Discover Sustainability

Review

Smart city and sustainability indicators: a bibliometric literature review

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Received: 10 April 2024 / Accepted: 12 June 2024
Published online: 08 July 2024

Abstract
This study delves into the pivotal role that indicators play in designing, assessing, and guiding policies for sustainable urban development. Indicators, encompassing both quantitative and qualitative measures, serve as essential tools in evaluating efforts toward sustainable development, providing a practical and objective means of understanding the complex urban environment. The lack of a robust database is identified as a hindrance to monitoring sustainable development progress, underscoring the importance of comprehensive indicators. The study employs a bibliometric literature review methodology, focusing on smart city and sustainability indicators (SSCI) from 2015 to 2022. A total of 818 articles were narrowed down to 191 through rigorous criteria. The study showcases a growing interest in this field, with the number of articles published experiencing a remarkable 288% increase from 2015 to 2022. China emerges as a focal point, leading in both article production and citations, emphasizing its commitment to sustainable development and smart city initiatives. The keywords "sustainable development", "sustainability" and "urban development" had the most occurrences in text analysis. We found three different clusters with k-means analysis, and the circular economy indicators were the most representative category. In conclusion, the study underscores the holistic vision of SSCI in the current scenario, balancing technology and sustainability to improve urban quality of life while safeguarding the planet. Encouraging further research into integrating resilience-focused indicators and innovative solutions is crucial for enhancing sustainable urban development and informing policy decisions.

Keywords Circular economy · COVID-19 pandemic · Sistematic literature review · Sustainable urban development · Resilience

1 Introduction

Amidst the rapid urbanization, challenges posed by climate change, and escalating urban population growth, the pursuit of sustainable urban development has emerged as a global imperative. As cities undergo unprecedented expansion, meeting inhabitants' needs while minimizing environmental impact and promoting social equity becomes paramount [1]. This rapid growth raises urgent issues affecting people's quality of life, the environment, and the future of urban communities [2, 3].

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43621-024-00328-w.

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In response to this dynamic urban landscape, the concept of 'smart cities' has emerged as an innovative solution to urban challenges. Smart cities leverage advanced technologies, data, and innovative strategies to enhance urban efficiency, quality of life, and sustainability [4, 5]. However, the definition of a truly 'smart' city extends beyond technology, with sustainability serving as its foundational principle [6, 7]. The 2030 Agenda for Sustainable Development, introduced in 2015, encompasses 17 Sustainable Development Goals (SDGs), with SDG #11 specifically focusing on 'Sustainable Cities and Communities' [8]. This goal aims to enhance urban sustainability, resilience, safety, and inclusiveness [8]. Aligned with the broader objectives of sustainable urban development, smart cities prioritize efficiency through intelligent information and communication technology (ICT) management [9].

The success of SDG 11 hinges on diverse stakeholders, encompassing citizens, organizations, and the environment [10, 11]. Recognizing and addressing their varied needs is vital for urban development [11, 12]. Integrating stakeholder value creation with urban sustainability prioritizes long-term goals over short-term gains, encouraging policies that promote engagement and align with the SDGs [10]. Despite obstacles such as limited resources and political willingness, these challenges present openings for creative solutions and cooperation. By adopting sustainable approaches, cities can advance towards their sustainability aims, bolstering economic robustness and societal unity [10–12].

The integration of smart cities and sustainability aims to establish technologically advanced, environmentally conscious, socially inclusive, and economically robust urban environments [9, 13]. This holistic vision underscores the importance of balancing technology and sustainable living, with the overarching goal of improving the quality of life for urban residents while safeguarding the planet for future generations [14–16]. Assessing sustainability becomes crucial, with the identification and application of appropriate indicators playing a pivotal role in measuring progress towards smarter and more sustainable cities [17, 18].

Indicators, representing generic variables derived from observations or estimates, are essential tools in the context of urban development. They make it possible to evaluate efforts toward sustainable development in a way that is both practical and objective. In urban development, indicators include both quantitative and qualitative measures that show how sustainable the environment is, how strong the economy is, how welcoming society is, and how resilient the city is [19, 20]. Cities can figure out what their current state is, set goals for sustainability, and plan a way to make their cities more livable, fair, and environmentally friendly by using indicators in a planned way [18, 21].

While previous studies have extensively explored the concepts of smart cities and sustainability independently, there is a notable gap in the literature concerning the integration of these two domains, particularly in terms of practical implementation and measurable outcomes [22, 23]. Current research often lacks comprehensive frameworks that effectively combine technological advancements with sustainability indicators to guide urban development [24]. This study aims to bridge this gap by a bibliometric literature review to address the intersection between smart city and sustainability (SSCI), emphasizing the fundamental role of indicators in the design, assessment, and guidance of policies for sustainable urban development. Through a systematic review of articles from 2015 to 2022, this study aims to identify the principal authors, articles, journals, countries, keywords, and networks, thus describing the current scenario of publications in SSCI topics.

SSCI are essential for systematically evaluating and guiding the progress of cities towards sustainability goals. These indicators provide measurable data that help cities understand their current sustainability status and identify areas for improvement [25, 26]. By incorporating SSCI, cities can track their performance in key areas such as energy efficiency, resource management, and social inclusiveness. This not only aids in effective urban planning and policy-making but also ensures that technological advancements contribute to long-term ecological balance, economic resilience, and social equity [25, 26]. Ultimately, SSCI bridge the gap between smart technologies and sustainable development, fostering urban environments that are not only intelligent and efficient but also sustainable and livable for future generations.

