric analysis of NBS research in urban stormwater mitigation between 2016 and 2022 was conducted using the Web of Science (WoS) database. Through comparative studies on the number of papers published by different countries, affiliations, authors, and sources, a comprehensive picture of the NBS research in terms of stormwater mitigation was obtained. Figure 3 reveals the relationship of annual publication and annual cumulative publication. The bibliometric analysis shows that from 2016 to 2022, 176 articles were published relative to NBS and USM research. During the growth process, the number of articles was low in the early years and gradually increased over time. The number of publications per year indicates an incredible and exponential increase after 2020. Although the number of publications per year was less than 15 before 2018, the value reached 62 in 2022. This finding implies a consistently growing research interest in this field, and there have been multiple factors contributing to the development of NBS in USM. In addition, the data were only collected until January 2023, so the line trend in Figure 3 has declined in year of 2023. Table 1 shows some main information generated by "bibliometrix" R. The 176 documents originate from 83 resources, with an annual growth rate of 45.53%. The document average age was 2.52, while the average citations per document was 18.69. As for author collaboration, only seven articles have a single author. The co-author number per document was 5.13, while the international co-authorship percentage was 43.75%.

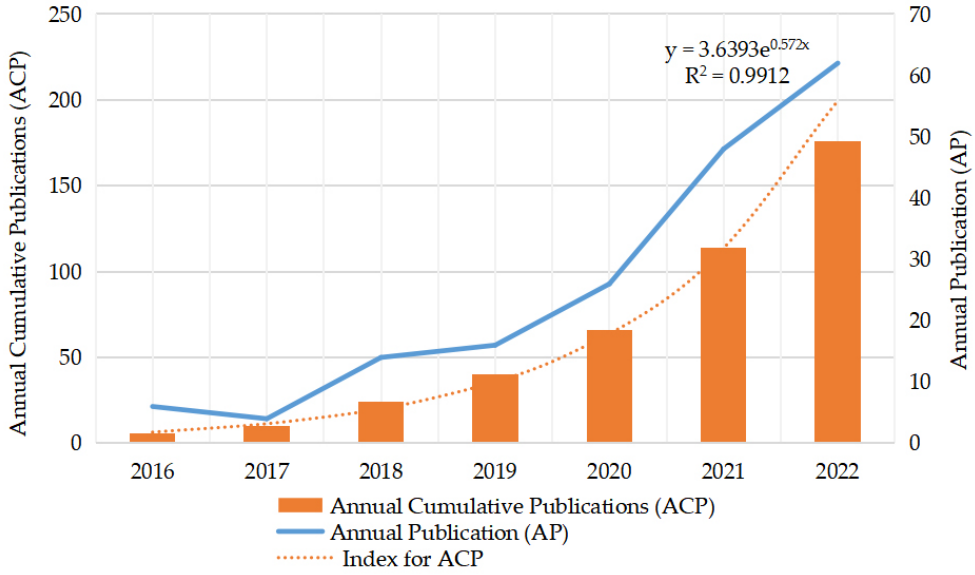


Figure 3. Annual publication and annual cumulative publication.

Table 1. Main information generated by "bibliometrix" R.

Description		Results
Main information about data	Timespan	2016:2022
	Sources (Journals, Books, etc.)	83
	Documents	176
	Annual Growth Rate %	45.53
	Document Average Age	2.52
	Average citations per doc	18.69
	References	10,207
Document contents	Keywords Plus (ID)	505
	Author's Keywords (DE)	607
Authors	Authors	778
Author collaboration	Single-authored docs	7
	Co-Authors per Doc	5.13
	International co-authorships %	43.75

3.1. Concepts and Terminologies

This study investigated the typologies of Nature-Based Solutions (NBS) used in the literature. NBS is a complex and multi-dimensional concept that encompasses a wide range of strategies and techniques to address environmental and social challenges [28]. There is a variety of terminologies associated with NBS which can sometimes cause confusion and inconsistencies in the research [29–31]. Therefore, the authors also included articles that used general definitions similar to NBS, such as green space, parks, urban forests, green roofs, green walls, memorial parking trees, and green swales, among others. Additionally, there are specific definitions related to terms such as UGI (Urban Green Infrastructure), EbA (Ecosystem-based Adaptation), ESS (Ecosystem Services), LID (Low-Impact Development), SUDS (Sustainable Urban Drainage Systems), water sensitive urban design, WSUD (Water Sensitive Urban Design), and BMPs (Best Management Practices), which are frequently used by authors in different research areas [32–35].

Several scholars have already conducted research on NBS from various perspectives. Hanson et al. [36] reviewed the core concepts and boundaries of NBS and determined that flood mitigation is the most commonly addressed topic. Similarly, Kumar et al. [37] advanced the research on the modelling approach of NBS, stating that studies related to NBS have experienced an exponential increase after 2010. Among these studies, 64% of the research focuses on models and tools to enhance the effectiveness of NBS against hydro-meteorological risks, while 18% of them focus on floods, which are the largest component. All of the above studies indicate that the application of NBS in USM will become increasingly important due to its flexible and dynamic nature.

NBS is undoubtedly an advanced and important method in urban flood management, as also confirmed by Ruangpan et al. [38]. In their study, most of the literature to date has focused on NBS in urban areas, and 82% of the articles deal with reducing runoff or mitigating flood risks in urban areas. However, it is worth noting that NBS can also be applied in rural and peri-urban areas, as well as in coastal and marine environments, to address various environmental and social challenges [39]. Future research should explore the potential of NBS in these contexts and identify the most effective strategies to enhance their sustainability and resilience.

The diversity of NBS terminologies and the multiplicity of research perspectives underscore the need for a comprehensive and integrated approach to NBS research and practice. Future research should aim to develop a common understanding of the key concepts and principles of NBS and provide a clear and coherent framework for their application [40]. This will not only help to advance the science and practice of NBS but also support the development of innovative and effective solutions to environmental and social challenges in different contexts.

