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Review

Trends and Interdisciplinarity Integration in the Development of the Research in the Fields of Sustainable, Healthy and Digital Buildings and Cities

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Abstract: This article provides a thorough bibliometric analysis of significant research trends in sustainability from 1988 until now, focusing on sustainable, healthy and digital buildings and cities. It exemplifies how research emphasis has shifted from explicit ecological investigations to nature-based solutions and city greening programs, with a rising interest in the many responsibilities of urban stakeholders in attaining sustainability. Despite weak integration at the literature and author cooperation levels, the "healthy buildings and cities" topic indicates promise for multidisciplinary integration. The "digital buildings and cities" topic, on the other hand, presents a more particular concern with strong cross-cluster collaboration and significant integration possibilities. Global relevance has been demonstrated through research on "sustainable buildings and cities," mainly in journal papers. This topic's study clusters show remarkable synergy across management, transportation, ecology, remote sensing and environmental engineering domains. In comparison to "healthy buildings and cities" and "digital buildings and cities" topics, the study of "sustainable buildings and cities" demonstrates a deeper level of interdisciplinary integration, highlighting the significant potential for further exploration within sustainability science research. This study emphasizes the ongoing worldwide relevance of sustainability science research and identifies significant opportunities for multidisciplinary integration across the investigated subjects.

Keywords: sustainable buildings and cities; healthy buildings and cities; digital buildings and cities

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Citation: Seduikyte, L.; Gražulevičiūtė-Vileniškė, I.; Povilaitienė, I.; Fokaides, P.A.; Lingė, D. Trends and Interdisciplinarity Integration in the Development of the Research in the Fields of Sustainable, Healthy and Digital Buildings and Cities. *Buildings* **2023**, *13*, 1764. https://doi.org/10.3390/buildings13071764

Academic Editor: Zhenjun Ma

Received: 16 June 2023
Revised: 3 July 2023
Accepted: 9 July 2023
Published: 11 July 2023

1. Introduction

The assessment of the sustainability of buildings and cities is at the forefront of the environmental analysis of the built environment. At this point, at the European and World level, a significant number of research projects, standards and methods have been developed, to assess the sustainability aspects. At the same time, all techniques to assess buildings are digitized, as we are moving fast to the Industry 4.0 era, where all buildings-related information should be easily communicated among designers, users and stakeholders.

Buildings are essential components of cities, where people spend a substantial part of their lives living, working, studying or relaxing. However, the same buildings and the whole construction industry are also responsible for considerable energy consumption, greenhouse gas emissions and waste generation. Therefore, how the buildings and entire cities are designed, constructed and configured to operate is crucial for reducing the environmental impact of urbanization, improving the health and well-being of the population and achieving the Sustainable Development Goals [1] adopted by 193 countries.

The concept of sustainable cities has evolved over time and has been defined in different ways by different scholars and organizations. According to one of the initial explanations of sustainable development, it is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. In other words, sustainable development seeks to find "a balance between economic development, environmental protection and social improvement" [3,4], and the main aim of sustainable urban development is to create "beautiful, distinctive, secure, healthy and high-quality places for people to live and work in that foster a strong sense of community, pride, social equity, integration and identity" [5]. Recently, there has been a growing recognition that achieving this certain objective is not solely reliant on tangible measures but "based on the principles of democracy, gender equality, solidarity, the rule of law and respect for fundamental rights, including freedom and equal opportunities for all" [6].

2. Theoretical Background, Literature Overview

Approaches to Sustainable Buildings and Cities

Several approaches towards sustainable buildings and cities were identified throughout the analyzed literature, depending on the context, priorities and resources available. The most common approaches are presented below.

Compact city: it is one of the leading paradigms of both sustainable development [7] and the New Urbanism movement [8]. The compactness of the city can be defined in the following three aspects [9]. Firstly, the urban form should be defined by high-density settlements, fewer dependences on automobiles and clear boundaries from the surrounding areas. Then spatial features should encourage mixed land use, diversity of life as well as clear and unique identities. Finally, social functions should aim for social equality, self-sufficiency in daily life and independence of government. The main critique of this approach is that compact cities, in order to reduce sprawl and minimize environmental impact, promote densification, whereas low-density urban forms are often considered to be more livable. However, that critique has been denied [10] as residents from compact cities are more satisfied with their neighborhood because, despite high density, this model also provides a better public transport network, accessibility and a variety of land uses.

Eco-city: the concept of eco-city is also broad; there are many overlaps with other approaches. Still, the following ten critical eco-city dimensions can be distinguished [11]: compact and mixed-use urban form, an abundance of the natural environment, walking and cycling infrastructure, extensive environmental technologies for water, energy and waste management, the central city with subcenters, high-quality public realm, human scale physical environment, innovation and driven economy, visionary—"debate and decide" and sustainability-based decision making. Essentially, eco-cities focus on environmental sustainability, promoting green infrastructure, renewable energy and zero-waste strategies while addressing social and economic issues [12–15].

Resilient city: resilience, in terms of cities, refers to the ability to absorb, adapt and respond to changes in an urban system. For this reason, cities should be conceptualized as complex adaptive systems and divided into components and analytical elements. Hence, this systematic approach allows a better understanding of how urban system design, planning and management work towards resiliency enhancements [16]. Overall, resilient cities focus on the adaptation to the challenges posed by climate change, such as extreme weather, natural disasters or sea-level rise, ensuring the continuity of essential services and minimizing the impact on the population [17–20].

Digital city: offer innovative services based on broadband communication and service-oriented computing [21]. Digital cities were built and made operational throughout the developed countries between the 1990s and the 2000s. Digital cities are distinguished by activities based on online services [22]. The fast spread of developing digital technologies, digital service creation and delivery necessitate new and more organized approaches to service design, development and management. There are numerous perspectives and strategic elements for developing digital services from diverse stakeholders, with different solutions stating how to design the digital service inside IT infrastructures or how to reuse design techniques learnt from prior Digital City initiatives [23–25].

According to a literature review, Digital City and Smart City are the most commonly used terms to describe a city's smartness. Smart cities appear to be the inevitable successors of digital cities.

Smart city: there are many definitions of smart cities. The reason for that is the application of the term for two different kinds of domains: "hard" and "soft" [26]. The "hard" one includes buildings, energy grids, natural resources, water and waste management and mobility, while the "soft one" covers culture, education, policy innovations, social inclusion and governments. Depending on the domain, the role of information and communication technologies (ICTs) is also different—decisive for the "hard" and not so much in the "soft" domain. Anyway, the common conception of smart cities is the use of digital technologies to optimize urban systems, such as transport, energy, water and waste management, improving efficiency, reducing costs and enhancing citizens' quality of life [27–29].

Healthy city: the World Health Organization (WHO) evolved the concept of "Healthy Cities" to improve city-based public health and environmental hygiene with a special focus on marginalized urban areas [30]. "Healthy Cities Project" was launched in Europe in the 1980s and has spread globally. The main principle of the initiative was that "health can be improved by modifying living conditions, namely, the physical environment and the social and economic conditions of everyday life" [31]. Eventually, the tools to measure the index of healthy cities were developed [32], and the index's indicators fall into four main sectors: health, health services, socioeconomic indicators and environmental indicators. The latter is strongly dependent on urban development strategies. To succeed in the creation of healthy and sustainable cities, urban development has to promote access to green spaces, sports and leisure facilities, mitigation measures of air, water and noise pollution, walkability and cycling and public transportation modes. The observed spatial inequality can also reveal the existence of social inequality [33].