The study encompassed a bibliometric literature review, aiming to comprehensively understand the role of SSCI. Initiated by a foundational set of keywords, a text mining approach optimized the search for relevant articles in Web of Science and Scopus databases. Eligibility criteria refined the dataset to 191 articles, subsequently analyzed using the bibliometrix R package in Rstudio, provided insights into scholarly contributions and research trends within SSCI. Additionally, K-means cluster analysis categorized indicators into sustainability dimensions, enhancing understanding of their distribution and relationships. This methodology integrated various techniques to examine the scholarly landscape, contributing to a comprehensive understanding of SSCI research.

2 Methodology

2.1 Bibliometric literature review

This study employed a systematic literature review methodology, leveraging the PECO approach to define the specific domain under investigation [27]. The domain of interest pertains to both direct and indirect indicators providing informative insights into the central research question. The deliberate application of the PECO approach facilitated the standardization of our systematic review protocol. The primary objective of this study is to comprehensively comprehend the functional role of sustainability and smart city indicators (SSCI). In the initiation phase of the literature gathering protocol, we engaged with a foundational set of seminal knowledge to guide our approach. To initiate the naïve step of data collection, a set of pertinent keywords was meticulously selected to aptly encapsulate the essential information. This preliminary step involves assembling an initial dataset of research studies aligned with the researcher's domain expertise. The initial dataset of keywords was: ((("sustainable development" OR "sustainability") AND ("smart cit*" OR "smart sustainable cit*")) AND (econom* OR social OR environment* OR ecolog* OR govern* OR technolog* OR transport* OR energ*) AND (indicator* OR variable*)).

In sequence, we used a text mining approach to analyze the textual content available in the title and abstract sections of the research articles obtained in the naïve step (hereafter enhanced step). This procedure was used to quantitatively obtain the most relevant words based on the co-occurrence network of words to assemble a new set of relevant terms that optimized the research for articles [28]. Then, we used the new keywords to search for research articles in the Web of Science (WoS) and Scopus databases that occurred between 2015 and August 2022. We did this using the Litsearchr package [28], implemented in the R software [29]. The databases were systematically searched using the keywords extracted in the text mining. These keywords were sought within the titles, abstracts, and keywords of the materials. The boolean operators "AND" and "OR" were incorporated into the query to ensure the presence of all specified keywords within the documents. Adopting a replicable process performed according to standards set by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [30].

2.2 Data collection

The process of data collecting involved searching for articles in databases. The WoS and Scopus databases were selected to ensure a thorough research approach, as they include thousands of peer-reviewed journals covering various subject fields.

The naive search using the initial keywords was performed in the WoS and Scopus databases, and the result was 262 files for WoS and 354 for Scopus, with 455 unique files shared between the databases. From this, the script in the R software was used by the litsearch package. Thus, based on the terms generated by the script in R, a new search was made in the databases, with the keywords after the text mining, and for this result, two criteria of eligibility were applied: peer-reviewed articles only and language, only English, Spanish, and Portuguese, being accepted (Table 1).

The enhanced research result was 885 articles for WoS and 1077 articles for Scopus; with the exclusion of the duplicated studies, we got a total of 960 unique articles. Then other criteria were applied to the date of publication, being selected articles from the year 2015 to August 2022, as it was the year in which the SDGs were proposed [8], thus the total number of articles was 818. Then, two criteria were applied to the 818 articles. We read the title and abstract of the articles in order to select those that have affinity with the topic addressed, sustainability and smart cities, for a total of 450 articles. For the last criteria, we selected the articles that presented indicators with a unit or description, and a total of 191 articles were selected (Fig. 1).

Table 1 Eligibility criteria for selection articles in bibliometric review

Inclusion criteria	Exclusion criteria
Peer reviewed studies	Duplicate studies
English, Spanish and Portuguese language	Other languages
Title and abstract related to sustainability and smart citites	Secondary studies
Document reporting indicators	Studies without indicators

From the initial search, a total of 191 articles were generated. These articles underwent a thorough examination to assess their relevance and content concerning the research topic of SSCI. Subsequently, the bibliographic data of these 191 publications was exported as a plain text file and then downloaded for further bibliometric analysis. The data was exported, including information such as authors, titles, author affiliations, publication years, citation counts, author-provided keywords, additional keywords, countries of publication, affiliated institutions, journals, and citations.

2.3 Data analysis

The collected data was imported into RStudio with the bibliometrix R package, which was employed for processing and analyzing bibliographic data. Subsequently, the biblioshiny app was utilized to create conceptual maps and network analyses. Finally, a presentation was developed to outline research trends and suggest directions for future investigations in the field of SSCI.

The research delved into various aspects, including authors, articles, journals, countries, and some factors such as contributions, keywords, H-indexes, and citations. The analysis examined the collaborative and co-citation networks among authors. Finally, we analyzed the keywords with the co-occurrence and word cloud.

2.4 Network analysis

By employing co-citation, co-authorship, and co-occurrence keyword networks, we sought to delve deeper into the scholarly contributions within the realm of the SSCI topic. These discoveries significantly enrich our comprehension of the subject matter, providing valuable insights into the dynamics of scholarly collaboration and knowledge dissemination. By integrating multiple network analysis techniques, we were able to construct a comprehensive picture of the scholarly landscape within the SSCI topic. This holistic approach not only deepened our understanding of the collaborative relationships among researchers but also provided valuable insights into the key themes and trends driving research in this area.