3.2. Qualitative and Quantitative Research

The analysis of the methodologies used in the literature indicates that a majority of the articles (82%) were research papers, while 18% were review papers, as shown in Figure 4a. In terms of review articles, most of the researchers detected the gap in NBS studies, that is lack of attention on economic and social components. Hanson et al. [36] reviewed 112 scientific peer-reviewed papers that use the term of NBS. They detected a gap which consisted in the fact that most empirical studies focused solely on environmental performance without the social and economic dimensions. Brink et al. [41] carried out an ecosystem-based adaptation (EbA is a concept under NBS umbrella) review of 110 article sources and obtained the same survey result, namely that there are seldom valuations under social and economic aspects. This was also confirmed by Choi et al. [42]; therefore, they further reviewed the evidence of trade-offs and co-benefits of applying NBS.

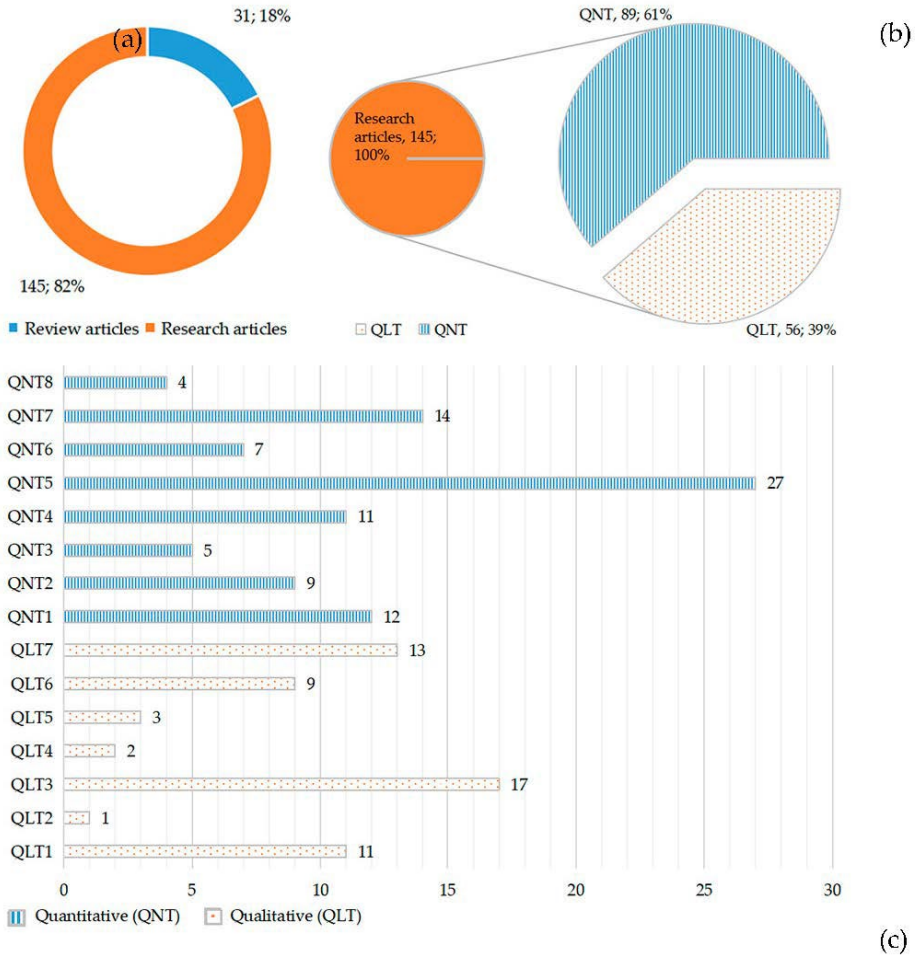


Figure 4. Overview of the systematic literature review. (**a**) Review and research papers; (**b**) distribution of general approaches; and (**c**) number of documents employing each method.

Among the research articles, 39% were primarily qualitative (QLT) papers and 61% were primarily quantitative (QNT) papers, as shown in Figure 4b. Figure 4c provides a detailed breakdown of the specific QLT and QNT methods used in the literature. Regarding QNT approaches, statistical analysis/modeling (QNT5) was the most frequently used method, with 27 articles using this approach. This suggests that researchers relied heavily on quantitative data analysis to support their research findings. Experiments (QNT7) was the second most commonly used QNT method, with 14 articles using this approach. Spatial analysis/mapping (QNT1) and performance/evaluation (QNT4) were used at 12 and 11 articles each. The popularity of quantitative methods may be due to the fact that

quantitative methods with evidence for measurable criteria are considered more convincing than qualitative methods. However, quantitative researches lack resources from large-scale research to interpret the data [43]. Therefore, in the near future, quantitative studies involving multiple criteria should be carried out to cover many elements of NBS at different urban scales, locations and distributions. This will require additional data collection, but will lead to a more comprehensive understanding of the research area.

It is worth noting that the most frequently used QLT method was interview/discussion (QLT3) with 17 publications, which suggests that researchers relied heavily on interviews and discussions to gather qualitative data. The second most common QLT method was frame/toolkit/definition/guide (QLT7) with 13 publications, which may indicate that researchers used pre-existing frameworks or tools to guide their qualitative research. Descriptive case study (QLT1) was the third most commonly used QLT method, and questionnaire survey/field survey (QLT6) was the fourth. There are few articles that focus on the participation of stakeholders (QLT4), although they may play an important role in sustainable urban development. Naserisafavi et al. [44] conducted a community value survey under NBS scenario, which reminded urban designers in future research they may feasibly gain help from decision-makers to improve user benefits. Participatory design (QLT2) and observation (QLT5) are two other interesting and scarce methods that the authors determined in the review.

3.3. Bibliometric Analysis

This section presents detailed descriptions of the information words that were counted, including the most relevant countries and organizations, the most relevant affiliations, the most relevant authors, and the most relevant sources.

3.3.1. Most Relevant Countries and Their Collaboration

The analysis of the countries or organizations that produced the NBS and USM literature revealed that the United States was the top producer with 23 published articles, followed by Italy and the United Kingdom with 19 each, China with 17, and the Netherlands with 15 (Figure 5a). This finding may suggest that these countries have invested more in research in the field of NBS and USM, or have greater awareness of these topics. In contrast, there were only a few case studies from Oceanian and African countries, indicating that more research is needed in these regions.