Differences in various approaches to sustainable buildings and cities are presented in Table 1.

This review aims to analyze patterns and trends of the scientific research related to sustainable, healthy and digital buildings and cities. Quantitative literature analysis and graphical visualization and analysis—knowledge mapping—were applied to understand better the current research situation and research frontiers [34] in the mentioned areas. According to Chen [35], the frontier of research reveals the emergence of theoretical trends and new topics. According to Price [34], the research frontier is the dynamic nature and ideological status of the research field; generally, the research frontier consists of approximately 40 or 50 recently published scientific papers. Knowledge mapping is part of the broader field of science metrology and is defined as a cross-disciplinary field of applied mathematics, information science and computer science; the purpose of it is to extract and visually reorganize the knowledge from a large number of previously published scientific research documents and to carry out knowledge discovery [36,37]. This study provides insights into research trends, identifies gaps and opportunities for multidisciplinary integration and highlights the global importance of sustainability science. By quantitatively analyzing the scientific literature, this analysis contributes to a deeper understanding of such areas as healthy, digital and sustainable buildings and cities and informs future research directions.

Table 1. Differences in various approaches to sustainable buildings and cities. Note: Approaches are not totally exclusive, there are overlaps in their goals, features and measures.

Approach	Goal	Conceptual Features					Measures
		Urban Form	Land Use	Social Realm	Governance	Technologies	
Compact city	to reduce sprawl, minimize car dependency and promote walkability and public transportation	Compact, high-density	Mixed use	Social equality, self-sufficience	Ingtegrating planinng	Intelligent transport	population density, mixed land use ratios, walkability indices, public transportation usage, etc.
Eco-city	to achieve environmental sustainability, conserve resources and promote ecological balance.	Compact, sustainable	Mixed use, green infrstructure	Community-based	Sustainable policies	Environmental technologies	green space coverage, energy consumption per capita, waste management practices, sustainable building certifications, etc.
Resilient city	to enhance adaptability and resilience to climate change, natural disasters and social challenges	Adaptive	Green infrastruture	Social cohesion	Collaborative-particiaptory	Resilient infrastruc-ture	climate adaptation plans, disaster preparedness indicators, social cohesion indices, infrastructure robustness, etc.
Digital city	to improve connectivity, access to digital services and enhance efficiency in urban operations	Digitallyconnected	Varied	Online communities	E-governance	Digital platforms	digital service accessibility, e-governance adoption and digital literacy rates
Smart City	to enhance quality of life, optimize resource management and foster innovation and economic development	Technologically advanced	Efficient	Data-driven	Smart governance	IoT, AI, sensors	IoT infrastructure deployment, data analytics usage, smart grid implementation and citizen engagement in smart initiatives
Healthy City	to improve public health, promote well-being and create a supportive and inclusive environment.	Health-oriented	Green infrastructure	Social wellbeing	Collaborative-particiaptory	Health monitoring	public health indicators, access to healthcare services, air and water quality and community engagement in health initiatives

3. Methods

Web of Science (WoS) database was selected as a source of information and bibliometric data for quantitative literature analysis and knowledge mapping. According to Su et al. [37], WoS provides more complete references, indexes and researcher relationships than other databases. Chen [38] also mentions this database's high standard and wide span: reference searches can be used to track previous research and monitor recent developments in content over the 100 years that are fully indexed.

CiteSpace 6.2.R2 Advanced was applied in this research. It is a citation visual analysis software developed from the background of scientometrics and knowledge visualization, which is specifically used to identify potential knowledge contained in the scientific literature [35,36,38,39]. According to its creator, this software can help researchers understand the basic knowledge of the discipline, find the classical literature in the field, discover research frontiers, and clarify the context of research evolution [39]. This software is widely used for bibliometric analysis and visualization. According to Su et al. [37], more than 15 000 papers have using the CiteSpace tool been published. The data format processed by CiteSpace software is based on the WoS data download format [38] and allows generating the merged networks, that characterize the development of the analyzed field over time, showing the most important footprints of the related research activities and performing cluster analysis, author cooperative analysis and co-citation (*the frequency with which two documents are cited together by other documents*) analysis [36,37]. The visual display of the bibliometric analysis of the CiteSpace tool can be characterized by network character with nodes (points in a network diagram at which links intersect or branch), links (the relationship between two nodes) and clusters (a group of similar findings that occur together).

This study collected the bibliometric data from the WoS core collection database, for the period 1988 until now, of the papers on the following topics:

- Healthy buildings and cities: word combination "healthy buildings and cities" was entered into WoS database search engine;
- Digital buildings and cities: word combination "digital buildings and cities" was entered into WoS database search engine;
- Sustainable buildings and cities: word combination "sustainable buildings and cities" was entered into WoS database search engine.

The data were collected on the 28 February 2023. Publications issued in the year 2023 were included in the analysis sample, as the aim of the research was to identify research frontiers. Considering this, excluding the newest publications would not allow comprehensive research outcomes. In total, the data of 13,804 papers were collected (Tables 2 and 3): 1064 papers on healthy buildings and cities, 2734 papers on digital buildings and cities and 10,006 papers on sustainable buildings and cities were identified.

Table 2. The type of records in the analyzed sample.

Search "Healthy Buildings and Cities"	Search "Digital Buildings and Cities"	Search "Sustainable Buildings and Cities"
Article—628	Article—1411	Article—6185
Proceeding paper—392	Proceeding paper—1289	Proceeding paper—3408
Review article—34	Review article—61	Review article—465
Book chapter—30	Book chapter—50	Book chapter—236
Editorial material—18	Early access—40	Early access—114
Early access—12	Editorial material—12	Editorial material—52
Data paper—1	Data paper—4	Book review—7
Meeting abstract—1	Book review—1	Data paper—6
Reprint—1	News item—1	Correction—2
		Meeting abstract—2
		Book—1
		Letter—1
		Retracted publication—1

Table 3. The yearly breakdown of the publications in the analyzed sample.

Publication Year	Search "Healthy Buildings and Cities"	Search "Digital Buildings and Cities"	Search "Sustainable Buildings and Cities"
1988	3	-	-
1989	-	-	-
1990	-	-	-
1991	1	-	-
1992	1	2	3
1993	-	1	-
1994	-	-	2
1995	1	1	6
1996	-	3	4
1997	1	5	10
1998	1	7	22
1999	2	6	10
2000	8	12	13
2001	1	14	15
2002	5	9	33
2003	6	18	29
2004	4	13	34
2005	13	29	222
2006	12	29	55
2007	13	28	84
2008	15	27	81
2009	17	45	144
2010	23	57	209
2011	19	56	287
2012	23	60	355
2013	26	97	416
2014	31	92	295
2015	39	117	440
2016	41	117	577
2017	51	175	791
2018	265	216	990
2019	89	394	1144
2020	86	317	1114
2021	130	391	1254
2022	125	366	1237
2023	13	30	130

This study performed the bibliometric analysis of this volume of the identified scientific literature and displayed the results visually.

Additionally, a separate topic of "sustainable cities" was analyzed, as the term "sustainable city" includes all previously mentioned fields. Result: 2060 articles selected for the systematic literature review.