2.4.1 Co-citation network

A co-citation network was generated. It is important to note that the nodes within a co-citation network represent cited articles, and while their connections indicate the frequency of co-citations, they can be used to measure whether the author is influential in the literature [31, 32]. Thus, the bibliometrix-biblioshiny tool was able to identify which of all the authors were the most cited and, from the lines connecting them, perceive those with the highest frequency of co-citation [33].

The distribution of authors in a network occurs through the application of the Louvain clustering algorithm. This method, known for its accuracy, particularly excels in handling extensive co-citation networks. It utilizes the concept of

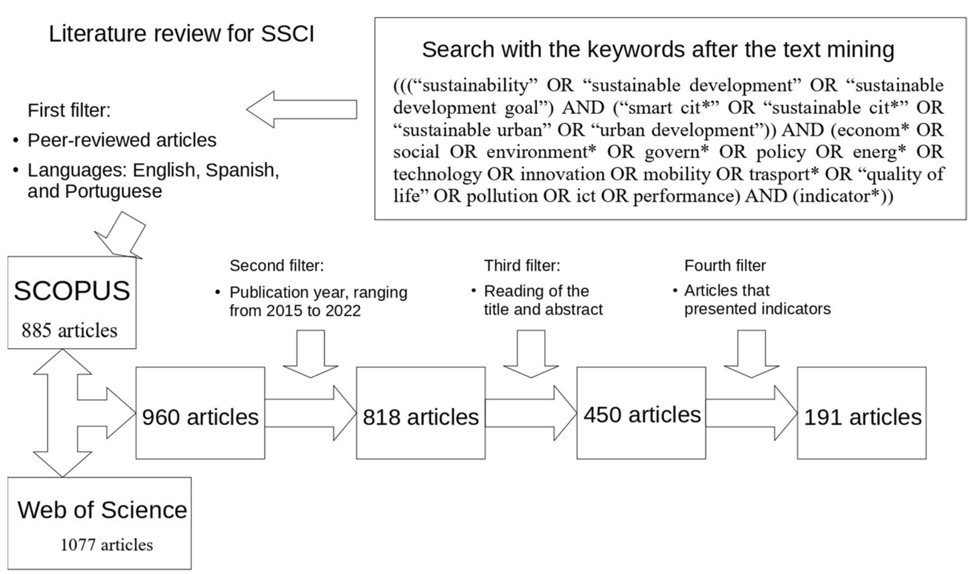

Fig. 1 The process of data collection for article selection in the bibliometric review, using the eligibility criteria and PRISMA guidelines

modularity, a measure that assesses the significance of partitioning the network into communities [34]. The map reveals two key elements defining the intellectual structure of the research field. Firstly, the node size signifies the extent of co-citation an author has garnered from peers [33]. Secondly, the distances between authors and subgroups indicate the level of intellectual affinity among them [33].

2.4.2 Co-authorship network

The global scientific collaboration among authors was generated by the bibliometrix-biblioshiny tool, and the research hotspots could be unraveled through the visualization of the co-authorship network. The size of the circles depicts the number of occurrences of documents, and the strength of research collaboration is revealed by the distance between circles in individual pairs [35, 36]. The thicker and shorter the line between two circles representing different authors, the more collaboration exists [35, 36].

2.4.3 Co-occurrence keywords network

To visualize the research hotspots in the SSCI scientific field, the co-occurrence keyword network was generated using the bibliometrix-biblioshiny tool. The size of the circles corresponded to the number of occurrences of the represented keywords, and the larger the circle, the more the keyword had been co-selected in the SSCI topic [32, 36]. The topical similarity and its relative strength were demonstrated by the distance between the elements of individual pairs [32, 36].

2.5 Indicators dataset

During the literature review, articles that presented indicators were selected, and the indicators were gathered. These indicators were organized in spreadsheets, containing information such as description, unit of measurement, and polarity (positive or negative effect). The indicators were categorized into sustainability dimensions, namely: environmental, economic, social, governance, performance, transportation, and technology and innovation.

We used the k-means cluster analysis to find cluster structures in our indicator dataset characterized by the greatest similarity within the same cluster and the greatest dissimilarity between different clusters [37]. Basically, k-means is a clustering algorithm that explores the data distribution and classifies the objects into different groups, partitions a dataset into subsets (clusters), and establishes rules for grouping data with similar characteristics [38, 39].

This results in the partitioning of a specific dataset according to clustering criteria without any prior knowledge of the dataset. In an ideal clustering scenario, each cluster comprises similar data instances that are significantly different from instances in other clusters [40]. The k-means algorithm assigned each point to the cluster whose center (also called the centroid) is nearest [38]. The center of a cluster is the average of all points in the cluster; that is, its coordinates are the arithmetic mean for each dimension separately over all the points in the center [38].

After selecting our indicator dataset, we performed our script program based on the R software package factoextra. We determined the optimal number of clusters using the function fviz_nb_clust () in the R package factoextra, and the method used was the silhouette. Principally, k-means clustering involved calculating distance measures for all values and creating a new center-based point that represented the means of values for each cluster [41]. This new center-based point was called a centroid professionally [41].

3 Results

The search was in SSCI, and the retrieval time was from 2015 up to 2022. A total of 191 articles were generated in 87 different journals for 592 authors, and these articles were verified and examined based on their content or contribution to the research topic SSCI. Table 2 presents the summary information of our dataset, with some information about the documents, keywords, authors, and collaborations.