China, the only developing country among the top five, had the highest number of co-authors from other countries, highlighting the importance of international collaborations in developing research capacity and improving the quality of research in developing countries (Figure 5b). In Asia, China leads NBS research, particularly in the area of sponge cities, a popular and hot research topic [45]. In South Asia, there have also been studies conducted in Ayutthaya (Thailand), an area that experiences urban flooding frequently [46–48]. It is crucial to note that lower publishing rates in developing nations do not necessarily indicate a lack of research ability or motivation, as these countries confront similar urbanization challenges as the rest of the world. Additionally, top producer countries may be more severely impacted by climate change and rapid urbanization, prompting increased research investment in nature-based solutions to address these pressing challenges [49]. Researchers in these locations may be less likely to publish in journals indexed by WoS, and may also speak languages other than English. Therefore, constraints on research capacity and dissemination must be considered when developing recommendations for improving research in these areas.

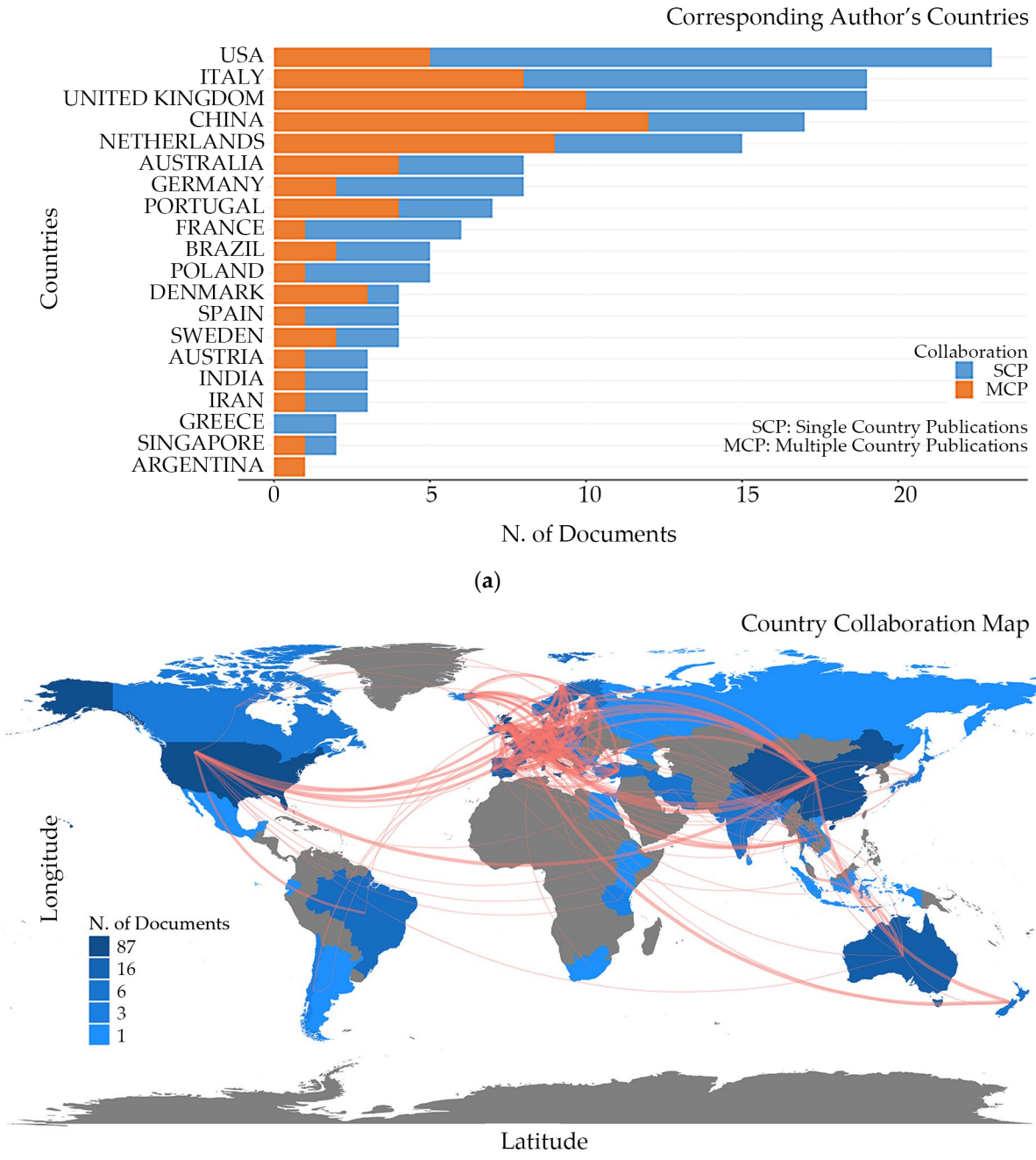


Figure 5. (**a**) The corresponding authors' countries, and (**b**) the country collaboration world map.