4. Results

4.1. Healthy Buildings and Cities

The search on "healthy buildings and cities" provided the smallest number of results compared to other searches. During the time span 1988–February 2023, 1064 papers were published. The first three papers appeared in 1988, and the growth of published research in this field started in 2005. In 2021 and 2022, 130 and 125 publications were recorded, demonstrating the growing interest in the field. In 2018, 265 publications were recorded due to several important conferences focused on this topic held that year, including the 34th International Conference on Passive and Low Energy Architecture (PLEA)—Smart and Healthy Within the Two-Degree Limit. It is important to note that the predominant publication type in this search was conference papers and proceedings. The dominant fields of research according to WoS categories are Green Sustainable Science and Technology (288 publications), Architecture (228 publications), Public Environmental Occupational Health (212) and Environmental Sciences (179 publications). Civil Engineering has 103 recorded studies and Urban Studies—91 in the analyzed period. Three most cited publications in this research area were published in 2013, 2003 and 2017. The most cited contribution—multidisciplinary peer-reviewed research on contributions of nature or ecosystems to human well-being by Russell et al. [40]—has 328 citations in total; theoretical analysis of sense of place as a public health construct by Frumkin [41] has 305 citations in total, and the contribution by Nieuwenhuijsen et al. [42] from the field of epidemiology with 263 total number of citations deals with the involvement of environmental epidemiologists in better understanding of health effects of green spaces in urban environments. This demonstrates that the topic of "healthy buildings and cities" is under a wide umbrella of sustainability research and is strongly related to architecture, civil engineering, environmental and urban studies, and public health.

CiteSpace visualization for the search "healthy buildings and cities" are presented in Figures 1–3.

Figure 1. CiteSpace visualization of keywords and cluster analysis for the search "healthy buildings and cities" in the period 1988–2023. The nodes represent keywords, lines that connect nodes are keyword co-occurrence links. The top 10 dominant keywords were: city (58), impact (52), physical activity (51), environment (46), built environment (43), health (42), public health (40), exposure (34), quality (29) and performance (26). The cluster analysis of keyword distribution demonstrates close integration of disciplines and according to analyzed topics except of toxicology.

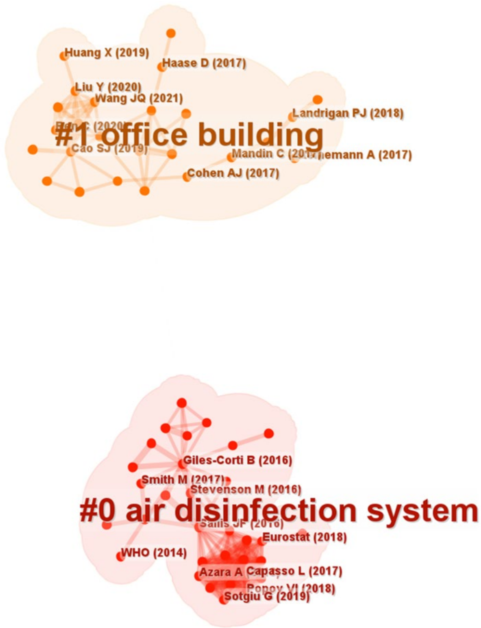

Figure 2. CiteSpace visualization of the reference co-citation network and cluster analysis for the search "healthy buildings and cities" in the period 1988–2023. The nodes are cited references, lines that connect nodes are co-citation links. Analysis reveals only two significant clusters of co-citation networks, labelled according to keywords: office building and air disinfection system. It is possible to conclude that there's very little integration in co-citation compared to keyword analysis.

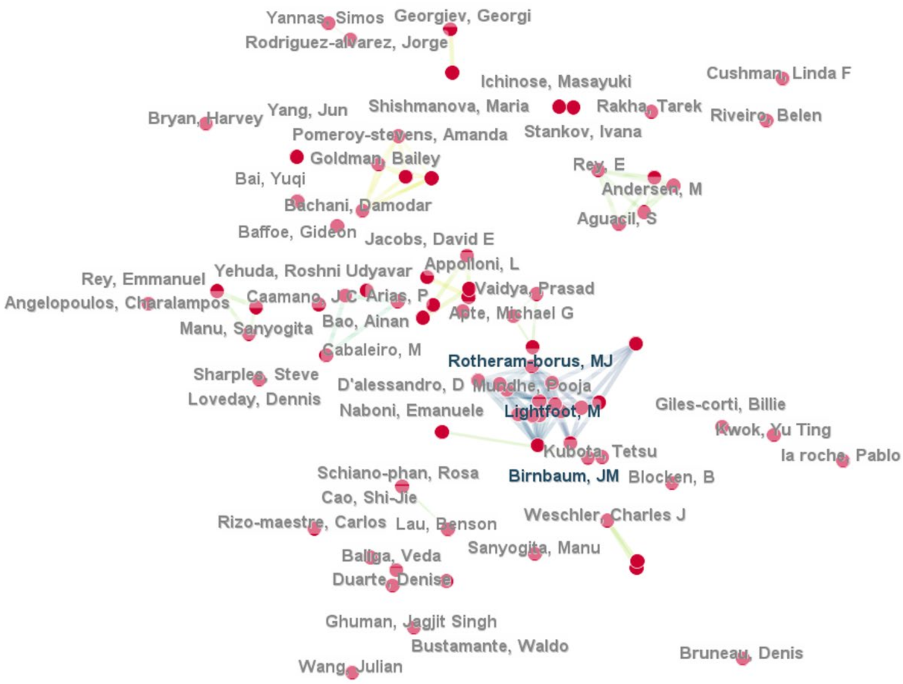

Figure 3. CiteSpace visualization of co-author network and cluster analysis for the search "healthy buildings and cities" in the period 1988–2023. The nodes represent the authors of publications in the author collaboration network. Analysis reveals only one significant cluster of co-authoring and several smaller ones. It is possible to conclude that there's much less integration in co-authoring compared to keyword analysis.

It is possible to summarize that knowledge mapping of the topic "healthy buildings and cities" as reflected in the WoS database in the period 1988–2023 reveals its untapped potential for interdisciplinary integration, as it shares multiple topics. However, the existing research appears little integrated from the points of view of the literature sources and authors collaboration.

4.2. Digital Buildings and Cities

During the time span 1992–2023, 2734 papers were published. The first two papers appeared in 1992, and the growth of published research in this field started in 2005, exceeding several dozens of publications per year. In 2020, 2021 and 2022, respectively, 317, 391 and 366 publications were recorded, demonstrating the growing interest in the field. In 2019 394 publications were recorded due to several important conferences focused on this topic held that year, including the International Conference on Climate Resilient Cities—Energy Efficiency and Renewables in the Digital Era (CISBAT). It is important to note that the predominant publication type in this search was conference papers and proceedings, similar to the previous search. The dominant fields of research, according to WoS categories, are Remote Sensing (474 publications), Construction Building Technology (470 publications), Green Sustainable Science Technology (465) and Energy Fuels (411 publications). Civil Engineering has 206 recorded studies in the analyzed period, Architecture—148 and Urban Studies—128. The most cited publication in this research area was published in 2014 by Zanella et al. [43] and is review of technologies of internet of things and their application to smart cities. This contribution has 3061 citations in total. Other two most cited contributions were published in 2014 and 2019, respectively. Publication by Neirotti et al. [44] has total number of 1081 citations and is analysis and classification of smart city initiatives aimed and policy makers and city managers. Publication by Sachs et al. [45] is cited 561 times in total; it is theoretical study of sustainability science distinguishing necessary transformations, including the digital revolution for sustainable development, for the achievement of sustainable development goals. This demonstrates that the topic of "digital buildings and cities" is more specialized compared to previously analyzed.