3.1 Authors

We identified a total of 592 different authors in this study. We are emphasizing those who had the most number of articles published (Table 3). In the top 10 authors, all of them are Chinese, and Wang C has the highest number of publications

Table 2 Overview of bibliometric review SSCI search from 2015–2022 resulted in 191 articles, summarizing the dataset information, including documents, keywords, authors, and collaborations

Information	Number
Timespan	2015:2022
Sources (Journals, Books, etc.)	87
Documents	191
Annual Growth Rate %	20.4
Document Average Age	3.53
Average citations per doc	18.63
References	8860
Document contents	
Keywords Plus (ID)	1181
Author's Keywords (DE)	728
AUTHORS	
Authors	592
Authors of single-authored docs	13
Authors collaboration	
Single-authored docs	15
Co-authors per Doc	3.64
International co-authorships %	8.38
Document types	
Article	191

with six articles, followed by the other six authors that have four publications. While some authors have published as primary authors, most have published as co-authors. With regards to research citations on the SSCI topic, the author Li J has the highest number of citations with 121, followed by Wang J with 90 citations and Shen L with 87 citations. The author with the highest H-index is Shen L. with four; this metric measures both productivity and citation impact.

3.2 Articles

A survey was conducted on the number of articles published per year between 2015 and August 2022. In 2015, when the SDGs were implemented, nine articles were published on the SSCI topic. In 2022, considering only the first 8 months of the year, there were 35 articles published. This represents a remarkable increase of 288% in eight years in the number of articles published (Fig. 2). It's worth noting that a significant surge in article publications occurred between 2017 and 2018, with a 100% increase in the number of articles published. The highest peak of publications about SSCI topics occurred in 2021 (37 articles), followed by 2020 and 2022 (35 articles). A quantity of articles published over the 8 years of analysis reveals a trend of growth over the years. Between 2015 and 2019, 84 articles (44%) related to the SSCI topic were published, while from 2020 to 2022, 107 articles (56%) related to the SSCI topic were published.

Table 3 Highlighting bibliometric insights, this study identifies 592 authors, emphasizing the top 10, all of whom are Chinese. Wang C leads with six publications, while Li J tops the citation count with 121. Shen L holds the highest H-index at four, reflecting a balance between productivity and citation impact

Ranking	Authors	No. of articles	Citations	H-index
1°	Wang, C	6	73	2
2°	Li, J	4	121	2
3°	Li, Y	4	66	3
4°	Ren, Y	4	58	2
5°	Shen, L	4	87	4
6°	Wang, J	4	90	3
7°	Wang, X	4	47	3
8°	Zhang, Y	4	33	2
9°	Chan, P	3	29	3
10°	Chen, W	3	23	2

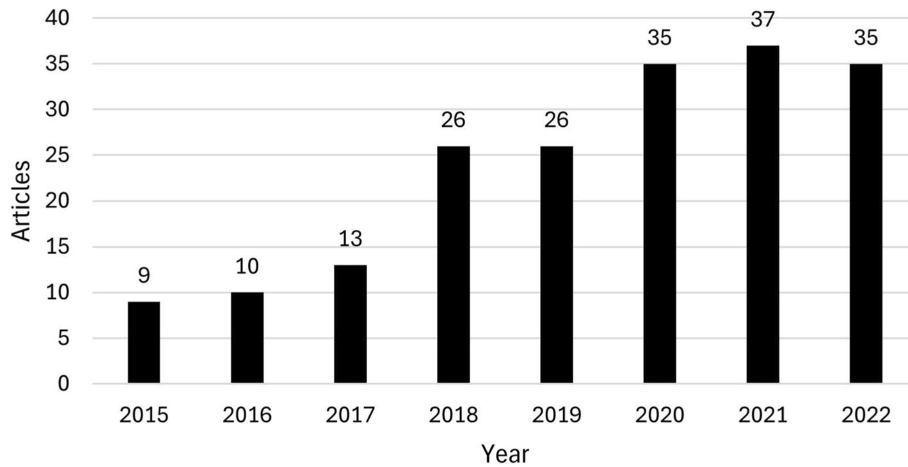

Fig. 2 The growth in SSCI article publications from 2015 to August 2022. The implementation of the SDGs in 2015 marked the beginning, with 9 articles, reaching a remarkable 288% increase in 2022 (35 articles). The analysis reveals a consistent growth trend, with 56% of articles published from 2020 to 2022 compared to 44% from 2015 to 2019

Table 4 presents the top 10 most cited articles on the SSCI topic. The most cited articles primarily focus on sustainability in urban areas as their main research axis, with variations leaning towards smart sustainable cities, environmental sustainability, and nature-based solutions. Out of the total articles on the survey, only 5 of them had more than 100 citations, and it is noteworthy that the publication years among the top 10 most cited articles varied between 2015 and 2019. Regarding the journals of the top 10 most cited articles, the most cited journals were Ecology and Society, Sustainability, and Journal of Cleaner Production, with two articles published.

The most cited article was published in 2016, with a total of 433 citations [42]. The article talked about how nature-based solutions (NbS) can provide benefits in terms of mitigating and adapting to climate change and therewith supporting human well-being in cities, and how they need to be recognized and developed as proactive investments, supported as such in planning procedures, and fostered in joint dialogues between policy, society, and science [42]. It was followed by the article published in 2018, with a total of 116 citations [43]. The article talked about how eco-efficiency can be achieved in cities. The government must realize the importance of environmental protection with the prioritization of ecology over economy in governmental thinking, with the continuous encouragement of technical innovation in every aspect of economic activities and human life, and, finally, with the relative balancing of resource supply [43].