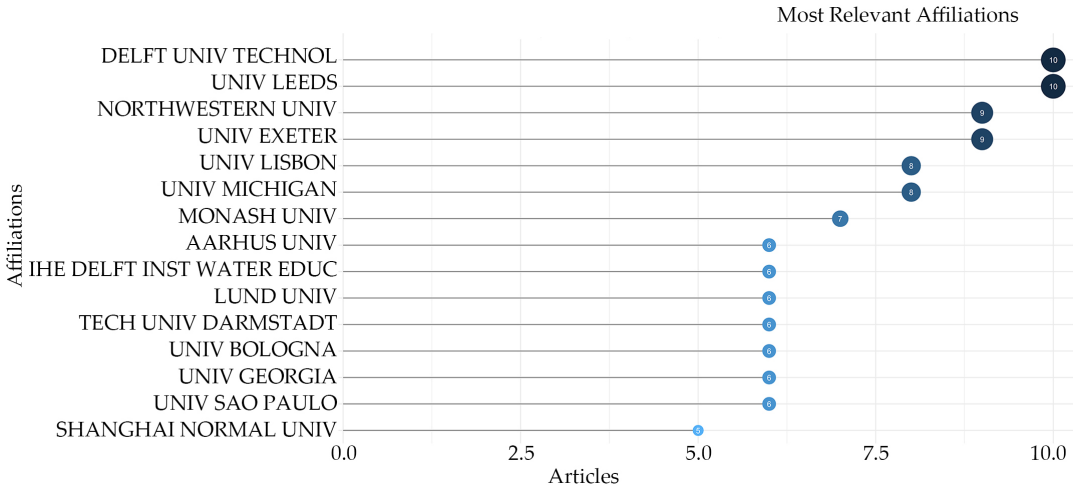
International collaboration is essential to further the field of NBS and USM. The study demonstrated that most collaboration in the NBS field is primarily concentrated in Europe, which is reasonable due to the region's early development of the NBS concept and its strong commitment to climate change mitigation and adaptation. However, it is essential to highlight that the lack of collaboration between countries, particularly less-developed countries, could have negative consequences on their ability to effectively address the challenges of urbanization and climate change impacts. Developing countries must cooperate with developed countries to enhance their research capacity and improve their understanding of NBS and USM. Based on Figure 5b, it is noteworthy that although the United States is one of the top countries in terms of published articles on the topic, only 24 items have a corresponding author from the country. This emphasizes significant

international collaboration between the USA and other countries on NBS. Such enhanced collaboration can lead to more innovative and effective solutions, benefiting not only the USA, but also other countries facing similar challenges. Therefore, it is crucial to establish broad cooperation networks, knowledge-sharing platforms, and capacity-building initiatives among countries to realize the potential of NBS and USM in addressing global urbanization and climate change challenges.

3.3.2. Most Relevant Affiliations, Authors, and Sources

(1) Affiliations

The analysis of scientific bibliometrics is essential to gain insight into the influence and potential collaborators of institutions in a particular field. Figure 6a displays the top 15 affiliations in the field of NBS and USM, which can aid researchers in identifying important institutions for potential collaboration. It is worth noting that the leading institutions are located in developed countries, with Delft University of Technology and the University of Leeds, both from European countries, at the top with 10 articles each. The presence of universities from developed countries in the top affiliations list is not unexpected given their historical and ongoing efforts in scientific research. Northwestern University from the USA and the University of Exeter from the UK are also among the top-ranked affiliations, with nine articles each. Next, Universidade de Lisboa in Portugal and University of Michigan in USA both have eight articles each. It is worth noting that the majority of the top-ranked institutions were from the USA and European countries, which indicates their dominance in the field of NBS and USM. Among the top 15 affiliations, there is an institution from developing country, it is Shanghai Normal University. This once again verified China's determination to implement the NBS. While this is not necessarily problematic, it is crucial to foster collaboration with researchers from less developed countries to improve their research capacity and strengthen their research in the field. Interestingly, although Italy ranks as the second top producer of research papers on nature-based solutions, no Italian university or research institution appears in the most relevant affiliations shown in Figure 6. This could be attributed to a more diverse and dispersed research landscape in Italy, with multiple institutions contributing to the overall research output without any single institution dominating the field. It is also possible that Italian researchers are collaborating with international institutions, resulting in a higher number of co-authored publications with affiliations outside of Italy. This finding highlights the importance of examining not only the top producer countries but also the distribution of research output within countries to fully understand the research landscape in the field of NBS and USM.



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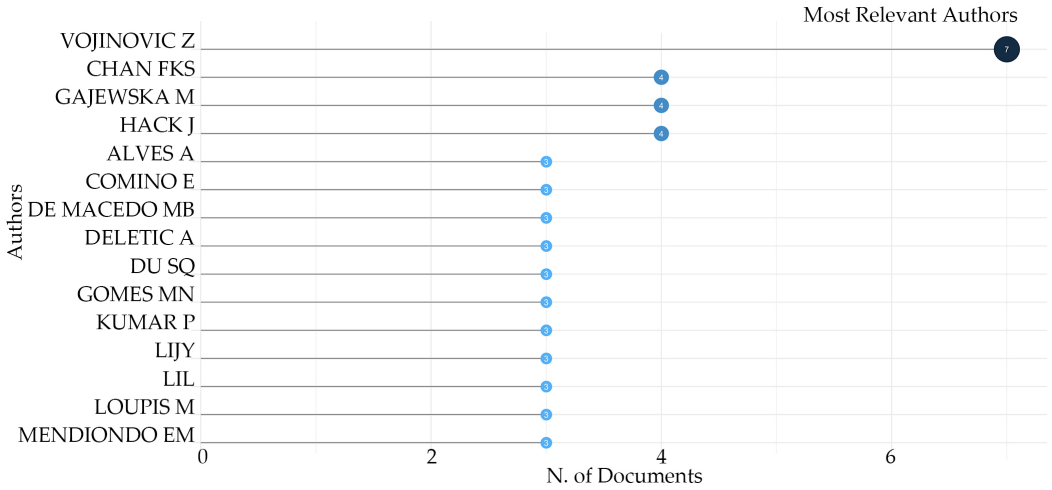

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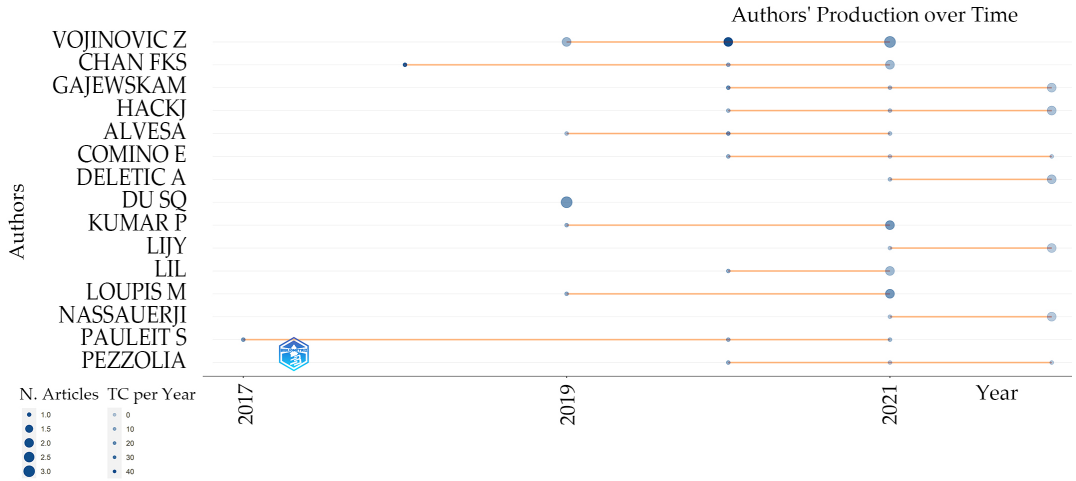


(**c**)

Figure 6. (**a**) The most relevant affiliations, (**b**) the most relevant authors, and (**c**) authors' production over time.