CiteSpace visualization for the search "digital buildings and cities" are presented in Figures 4–6.

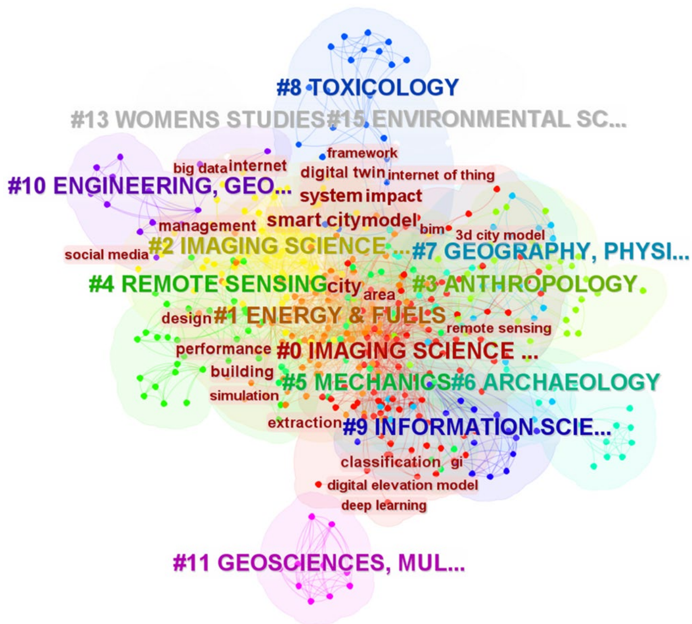

Figure 4. CiteSpace visualization of keywords and cluster analysis for the search "digital buildings and cities" in the period 1992–2023. The nodes represent keywords, lines that connect nodes are keyword co-occurrence links. The top 10 dominant keywords were: city (138), smart city (119), model (110), system (77), impact (60), area (49), digital twin (48), performance (47), management (44), building (44). The cluster analysis of keyword distribution demonstrates close integration of disciplines and according to analyzed topics.

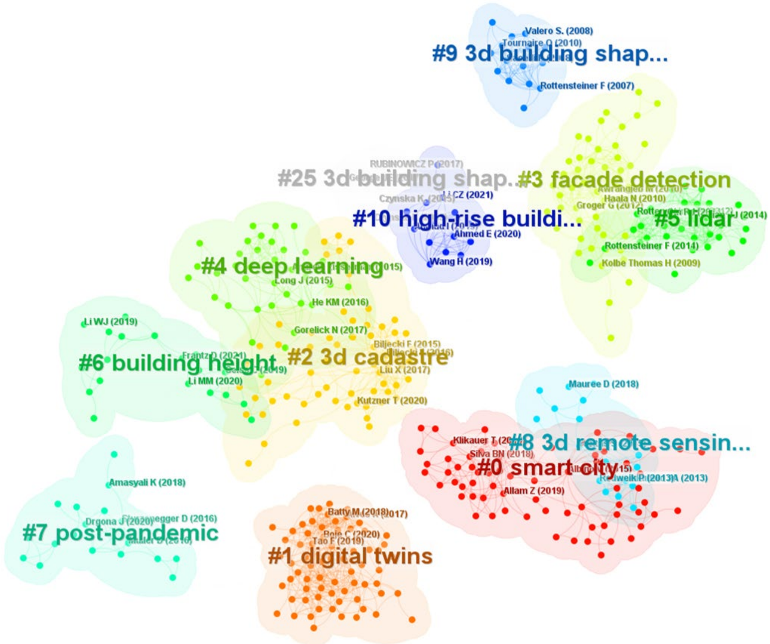

Figure 5. CiteSpace visualization of the reference co-citation network and cluster analysis for the search “digital buildings and cities” in the period 2000–2023. The nodes are cited references, lines that connect nodes are co-citation links. Analysis reveals 11 significant clusters of co-citation network, labelled according to keywords in the graph. It is visible that part of the clusters are separated and part are very closely merged. This graph reveals close integration between fields of remote sensing and chemical engineering, civil engineering and computer science and physical geography and imaging science according to cited references.

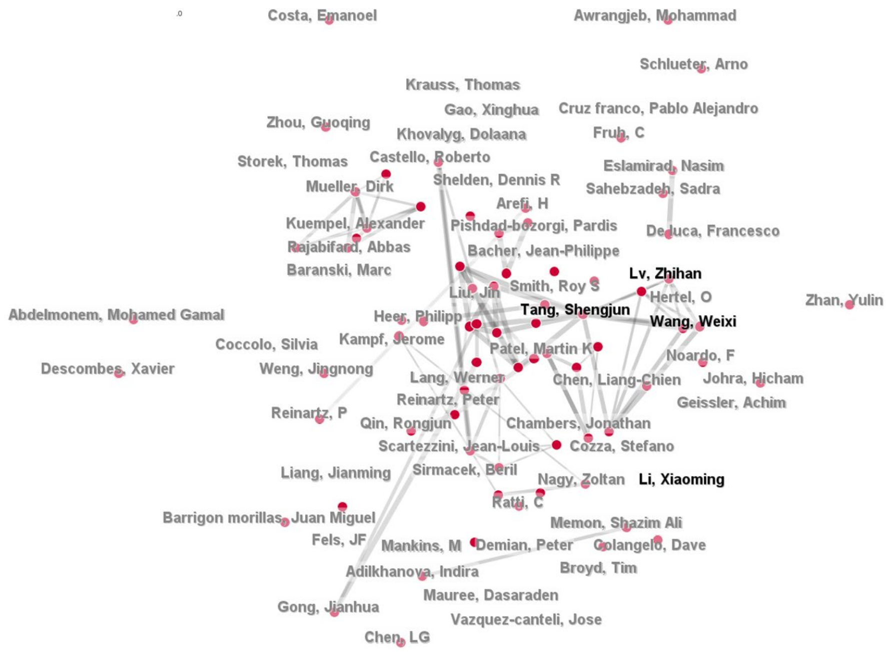

Figure 6. CiteSpace visualization of co-author network and cluster analysis for the search “healthy buildings and cities” in the period 1988–2023. The nodes represent the authors of publications in the author collaboration network. Analysis reveals several clusters of co-authors and wide cross-cluster author collaboration.

It is possible to summarize that knowledge mapping of the topic “digital buildings and cities” as reflected in the WoS database, reveals multiple shared topics and a wide array of research clusters with significant cases of cross-cluster collaboration and cluster integration. Compared to previously analyzed topic, research in the “digital buildings and cities” field appears more integrated, although with remaining untapped integration potential.

4.3. Sustainable Buildings and Cities

The search on “sustainable buildings and cities” provided the most significant number of results compared to other searches. During the time span 1988– 2023, 10 006 papers were published. The first three papers appeared in 1992, and the growth of published research in this field started in 2005. In 2019, 2020, 2021 and 2022, respectively 1144, 1114, 1254 and 1237 publications were recorded, demonstrating the growing interest in the field. It is important to note that the predominant publication type in this search is a journal article, with two leading journals—Sustainable Cities and Society and Sustainability. The dominant fields of research according to WoS categories are Green Sustainable Science and Technology (3650 publications), Construction Building Technology (3130 publications), Energy Fuels (2779) and Environmental Sciences (2193 publications). Civil Engineering has 1637 recorded studies in the analyzed period, Urban Studies—1002, Architecture—558. The most cited publications in this area of research were published in 2014, 2007 and 2015, respectively. Contribution by Cabeza et al. [46] has 730 citations in total; it is the literature review on life cycle assessment, life cycle energy analysis and life cycle cost analysis studies carried out for environmental evaluation of buildings and building related industry and sector. Publiaction by Kennedy et al. [47] is cited 730 times in total as well and is comparative study of metabolism in cities—water, materials, energy and nutrient flows. The study by Haaland and van den Bosch [48] is cited 608 times in total and provides a literature review on the effects of urban densification and compact city development on urban green space and its planning. The research areas of “digital buildings and cities” and “sustainable buildings and cities” share common most cited publication—the previously mentioned study on implementation of sustainable development goals by Sachs et al. [45]. This demonstrates that “sustainable buildings and cities” is under a broad umbrella of sustainability research with currently predominant technological disciplines.