Closing the top 3 most cited articles were two articles published in 2016 and 2019, with a total of 111 citations [44, 45]. In the first one, the article talked about the development of an urban carrying capacity evaluation model and its strategic importance in sustainable development through the promotion of urban sustainability as a priority policy objective. In the second one, they talked about how cities can be viewed as the source of and solution to many of today's economic, social, and environmental challenges, and it is necessary to promote initiatives to enhance sustainability, resource efficiency, and inclusiveness in cities. Regarding the total citations per year, [42] is the highest article with 54,13 citations per year, followed by [45] with 22,2 citations per year and [43] with 19,33 citations per year (Table 4).

3.3 Journals

In the survey, a total of 87 journals were founded, showing the global distribution of publications in SSCI literature. Table 5 presents the list of the top 10 journals in which results from SSCI were mostly published. A total of 103 articles are presented in Table 5, representing 54% of the total 191 publications during 2015–2022. The journal with the most articles published on the topic under consideration was Sustainability, with 39 articles, followed by Sustainable Cities and Society with 17 articles, and Journal of Cleaner Production with 16 articles. In total, the sum of articles from these top three journals represents a total of 72 articles out of the 191 analyzed, which accounts for 37.5% of the total.

With regards to journal citations, Sustainability was the most cited journal with 614, followed by Journal of Cleaner Production with 468 citations and Ecology and Society with 435 citations. In general, journals with high citations usually have a high H-index and tend to have a more important academic effect in SSCI, except for the journal Ecology and Society, which registered a lot of citations in just one article but had a lower H-index than other journals that had fewer citations.

Table 4 Top 10 most cited articles in SSCI, between 2015 and 2022. Notably, [42] leads with 433 citations, emphasizing the importance of Nature-based solutions in addressing climate change in urban areas

Ranking	Paper	Total citations	Total citations per year
1°	Kabisch, N., Korn, K., Stadler, J., Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society 21(2):39. https://doi.org/10.5751/ES-08373-210239	433	54.13
2°	Zhou, C., Shi, C., Wang, S., Zhang, G. (2018). Estimation of eco-efficiency and its influencing factors in Guangdong province based on Super-SBM and panel regression models. Ecological Indicators, 86: 67–80. https://doi.org/10.1016/j.ecolind.2017.12.011	116	19.33
3°	Wei, Y., Huang, C., Li, J., Xie, L. (2016). An evaluation model for urban carrying capacity: A case study of China's mega-cities. Habitat International, 53: 87–96. https://doi.org/10.1016/j.habitatint.2015.10.025	111	13.88
4°	Akande, A., Cabral, P., Gomes, P., Casteleyn, S. (2019). The Lisbon ranking for smart sustainable cities in Europe. Sustainable Cities and Society, 44: 457–487. https://doi.org/10.1016/j.scs.2018.10.009	111	22.2
5°	Phillis, Y. A., Kouikoglou, V. S., Verdugo, C. (2017). Urban sustainability assessment and ranking of cities. Computers, Environment and Urban Systems, 64: 254–265. https://doi.org/10.1016/j.compenvurbsys.2017.03.002	106	15.14
6°	Li, F., Liu, X., Zhang, X., Zhao, D., Liu, H., Zhou, C., Wang, R. (2016), Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems. Journal od Cleaner Production, 163: 512–518. https://doi.org/10.1016/j.jclepro.2016.02.079	90	12.86
7°	Ding, L., Shao, Z., Zhang, H., Xu, C., Wu, D. (2016). A Comprehensive Evaluation of Urban Sustainable Development in China Based on the TOPSIS-Entropy Method. Sustainability, 8(8): 746. https://doi.org/10.3390/su8080746	88	11
8°	Wei, Y., Huang, C., Lam, P. T. I., Sha, Y., Feng, Y. (2015). Using Urban-Carrying Capacity as a Benchmark for Sustainable Urban Development: An Empirical Study of Beijing. Sustainability, 7(3): 3244–3268. https://doi.org/10.3390/su7033244	67	7.44
9°	Egilmez, G., Gumus, S., Kucukvar, M. (2015). Environmental sustainability benchmarking of the US and Canada metropoles: An expert judgment-based multi-criteria decision making approach. Cities, 42: 31–41. https://doi.org/10.1016/j.cities.2014.08.006	64	7.11
10°	Peng, Y., Lai, Y., Li, Y., Zhang, X. (2015). An alternative model for measuring the sustainability of urban regeneration: the way forward. Journal of Cleaner Production, 109: 76–83. https://doi.org/10.1016/j.jclepro.2015.06.143	63	7

Table 5 Top 10 journals in SSCI literature. Sustainability leads with 39 articles, followed by Sustainable Cities and Society (17), and Journal of Cleaner Production (16), contributing significantly to the overall analysis

Ranking	Journal	H-index	Citations	Number of articles
1°	Sustainability	14	614	39 (20%)
2°	Journal of Cleaner Production	13	468	16 (8%)
3°	Sustainable Cities and Society	9	359	17 (9%)
4°	Ecological Indicators	7	244	12 (6%)
5°	Cities	3	92	4 (2%)
6°	Habitat International	3	131	4 (2%)
7°	Social Indicators Research	3	67	3 (1.5%)
8°	Ecology and Society	2	435	2 (1%)
9°	Environmental Science and Pollution Research	2	14	4 (2%)
10°	IEEE Access	2	23	2 (1%)

3.4 Country

The total of 191 articles selected for the SSCI literature were produced in 44 different countries, with a range of 1 to 64 articles published per country. As a result, the country with the highest number of articles published was China, with 64 studies. It was followed by articles that are not specific to any location and are represented as "No Data." Accounting for 17 articles, these studies are theoretical and are not applied to a specific locality; therefore, they were considered in this manner. Additionally, there are 12 articles conducted on Spain (Fig. 3).