(2) Authors

The analysis of influential authors in the field of NBS and USM provides important insights into the researchers who are leading the way in this area. As shown in Figure 6b, Vojinovic Z is the most productive author with seven papers, indicating his significant contributions to the field. Other authors who have made notable contributions include Chan FKS, Gajewska M, and Hack J, with four papers each. The annual evolution of published research in this field (Figure 6c) shows that Pauletis S was among the first to delve into this area of research in 2017, with a focus on urban catchment. However, after 2020, more and more researchers have shown their interest and conducted research on NBS and USM, indicating a growing trend in the application of NBS in metropolitan areas.

The use of the 'bibliometrix' R package to analyze fractionalized frequency (FF) is a novel statistical approach that provides a more precise reflection of an author's contribution to the field (Table 2). Table 2 shows the articles fractionalized index above 1.0. Among the 11 most productive authors, Hack J exhibits the highest FF at 1.42, followed by Aerts JCJH at 1.14 and Vojinovic Z at 1.05, indicating their significant impact on the field. This information could be useful for readers who want to select pertinent scholarly papers for further study. The analysis of influential authors in the field of NBS and USM highlights the need for greater collaboration and capacity-building initiatives, as well as the potential for further research in this area.

Table 2. Most frequently cited local authors.

Authors	Articles	Articles Fractionalized
HACK J	4	1.42
AERTS JCJH	2	1.14
VOJINOVIC Z	7	1.05
LI JY	3	1.03
NASSAUER JI	3	1.03
BULDAKOVA E	1	1.00
GEAREY M	1	1.00
KALUARACHCHI Y	1	1.00
LEHMANN S	1	1.00
MEEROW S	1	1.00
STEFANAKIS AI	1	1.00

Figure 7 presents a three-field plot relating countries, authors, and keywords. The maximum number for each field was set to 20, resulting in a figure showing the relationship among 18 countries, 20 authors, and 15 keywords. The most frequently occurring keywords were "nature-based solutions" and "green infrastructures." Furthermore, European countries, especially the UK and Italy, demonstrated numerous connections.

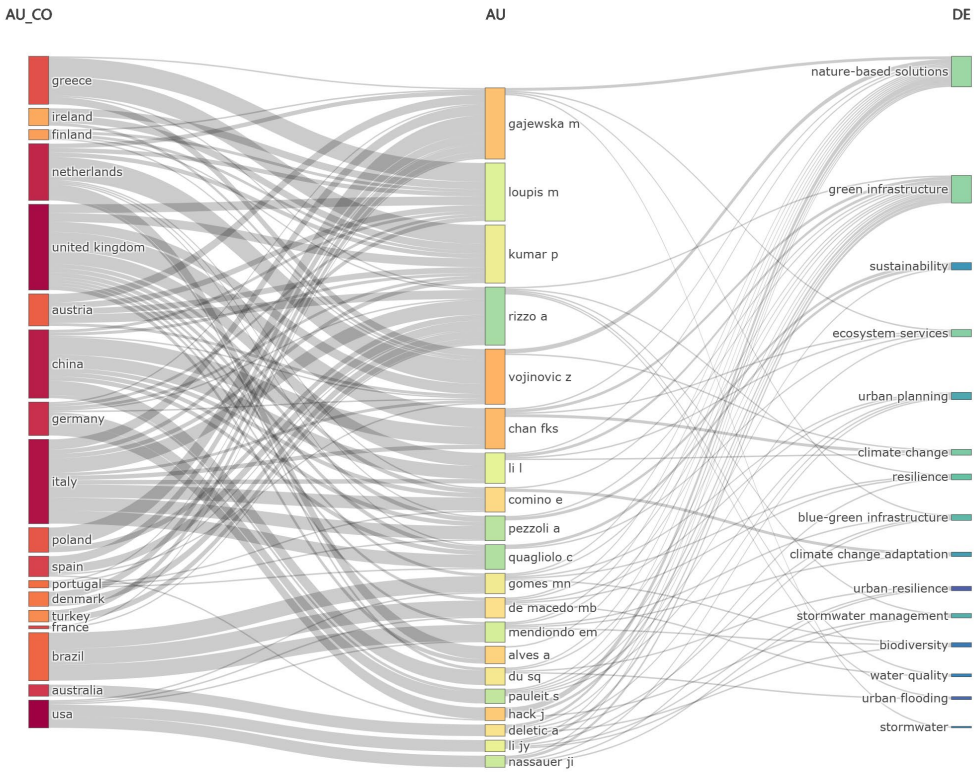


Figure 7. The three-field plot between countries, authors, and keywords.

(3) Sources

The analysis of source journals is an important aspect of bibliometric research. In this study, the authors used the Web of Science database to identify the top 15 journals in the field of NBS and USM, ranked by the number of documents published (Figure 8a). The journal *Sustainability* leads the list with 20 articles published, which highlights the journal's significance in this field. *Journal of Environmental Management* follows closely behind with 12 articles published, also indicating its importance in the field. *Urban Forestry and Urban Greening* has published 10 articles while *Science of the Total Environment* and *Water* both have 8 articles published, suggesting their growing significance in this field. Interestingly, half of the journals are from Europe, which further reinforces the strong research emphasis on NBS in Europe. The authors also identified the most highly cited sources in the Web of Science database (Figure 8b), with *Landscape and Urban Planning* having the highest number of citations at 369 articles. This finding further confirms the importance of NBS in urban hydrological management, with this journal serving as a key outlet for publishing research in this field. The high number of citations for *Science of the Total Environment*, *Water*, and *Journal of Environmental Management* also highlights the importance of these journals in the field of NBS and USM. This analysis of source journals and their citations provides valuable insights into the importance of specific outlets for publishing research in the field of NBS and USM. Researchers in this field may use this information to prioritize publishing their work in high-impact journals and to identify potential collaborators and research trends.