CiteSpace visualization for the search “sustainable buildings and cities” are presented in Figures 7–9.

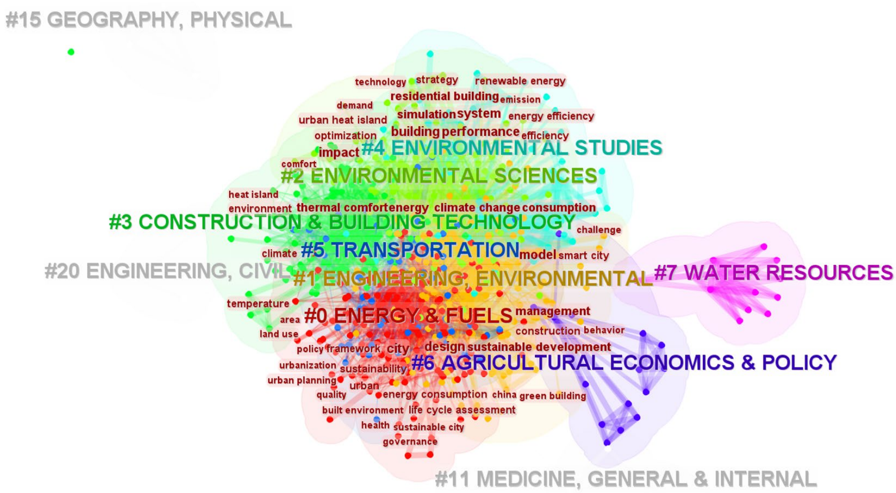

Figure 7. CiteSpace visualization of keywords and cluster analysis for the search “sustainable buildings and cities” in the period 1992–2023. The nodes represent keywords, lines that connect nodes are keyword co-occurrence links. The top 10 dominant keywords were: city (878), performance (636), impact (621), system (565), model (492), building (459), design (430), climate change (357), energy (350) and management (339). The cluster analysis of keyword distribution demonstrates close integration of disciplines and according to analyzed topics.

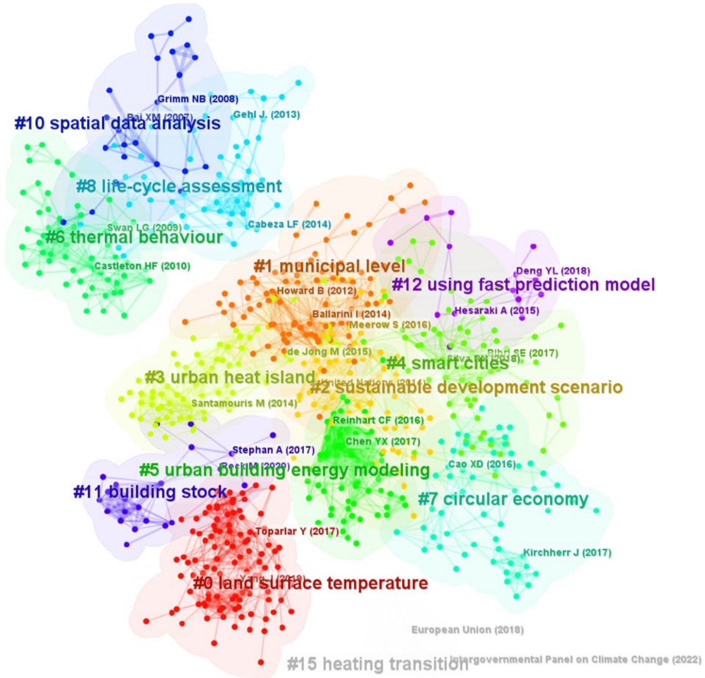

Figure 8. CiteSpace visualization of the reference co-citation network and cluster analysis for the search "sustainable buildings and cities" in the period 2006–2023. The nodes are cited references, lines that connect nodes are co-citation links. Analysis reveals 12 significant clusters of co-citation network, labelled according to keywords in the graph. It is visible that there are no separate clusters; they are merged at least with one or two clusters. Two groups of clusters can be identified, revealing close integration between fields of (1) management, transportation, ecology and (2) remote sensing and environmental engineering, according to cited references.

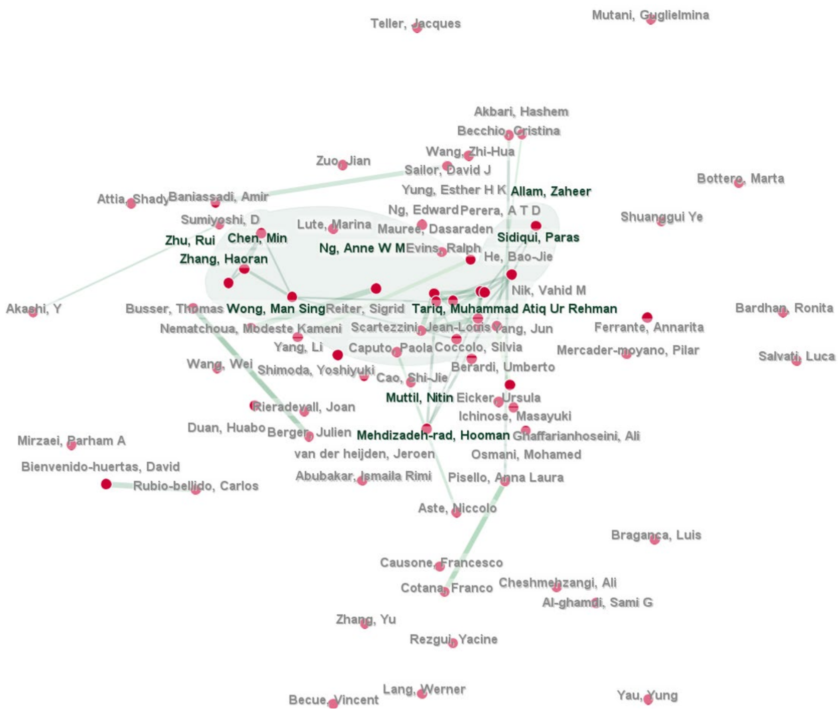

Figure 9. CiteSpace visualization of co-author network and cluster analysis for the search "sustainable buildings and cities" in the period 2006–2023. The nodes represent the authors of publications in the author collaboration network. Analysis reveals interlinked clusters of co-authors and cross-cluster author collaboration.

It is possible to summarize that knowledge mapping of the topic "sustainable buildings and cities" as reflected in the WoS database, reveals multiple shared topics and a wide array of interrelated research clusters with significant cases of cross-cluster collaboration and cluster integration. Compared to the topics "healthy buildings and cities" and "digital buildings and cities", research in "sustainable buildings and cities" appears more integrated, demonstrating that sustainability science research holds integration potential.