It is immediately evident how the theme has developed in countries located on different continents, highlighting a growing interest in the SSCI topic. In Asia, China has the highest number of articles published in SCCI literature, with Iran and Turkey closing the top 10 countries. Spain, Italy, Germany, and Portugal published the maximum number of articles on the topic in Europe, while in South America, Brazil is the most representative country.

The following graphs relate to the citations recorded for the countries. Figure 4 presents the total number of citations recorded for each country, with China leading with 1176 citations, followed by Germany and Italy with 457 and 247 citations, respectively. In Asia, China is the most cited country, with Turkey and Iran in the top 10 countries. Germany, Italy, Spain, Greece, and Portugal are the most cited countries in Europe. Followed by the USA in North America and Australia in Oceania.

Meanwhile, Fig. 5 shows the average number of citations per article per country, with Germany leading at an average of 91.4 citations per article, followed by the United Kingdom and Greece with averages of 42 and 39.2 citations per article, respectively. In Europe, Germany is the most cited country per article, followed by the United Kingdom, Greece, Finland, Italy, Switzerland, Portugal, and Slovenia. Closing the top 10 countries. Australia is in Oceania, and Chile is in South America.

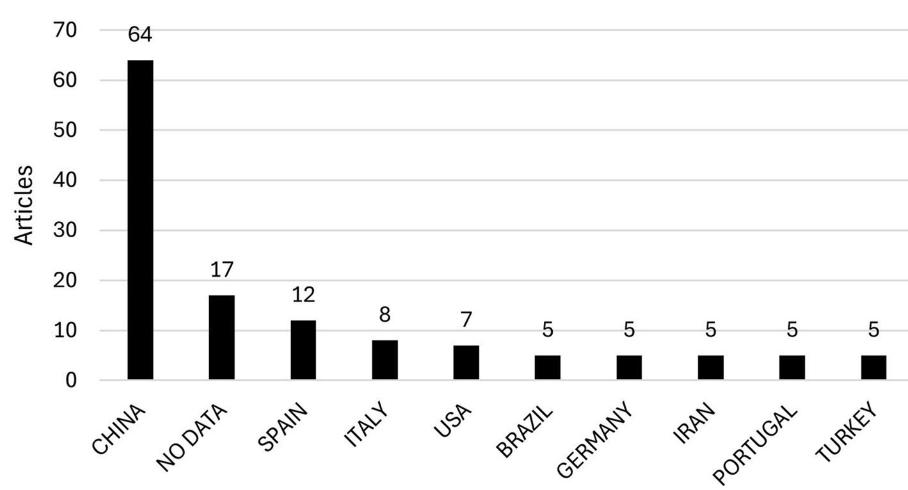

Fig. 3 Global distribution of SSCI literature—China stands out with 64 articles, leading in Asia, while Spain, Italy, Germany, and Portugal contribute significantly in Europe. Brazil emerges as the focal point in South America

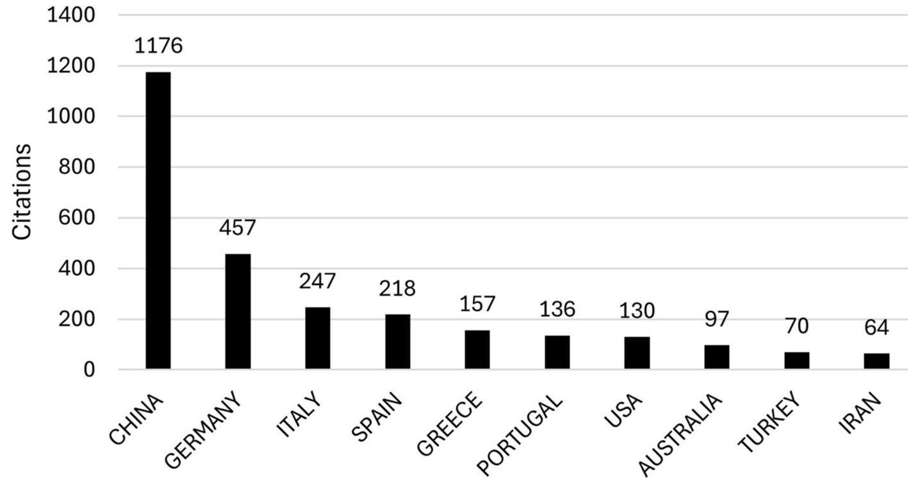

Fig. 4 Total citations by country, with China leading at 1176 citations, followed by Germany and Italy