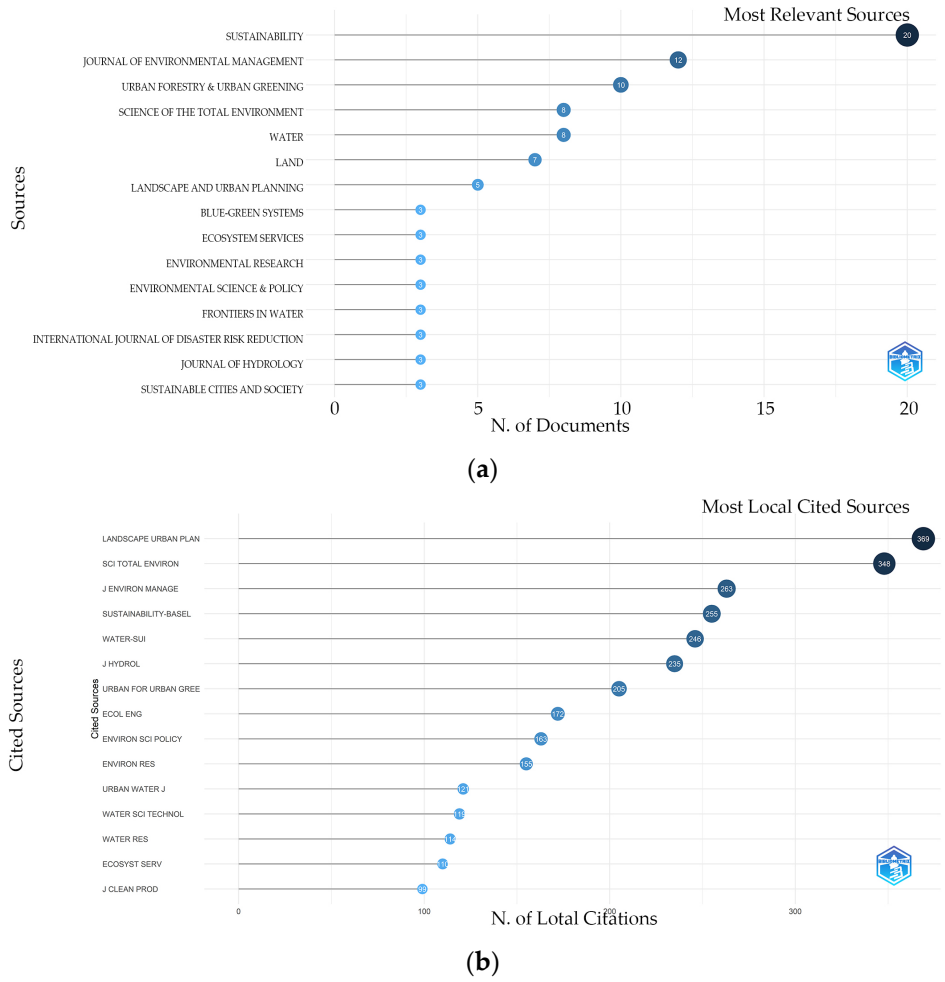


Figure 8. (**a**) The most relevant sources and (**b**) most locally cited sources.

3.3.3. Hot Topics

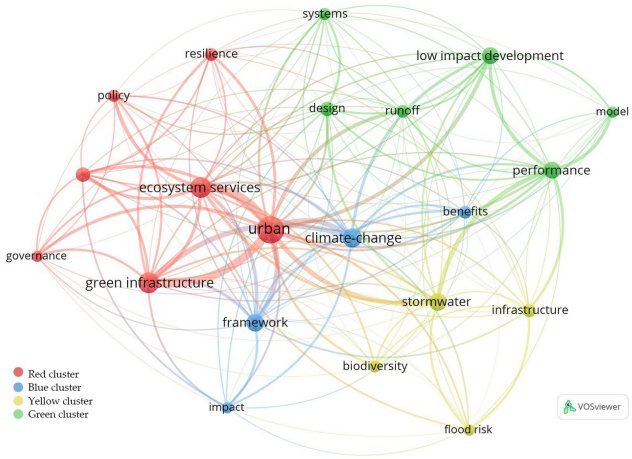
The co-occurrence and clustering analysis using VOSviewer software provide an insightful way to identify research direction and trends within a field. The keyword "co-occurrence map" incorporates both author keywords and keywords plus, with a minimum occurrence threshold set to 11. The total strength of co-occurrence links between the 22 keywords was calculated (Table 3), illustrating that researchers mainly focus on integrating NBS with ecosystem services, climate change, and sustainability (Figure 9a). The overlay timeline of occurrences is depicted in Figure 9b.

Table 3. Main parameters of the top keywords (ranked by the total link strength) in the co-occurrence network.