4.4. Sustainable Cities

As sustainable cities include healthy and digital buildings and cities, separate analyses were conducted for this topic. The data for that were collected on the 11 April 2023, and they include articles published until that time. Articles were selected based on the following inclusion and exclusion criteria: topic "*sustainable city*" or "*sustainable cities*", document type: "*article*", language: "*English*", categories: "*Construction Building Technology*", "*Engineering Civil*", "*Green Sustainable Science Technology*", "*Environmental Sciences*"; "*Environmental Studies*", "*Architecture*", "*Urban Studies*", "*Regional Urban Planning*" and "*Geography*". The number of published articles to some extent analyzing sustainable cities is growing each year. There are 64 articles published in 2023, 393 articles in 2022, 388 in 2021, 287 in 2020, 207 in 2019, 168 in 2018, etc.

The top 10 most-cited articles of the analyzed period are articles from 2004–2019 (see Table 4). They explore topics such as the importance of green urban spaces and ecosystems [49–52], the differences between concepts of sustainable, smart or digital cities [27,53,54], as well as transformative governance issues [45,55,56].

Table 4. Top 10 most-cited articles from the ones selected for the research.

No.	Citations	Author (Year)	Topics
1	1329 *	Chiesura (2004) [48]	role of urban parks in creating sustainable cities
2	730 *	Kennedy et al. (2007) [46]	changing metabolism of cities
3	647 *	Bulkeley and Betsill (2005) [49]	multilevel governance in sustainable cities
4	563 *	Sachs et al. (2019) [44]	transformations to achieve the SDGs
5	549 *	Ahvenniemi et al. (2017) [50]	differences between sustainable and smart cities.
6	507 *	De Jong et al. (2015) [51]	various concepts promoting sustainable urbanization
7	436 *	Hasse et al. (2014) [52]	ecosystem services in urban landscapes and their governance implications
8	436 *	Cocchia (2014) [53]	systematic literature review on smart and digital cities
9	375 *	Nevens et al. (2013) [54]	urban transition labs and their role in co-creating transformative actions for sustainable cities
10	366 *	Venter (2020) [55]	increased use of urban green spaces during the COVID-19 outbreak in Oslo

*—number of citations on 30 June 2023.

To not solely rely on the citation frequency, the co-citation analysis was carried out as it considers the collective influence of articles by examining the co-citation relationships between them, uncovers hidden connections, discovers emerging trends, overcomes biases and assesses research impact. In co-citation analysis conducted using CiteSpace, different elements are represented by colors, nodes and links to visualize and analyze the co-citation network. *Nodes* in the co-citation analysis represent individual articles or documents.

Links, also known as edges or lines, connect the nodes in the co-citation network. They represent the co-citation relationships between articles. The thickness or intensity of the links indicates the strength or frequency of co-citation between two articles. CiteSpace enables the identification of clusters of related articles based on their co-citation patterns. A cluster represents a group of articles that are conceptually or thematically similar and frequently cited together. Clusters are visually depicted as densely connected groups of nodes, often with a different color or shading to differentiate them from the overall co-citation network.

After the data processing procedure, 1181 nodes out of 2060 sources were identified as connected via 3992 co-citation links, i.e., average 3.38 links per node. Then the data were visualized using automatic cluster identification and computation of nodes centrality (see Figure 10). This visualization reveals the significance of different articles in the network, their links and the relationship between different clusters: some overlap, and others are almost isolated.

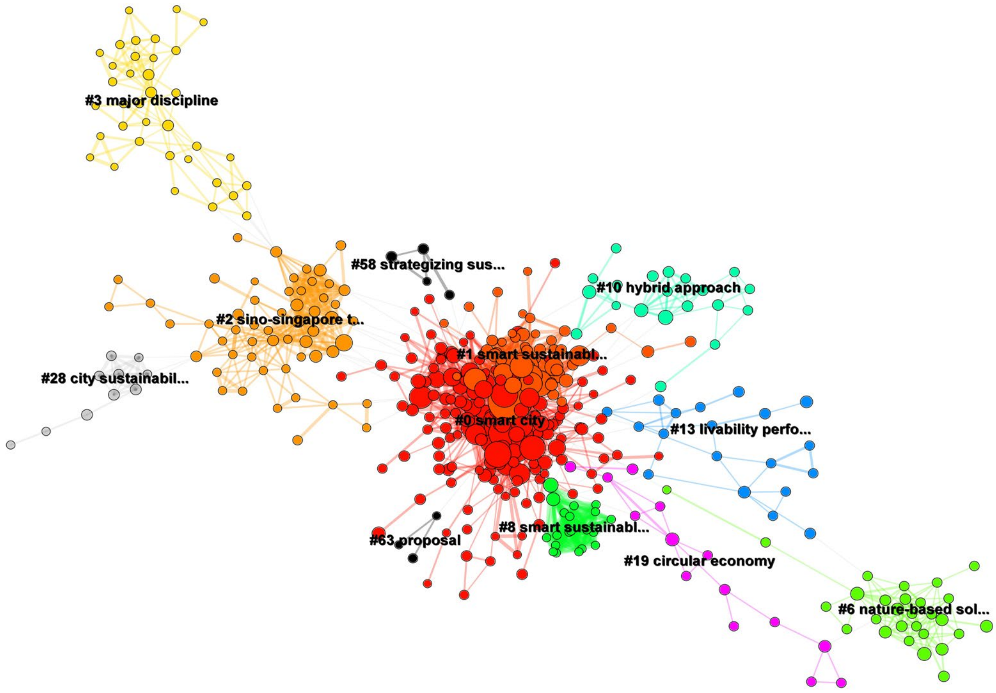

Figure 10. CiteSpace visualization of co-author network and cluster analysis for the search "sustainable cities" and its clusters in the period 1990–10 April 2023 Colours represent different clusters, nodes—different articles, links—co-citation relationships among articles.

The analyzed network consists of 12 major clusters. The ten largest clusters are presented in Table 5. Labels of the clusters are based on the top key terms, but those can be assigned using different algorithms—Latent Semantic Indexing (LSI) or Log-Likelihood Ratio (LLR). LSI is a more general summary of the concepts surrounding each cluster, while LLR provides a more concrete description of the topics within the cluster. Table 5 also reveals the main issues tackled in each of the most cited articles of the clusters.

Looking at the processed data (Figures 10 and 11 and Table 5), it is clear that a certain topic unites the articles in clusters, and there is not much of the overlap between the different clusters except for the first two—"smart cities" and "smart sustainable cities".

Cluster 1 is the largest and consists of 176 articles analyzing the relationship between sustainable and smart city concepts [27,28,50]. The shift from a more ecological approach (eco-city) to a more technocratic one (smart city) is recognized here. Yet, the limitations of both of those approaches are already highlighted as well.

Table 5. Research on Sustainable cities categorized by the clusters and the main articles distinguished (compiled by authors, using WoS data and the CiteSpace software).