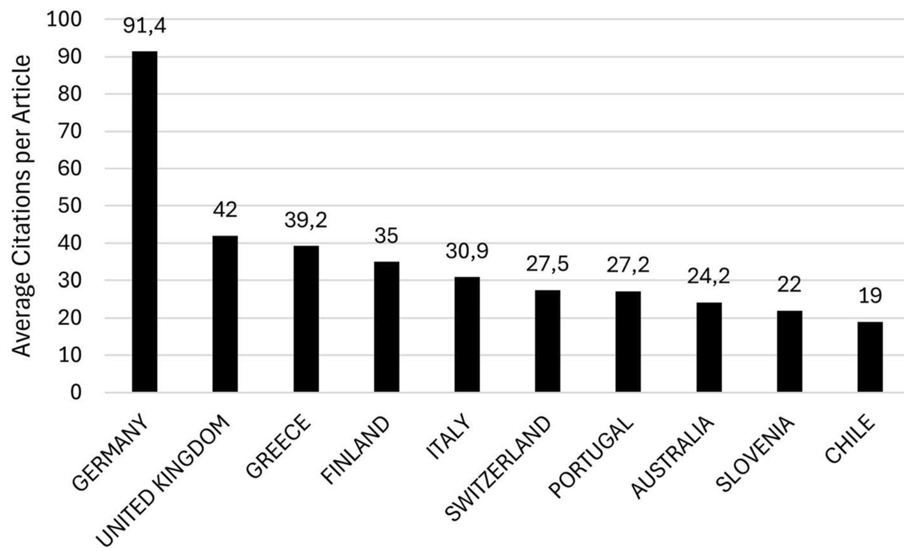

Fig. 5 Average citations per article per country, showcasing Germany with the highest average at 91.4, followed by the United Kingdom and Greece

China held a leading position in terms of publication and citation quantity; however, Germany came in first in terms of citations per article, meaning that research works from China are more consulted and referenced as compared to the other countries, and Germany has the most referenced average among the countries. China doesn't appear in the top 10 countries in citations per article, which is attributed to the large number of papers published on the topic, ultimately reducing the average number of citations per article.

3.5 Network analysis

This section aims to present the results of networks involving authors and keywords, highlighting both co-citation and collaboration among researchers, and the principal keywords. This analysis provides a comprehensive view of the interactions and connections occurring within the academic environment, revealing patterns of collaboration and influences among members of the scientific community and the principal keywords identified in the analysis.

3.5.1 Author co-citation network

The results in Fig. 6 show five subgroups of cited authors that help represent the intellectual structure of publications in SSCI. The largest network (blue) consists mainly of authors Wang, Liu, Zhang, Wu, Li, and Huang. These authors compose a cluster of 41 occurrences and have the highest values of citation frequency. The second-largest network (green and red) is distinguished by its high closeness to the main network (blue); the distance of the blue subgroup from both the

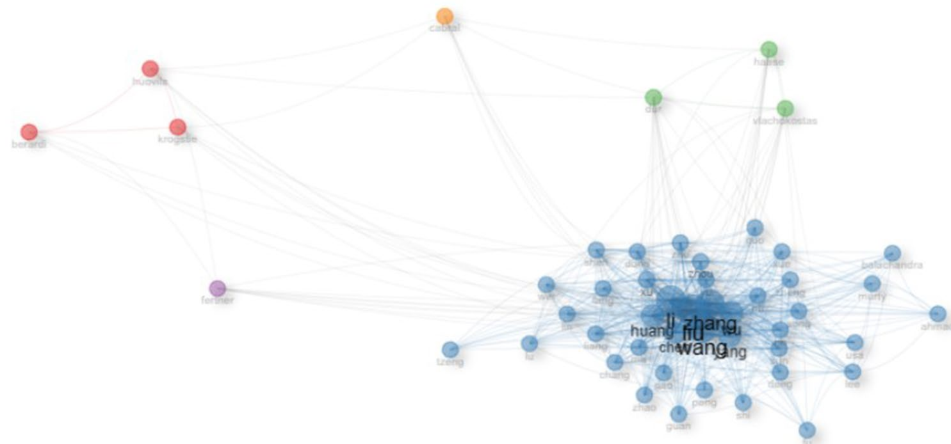

Fig. 6 Utilizing the bibliometrix-biblioshiny tool, a co-citation network was generated to identify influential authors in SSCI literature. The key cluster is represented by Chinese authors, including Wang, Liu, Zhang, Wu, Li and Huang

green and red subgroups indicates less frequent co-citation among its authors and consequently less intellectual affinity. The third subgroup (orange and purple) is represented by Cabral in the orange group, which emphasizes sustainability in urban areas, and Fertner in the purple group, which emphasizes smart cities.

3.5.2 Colaboration network

With regards to collaboration between authors, the analysis formed 10 clusters: Zhang Y, Wang J, and Shen L have the highest co-authorship (green), followed by Wang C, Wang X, and Chen N, who have the second highest co-authorship (red), and then Wang W, Xue B, and Sun X, who have the third highest co-authorship (purple) (Fig. 7). The aforementioned information about the authors and sources with the highest number of publications and citations could assist future researchers on the SSCI topic.

It is possible to observe a relationship between authors and their respective countries, with the Chinese author community having a large network of collaboration, while authors from other countries have smaller collaboration networks among themselves. Partnership among authors from different countries could contribute to increasing knowledge production on the SCCI topic.