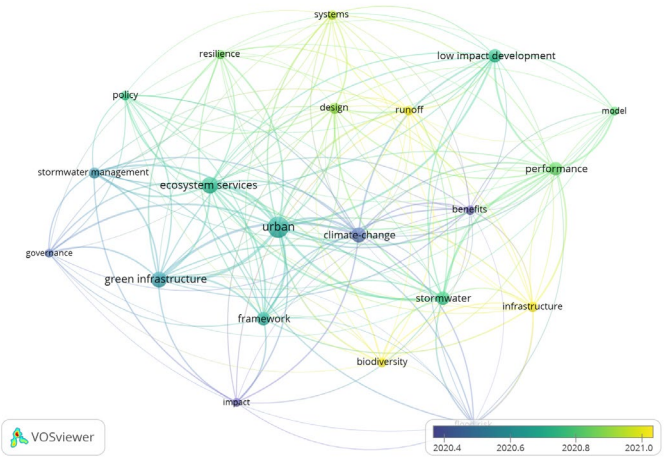
Keyword	Occurrences	Total Link Strength
Urban	59	55
Ecosystem services	35	35
Green infrastructure	34	34
Management	35	33
Climate change	29	26
Framework	25	24

Table 3. *Cont.*

Keyword	Occurrences	Total Link Strength
Stormwater	25	24
Low impact development	23	23
Performance	23	23
Stormwater management	17	17
Design	17	15
Infrastructure	14	13
Runoff	13	13
Benefits	13	12
Resilience	13	12
Systems	12	12
Governance	11	11
Policy	12	11
Impact	11	11
Flood risk	11	10
Biodiversity	12	10
Benefits	11	10



(**a**)



(**b**)

Figure 9. (**a**) The cluster map and (**b**) overlay timeline map of co-occurrence keywords.

In Figure 9a, four distinct clusters are revealed, each representing a particular thematic focus within the research area. Cluster 1 (red) includes keywords such as "urban", "ecosys-

tem services", "green infrastructure", "governance", "policy", and "resilience". This cluster emphasizes the importance of considering the urban context and the role of green infrastructure in providing ecosystem services, enhancing resilience, and supporting sustainable urban development [50]. The presence of governance and policy keywords indicates a strong emphasis on the regulatory and institutional aspects of implementing and managing NBS in urban areas. Cluster 2 encompasses keywords such as "low impact development", "design", "runoff", "systems", "benefits", "performance", and "model". This cluster focuses on the technical aspects of NBS, specifically low impact development strategies, and their effectiveness in managing stormwater runoff. It also suggests that researchers are interested in understanding the benefits, performance, and design aspects of these solutions, as well as in developing models to assess and optimize their implementation [51]. Cluster 3 consists of keywords such as "climate change", "framework", and "impact". This cluster reflects the growing recognition of the role NBS play in mitigating and adapting to climate change impacts in urban areas. The presence of the keyword "framework" suggests that researchers are working on developing comprehensive and integrated approaches to assess and implement NBS within the context of climate change [52]. Cluster 4 contains keywords such as "stormwater", "infrastructure", "biodiversity", and "flood risk". This cluster highlights the primary focus of NBS on USM and flood risk reduction [53], as well as the co-benefits they offer in terms of preserving and enhancing urban biodiversity. The co-occurrence of these keywords underscores the multifunctionality of NBS and their potential to address multiple urban challenges simultaneously.

When the authors clustered the co-occurrence of keywords, "urban" was shown in the chart with the biggest red circle. This indicates that current research on NBS is focused on urban areas. The keyword "urban" also has a strong link with "climate change", "ecosystem services", and "green infrastructure", which are the main terms related to NBS. These three words could be considered as research topics that were not directly addressed by our search but were used for the literature review [54–56].

One of the key benefits of NBS is their potential to enhance biodiversity and promote the sustainable management of ecosystems. Biodiversity is essential for human well-being, as it provides many ecosystem services such as air and water purification, soil fertility, pollination, and pest control, which are crucial for the sustainability of urban agricultural, food security and hydrological cycle [57]. Biodiversity is also crucial for the resilience of ecosystems and their ability to adapt to changing conditions [58]. NBS can provide a range of benefits for biodiversity, such as restoring degraded ecosystems, protecting and enhancing habitats for species, and promoting the sustainable use of natural resources [59]. For example, green infrastructure, such as urban green spaces, can provide habitats for birds and insects while also providing a range of other benefits for people such as recreation, relaxation, and improved air quality. It is important to note that biodiversity is not just a co-benefit of NBS, but a fundamental aspect of the concept. IUCN defined NBS as actions that "protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [60]. Therefore, any NBS that does not consider biodiversity as a core element risk being incomplete and less effective in achieving its intended goals.

3.4. Future Research Perspectives

3.4.1. Insights into Potential Future Hot Topics in NBS Research Based on Trends in Research Topics

The trends in research topics can provide insights into potential future hot topics based on the frequency of words in the current year. The authors also combined synonyms as in the previous section on cluster maps. Figure 10 reveals that in 2018, "restoration" was the primary objective of NBS, with a term frequency of eight. "Vegetation" was another term that appeared in the same year and has continued to be an important focus, indicating the significance of plants and trees in controlling USM. The continued emphasis on vegetation and trees in urban areas suggests a potential focus on understanding the specific benefits

and mechanisms of different types of plants for managing stormwater, mitigating heat island effects, and enhancing biodiversity. Future research could explore the ways in which different types of vegetation can be used to achieve specific urban resilience goals, and how different factors such as soil quality, species diversity, and urban design affect the effectiveness of vegetation-based strategies.

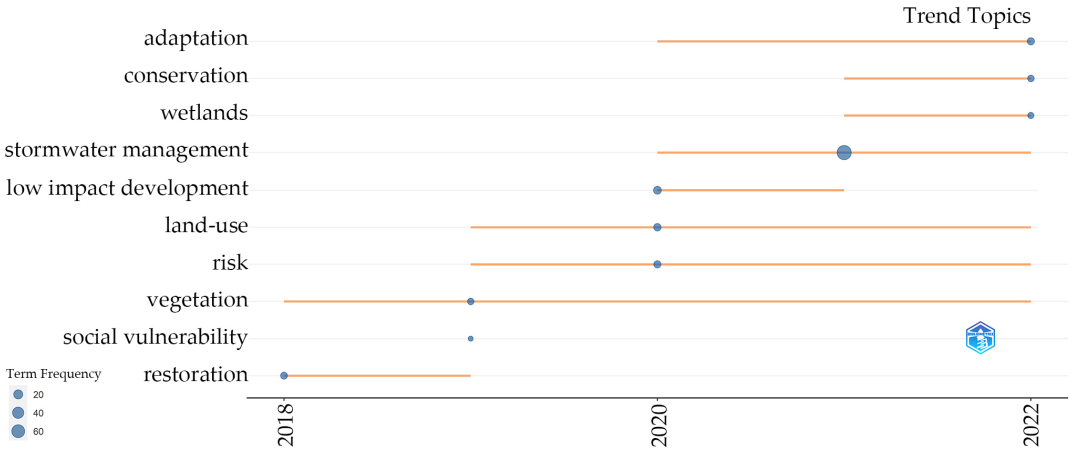


Figure 10. The trend topics.