No. ID	Cluster Label (LSI/LLR)	Size	Average Year	The Most Cited Articles in the Cluster	The Main Issues Analysed in Articles
1 #0	smart city/smart city	176	2017	Lim et al. (2018) [27]	*smart cities, big data, value creation for different stakeholders*
				Ahvenniemi et al. (2017) [50]	*sustainable city vs. smart city, shift from sustainability assessment to smart city goals, concept of smart sustainable cities*
				Doan et al. (2017) [56]	*green building rating systems, sustainability of construction*
				Yigitcanlar et al. (2019) [28]	*smart vs sustainable, smart without sustainable, techno-centricity in smart development, systematic literature review (SLR)*
2 #1	smart sustainable cities/smart city	58	2015	Bibri (2019) [57]	*smart sustainable cities, big data, limitations of compact and eco-cities*
				Bibri and Krogstie (2017) [58]	*smart sustainable cities, urban sustainability, sustainable city models, smart city approach, big data*
				Bibri (2018) [59]	*smart sustainable cities, internet of things, big data analitics, environmental sustainability*
				Höjer and Wangel (2015) [60]	*smart sustainable city concept, five influential developments, challenges*
3 #2	sino-singapore/eco-city china	55	2012	Caprotti et al. (2015) [13]	*eco-city, urban environmental impacts, benefits for residents vs broader socio-environmental landscape*
				Caprotti (2014) [12]	*eco-city, future challenges, social resilience and emerging communities, new urban poor*
				Cugurullo (2013) [14]	*eco-city, sustainability ideology, case study, UAE, Masdar City*
				Shwayri (2013) [15]	*eco-city, global crisis, green infrastructure, South Korea, Songdo*
4 #3	major discipline/ecological-infrastructural systems framework	36	2009	Ramaswami et al. (2012) [61]	*sustainable city systems, social–ecological–infrastructural systems, social actors, multidisciplinarity*
				Grimm et al. (2008) [62]	*global change, ecology of cities, land use and cover, environmental changes, urban socioecosystems*
				Pickett et al. (2011) [63]	*socioecology, humane metropolis, urban system, human ecosystem, eco system services*
				Ernstson et al. (2010) [18]	*urban resilience, human dominated ecosystems, case studies, urban governance, system of cities*
5 #6	nature-based solution/nature-based solution	28	2017	Brokking et al. (2021) [64]	*green infrastructure, municipal practices, governance, urban development, case studies, Stockholm*
				Raymond et al. (2017) [65]	*shift from eco-based to nature-based solutions, 10 societal challenges, co-benefits and costs of sustainability*
				Haase et al. (2017) [66]	*city greening, social inclusivity, well-being, social effects of greening*
				Andersson (2019) [17]	*green and blue infrastructure, environmental justice, resilience*

Table 5. *Cont.*

No. ID	Cluster Label (LSI/LLR)	Size	Average Year	The Most Cited Articles in the Cluster	The Main Issues Analysed in Articles
6 #8	smart sustainable cities/bridging stakeholder value creation	20	2019	Beck and Ferasso (2023) [67]	*urban stakeholders, stakeholder value creation (SVC), urban sustainability, significance of environmental dimension*
				Macke et al. (2019) [68]	*smart sustainable city, sense of community, Brazil, residents satisfaction, social capital, shared values*
				Camboim et al. (2019) [69]	*smart city dimensions: governance; environ-urban; techno-economic; socio-institutional, urban innovation ecosystems*
				Beck and Storopoli (2021) [70]	*stakeholder theory, urban governance, literature review, urban strategy (stakeholders expectations) and urban marketing (urban image attractiveness)*
7 #10	hybrid approach/uk context	20	2018	Stevenson et al. (2021) [71]	*climate action (SDG 13) interaction with other SDGs—synergies and trade-offs, expert survey, UK*
				Nilsson et al. (2016) [72]	*interactions among SDGs, goals scoring*
				Pradhan et al. (2017) [73]	*SDGs interaction, SDG indicator data, sinergies (SDG 1—no poverty) and trade-offs (SDG 12—responsible consumption and production)*
				Klopp and Petretta (2017) [74]	*urban sustainable development goal (USDG), indicators, politics of measurement*
8 #13	livability performance/learning approach	19	2018	Kutty et al. (2022) [19]	*city resilience, urban livability, machine learning, European smart cities*
				Sharifi and Khavarian-Garmsir (2020) [75]	*smart cities, pandemics, environmental factors, air quality, urban design*
				Brelsford et al. (2017) [76]	*heterogeneity, scale of sustainable development, sustainable development indices, Brazil, South Africa*
				Ugolini et al. (2020) [77]	*pandemics, urban green spaces, people perception, European countries*
9 #19	circular economy/circular economy	14	2018	Rama et al. (2021) [78]	*key sustainability indicators, unemployment rates, waste collection, Spanish cities*
				Feleki et al. (2018) [79]	*systems of indicators, "traditional" dimensions of sustainability, European urban areas*
				Azunre et al.(2019) [80]	*urban agriculture, indicators of sustainability, economic, social and environmental benefits of urban agriculture*
				Meerow et al. (2016) [20]	*definition of urban resilience, climate change, review*
10 #28	city sustainability index/city sustainability index	10	2012	Mori and Yamashita (2015) [81]	*city sustainability index, concept of constraint and maximization indicators, limitations and benefits*
				Haghshenas and Vaziri (2012) [82]	*9 sustainable transportation indicators, millennium cities database for sustainable mobility*
				McCormic et al. (2013) [83]	*urban initiatives on sustainability, 35 cases, Europe and some other locations, sustainable urban transformation, governance*
				Shen et al. (2011) [84]	*sustainability indicators, comparison of different practices*

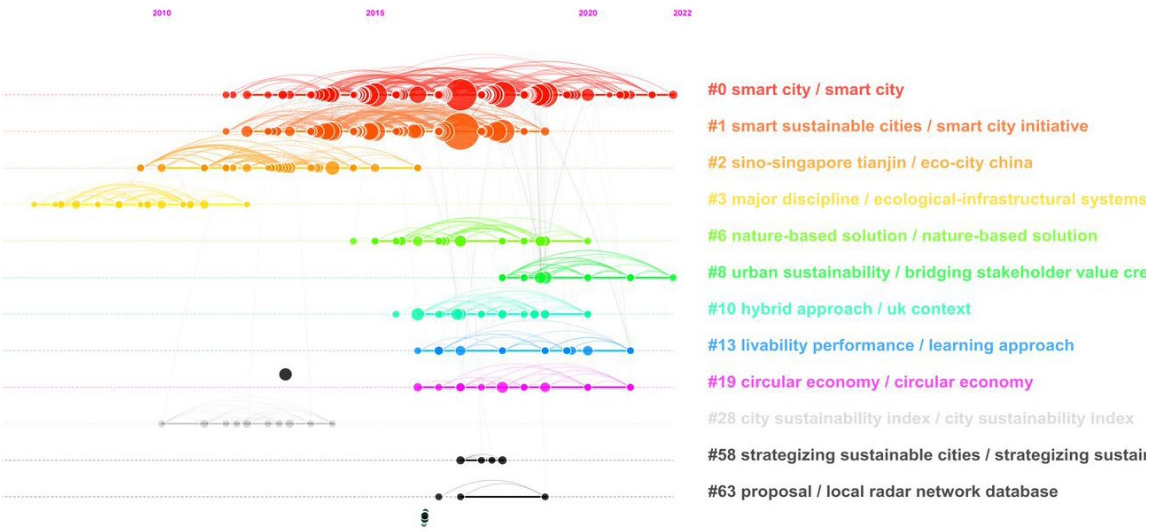

Figure 11. CiteSpace Timeline visualization of the co-citation network of scientific research on sustainable cities and its clusters. Colors represent different clusters, nodes—different articles, links—co-citation relationships among articles.