In 2019, some researchers studied the topic of "social vulnerability" with a term frequency of five, but there has not been a noticeable frequency since then. The relatively low frequency of the keyword "social vulnerability" suggests a need for more research on how NBS can be used to address social equity issues related to urban flood risks. Understanding the ways in which vulnerable populations are disproportionately affected by urban flooding and how NBS can be used to mitigate these impacts will be an important area of future research. In the same year, the keywords "risk" and "land-use" were studied and have continued to be researched. The continued focus on risk and land use suggests a need for research on how NBS can be integrated into urban planning and development processes to reduce the vulnerability of urban areas to flooding and other climate-related risks. "Land-use" emerged as a keyword in the same year, suggesting that integrating various types of NBS within existing land-use planning frameworks is another area of research focus. Future research could explore how NBS can be used to support more sustainable and resilient urban development patterns, and how different types of NBS can be integrated into existing land use planning frameworks.

In 2020, various emerging terms started to appear. The increasing frequency of terms related to USM and the adaptation strategies to overcome flood risks suggests that future research on NBS is likely to continue to focus on the development and implementation of specific NBS technologies and strategies in urban areas. This could include exploring the ways in which different types of NBS can be integrated into existing urban infrastructure systems and how NBS can be designed to be more effective and resilient in the face of changing climate and environmental conditions.

3.4.2. Interdisciplinary and Collaborative Research

NBS is a complex and multi-dimensional concept that requires interdisciplinary and collaborative research to fully understand its potential and effectiveness [61]. The analysis of the literature reveals that there is a need for more collaboration between different disciplines, including ecology, hydrology, environmental science, geography, urban planning, architecture, social sciences, economics, and engineering. Several studies have highlighted the need for interdisciplinary and transdisciplinary research to support the development and implementation of NBS in urban areas [62,63].

Interdisciplinary and collaborative research can bring together different perspectives and expertise to address complex environmental and social challenges. For example, the integration of engineering and economy can help to understand the infrastructures and economic interactions in urban areas and their implications for NBS design and implementation [64]. Similarly, the collaboration between urban planning and engineering can help to develop innovative and effective solutions to USM [65]. Future research should continue to promote interdisciplinary and collaborative research in NBS and explore new ways of integrating different disciplines and stakeholders in the research process.

3.4.3. Scaling up and Mainstreaming NBS

While NBS has shown great potential in addressing environmental and social challenges, there is still a need to scale up and mainstream NBS in different contexts and at different scales. The analysis of the literature reveals that most of the studies have focused on small-scale or local interventions [66–68], and there is a need to explore the potential of NBS at larger scales and in different contexts. Several studies have highlighted the need for scaling up and mainstreaming NBS to support sustainable and resilient urban development [69,70].

Scaling up and mainstreaming NBS requires a comprehensive and integrated approach that involves different stakeholders and sectors [71]. It also requires the development of policies, regulations, and financing mechanisms to support the implementation of NBS at different scales [72,73]. Future research should focus on identifying the barriers and opportunities for scaling up and mainstreaming NBS and developing strategies and solutions to overcome these challenges. This will require a collaborative and interdisciplinary approach that involves different stakeholders and sectors, including policymakers, practitioners, researchers, and the public.

Overall, the future research perspective of NBS should focus on developing a comprehensive and integrated approach to NBS research and practice, promoting interdisciplinary and collaborative research, and scaling up and mainstreaming NBS in different contexts and at different scales. This will not only help to advance the science and practice of NBS, but also support the development of innovative and effective solutions to environmental and social challenges in different contexts.

4. Conclusions

The literature review under consideration herein provides noteworthy insights regarding the concept, potential, and challenges of nature-based solutions (NBS) in the context of urban sustainability and resilience. Several crucial findings and research perspectives for future inquiry were discerned through the analysis of the literature.

To begin with, NBS is an all-encompassing, multifaceted concept that includes an extensive range of interventions reliant on nature, such as green infrastructure, urban agriculture, sustainable drainage systems, and blue–green infrastructure. NBS has the potential to tackle various environmental and social challenges that urban areas face. The effectiveness of NBS is contingent upon several factors, such as the nature and scale of the intervention, the local context, and the involvement of stakeholders.

Furthermore, the implementation of NBS necessitates an integrated and comprehensive approach that involves multiple stakeholders and sectors, including policymakers, practitioners, researchers, and the public. Policies, regulations, and financing mechanisms are pivotal to supporting the implementation and scaling up of NBS. However, several impediments stand in the way of NBS implementation, including insufficient funding, limited knowledge and awareness, and conflicting interests and priorities.

Interdisciplinary and collaborative research is critical to gain a complete understanding of the potential and efficacy of NBS. NBS research must integrate various disciplines, such as ecology, hydrology, and social sciences. Interdisciplinary and collaborative research facilitates the integration of diverse perspectives and expertise to address complex environmental and social challenges in urban areas.

Additionally, future research should concentrate on promoting the mainstreaming and scaling up of NBS in diverse contexts and at different scales. This involves identifying the barriers and opportunities for scaling up and mainstreaming NBS, developing strategies and solutions to overcome these challenges, and investigating the potential of NBS at larger scales. The scaling up and mainstreaming of NBS will not only enhance the science and practice of NBS but also bolster the development of innovative and effective solutions to environmental and social challenges in various contexts.

Overall, NBS represents a promising approach for achieving sustainable and resilient urban development. The successful implementation of NBS requires an integrated and comprehensive approach that involves multiple stakeholders and sectors. Future research should concentrate on promoting interdisciplinary and collaborative research, scaling up and mainstreaming NBS, and exploring novel approaches to integrating various disciplines and stakeholders in the research process. These efforts will advance the science and practice of NBS and support the development of innovative and effective solutions to environmental and social challenges in diverse urban contexts.

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