Cluster 2 is closely related (almost overlapping) to the previously described cluster "smart city". The main difference is that "sustainable cities" are not compared with the "smart ones" anymore. Instead, the term "smart sustainable city "(SSC) is established and conventionally used. Thus, there is also a change in the research strategies: it shifted from the concept definition towards studying the possibilities of using big data and information technologies to improve SSG development [57–60].

Cluster 3 is not linked to the first two but reveals a group of articles focused on sustainable development of eco-cities in Asia (i.e., Tianjin in China [12,13], Masdar City in the United Arab Emirates [14] or Songdo in South Korea [15].

Cluster 4 unifies articles about social–ecological–infrastructural systems [61], human-dominated [18] or human ecosystems [62,63]. The main idea of those articles is that cities or their parts do not function in isolation, but they are connected through the flows of energy, matter and information.

Cluster 5 consists of articles related to nature-based solutions (NBS) for urban development. They discuss the role of appropriate governance [67] and the benefits of greening the cities, such as social effects, increased inclusivity and environmental justice [17,65,66].

Cluster 6 brings together articles that examine the role and significance of urban stakeholders (i.e., municipalities, housing corporations, developers, city inhabitants and urban designers) [67,69]. Those articles also highlight the importance of social capital, a sense of community and attractiveness [68,70].

Cluster 7 includes articles analyzing the SDGs [1] and their interrelations, as the interactions among them did not always cause positive results [71,72]. For example, a systematic study [73] revealed that SDG 1 (no poverty) has a synergy with most of the other goals, while SDG 12 (Responsible consumption and production) is most commonly associated with trade-offs.

Cluster 8 includes articles aiming to understand how it is possible to create a more livable environment, considering such issues as pandemics [75,78] in both highly developed cities [19] as well as in developing ones [76].

Cluster 9 covers articles to some extent related to a circular economy, either it would be analysis of different indicators such as unemployment or waste management [78,79] or the role of urban agriculture [80], or the theoretical clarification of urban resilience [20].

Cluster 10 consists of articles tackling the issues of sustainability index construction and measurement—formulation of methodological frameworks [81,82] and overviewing and evaluating the existing practices [83,84].

From a temporal standpoint (see Figure 11), the oldest topic that emerged in the analyzed data set of the sustainability literature is the one that examines the social–ecological–infrastructural systems. It is followed by a group of research papers presenting the eco-city cases and their analysis. Subsequently, there was a shift in research emphasis towards nature-based solutions and the additional values generated by city greening initiatives, and the most recent cluster of articles deals with more intangible matters—the roles and contributions of various urban stakeholders in the process of reaching sustainability. It is also important to note that after 2015, when the UN General Assembly adopted SDGs [1], a group of articles examined the compatibility and mutual impact of different SDGs. Moreover, even though the idea of a circular economy has been known as far as the 1980s [85], in the sustainability literature, its importance also grew more significantly after the adoption of SDGs, as this particular economic system is based on the reuse and regeneration of materials or products, especially as a means of continuing production in a sustainable or environmentally friendly way. The quality of life and the requirements for the design of livable urban spaces is another cluster of articles relevant at that time. Still, the most enduring trend in sustainability research is the theme of "smart cities," which emerged circa 2012, peaked in 2016, and continues to be a prominent topic of investigation in the contemporary literature. Almost parallel to this trend, the development of interest in the "smart sustainable cities" topic is also observed, although in the most recent years, there has been a decrease in scientific articles on the latter topic.

5. Conclusions and Discussion

This study is a general quantitative literature overview with qualitative insights; further research is required in order to understand deeper each distinguished subtopic. According to some researchers, CiteSpace bibliometric analysis has some limitations, for example, some maps and clusters are complex and require specialized domain knowledge for interpretation or the learning curve required to set accurate visualization parameters [86]; however it proved to be a valuable tool in this research.

The earliest theme that emerged from the examined data set of the sustainability literature is the one that investigates social–ecological–infrastructural systems. The research emphasis has shifted toward nature-based solutions and the additional values generated by city greening initiatives, and the most recent cluster of articles addresses more intangible issues—the roles and contributions of various urban stakeholders in achieving sustainability.

Following the adoption of the SDGs by the UN General Assembly in 2015, a set of papers appeared explicitly investigating the concerns of compatibility and mutual impact of multiple SDGs.

The concept of "smart cities," which peaked in 2016 and remained a popular examination area in modern literature, is the most durable trend in sustainability research. Almost simultaneous to this trend is the growth of interest in the concept of "smart sustainable cities;" however, in recent years, there has been a reduction in research on the latter.

Research showed that studies on "healthy buildings and cities" yielded the fewest findings. 1064 articles were published in the WoS database between 1988 and 2023. The first articles were published in 1988, and the increase in published research on this topic began in 2005. In this search, conference papers and proceedings were the most common kind of publishing. "Healthy buildings and cities" fall under the broad banner of sustainability study and are closely connected to architecture, civil engineering, environmental and urban studies and public health. The knowledge mapping of the topic "healthy buildings and cities" demonstrates its latent potential for interdisciplinary integration, as it shares various issues, despite the fact that the present study appears to be poorly integrated from the standpoint of literature sources and author collaboration.

Between 1992 and 2023, 2734 papers on "digital buildings and cities" were published. The first articles were published in 1992, and the increase in published research on this topic began in 2005. Similar to the "healthy buildings and cities" search, the most common publication type in this search was conference papers and proceedings. Compared to prior studies, the issue of "digital buildings and cities" is more specific. This topic offers a wide range of research clusters with notable examples of cross-cluster collaboration and cluster integration. Compared to prior topics studied, research in "digital buildings and cities" looks more integrated, yet with unrealized integration potential.

Research showed that the research topic of "sustainable buildings and cities" was and still is very important worldwide, as from 1988 to 2023, 10 006 papers were identified in WoS database. The first articles were published in 1992, and the increase in published research in this topic began in 2005. The most common type of publication in this search is a journal article. The issue of "sustainable buildings and cities" falls within the broad umbrella of sustainability research, which includes the currently leading technical fields. According to our study, two sets of clusters were discovered, demonstrating tight integration across the domains of:

- Management, transportation, ecology;
- Remote sensing and environmental engineering, according to cited references.

In comparison to other analyzed topics ("healthy buildings and cities" and "digital buildings and cities,") research in the field of "sustainable buildings and cities" looks more integrated, demonstrating that integration potential exists in sustainability science research.

This study revealed the ongoing worldwide relevance of sustainability science research and identified significant opportunities for multidisciplinary integration across the investigated subjects. As such, it sets the path for further study into these tendencies and prospective partnership opportunities in pursuing sustainability in the cities.

Even though the potential future development of sustainable cities remains complicated and not fully answered question; but, based on the results of the literature review, to successfully develop future cities, a multidisciplinary and integrated approach is essential. It involves embracement of compact city planning and development practices, integration of green and blue infrastructure, and promotion of resilience. Smart city concepts, supported by digital technologies and data-driven approaches, can also enhance urban livability and efficiency. Additionally, the creation of healthy cities requires considering factors such as urban sports facilities, access to nature and the well-being of residents. It is crucial to address spatial and social inequalities. Overall, the development of future cities should aim to achieve the balance between environmental, social and economic aspects to create livable, resilient and sustainable urban environments.

Author Contributions: Conceptualization, L.S.; data curation, D.L.; formal analysis, I.G.-V. and I.P.; investigation, I.G.-V. and I.P.; supervision, L.S.; validation, D.L.; writing—original draft, I.G.-V. and I.P.; writing—review and editing, L.S. and P.A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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