3.5.3 Co-occurrence keyword network

The co-occurrence keyword network in Fig. 8 illustrates seven distinct clusters, representing individual subfields of the research areas in the SSCI topic. The highest cluster (blue) had the words "sustainable development", "sustainability", and "urban development" as the circles with the most occurrences and linkages. The second-highest cluster (green) had the word "urban growth" as the most occurrences. The third-highest cluster (red) had some words "city" and "cities" as

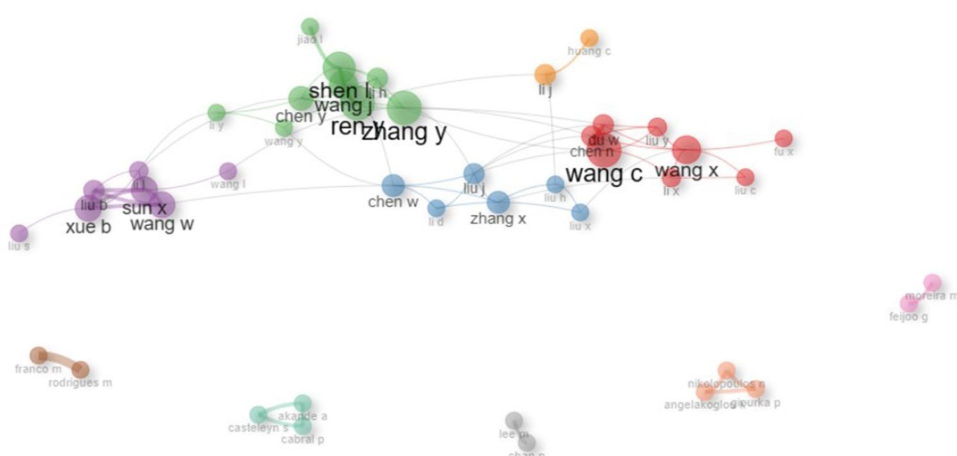

Fig. 7 Global scientific collaboration among authors. The analysis formed 10 clusters, highlighting leading co-authorships, particularly in the Chinese author community (green) in the SSCI field

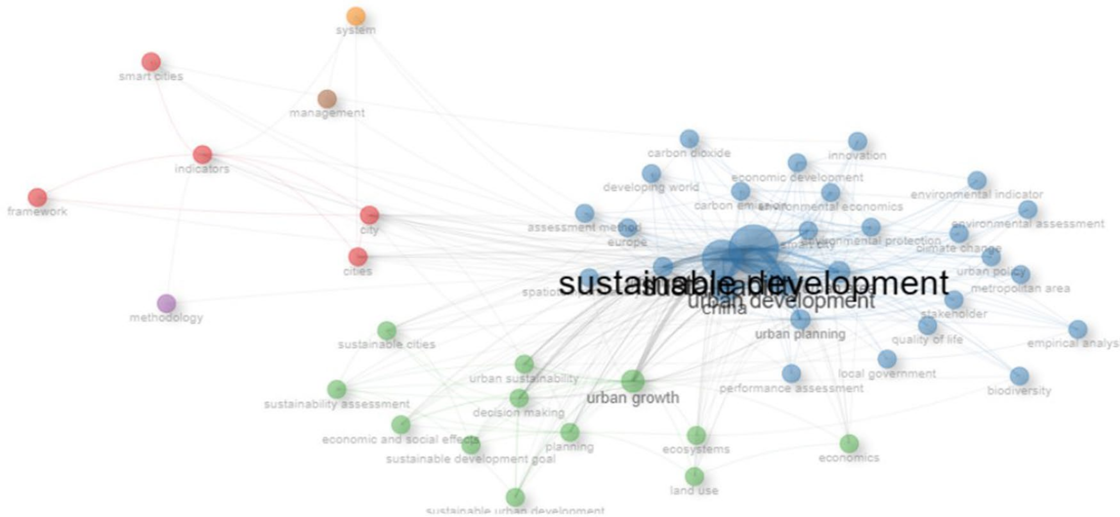

Fig. 8 The co-occurrence keywords network delineates 7 clusters, showcasing subfields in the SSCI research

the most linkages. The other three clusters were identified with just one occurrence: the orange one with "system", the brown one with "management", and the purple one with "methodology".

3.6 Clustering indicator categories

We found 4896 indicators, dividing them into 7 dimensions: social (1804 indicators), environmental (1382 indicators), economic (593 indicators), transport (370 indicators), governance (294 indicators), performance (249 indicators), and technology and innovation (204 indicators, see Supplementary Material 1 and 2). The total indicators were categorized into 269 categories, with a range of 1 to 159 indicators per category. We found that 37 categories registered only 1 indicator, and 159 indicators were registered in 1 category (circular economy).

In the k-means analysis, we found that dimension 1 had 28.4% in total explanation and dimension 2 had 14.9%. The analysis indicated that the ideal number of clusters was 3, classified into A, B, and C. In the A cluster, we found economic, governance, and transport indicators representing the cluster. In the B cluster, we found technology and innovation indicators representing the cluster. Finally, in the C cluster, we found environmental and social indicators representing the cluster. Performance indicators were represented in the three clusters (Fig. 9).

4 Discussion

The bibliometric analysis conducted in this study provides a comprehensive overview of the state of research in the field of SSCI from 2015 to 2022. A total of 191 documents from 87 different sources were analyzed. The findings revealed several key insights. The principal authors in terms of publications, citations, and H-index are Chinese. China led in terms of the number of articles published and the number of citations, and six of the 10 most cited articles in SSCI literature were developed by Chinese authors. Furthermore, China had a large network of collaboration, while authors from other countries had smaller networks, showing the importance of the country in the development of indicators for sustainability and smart cities.

China plays a crucial role in formulating SSCI, reflecting its prominent position on the global stage and its commitment to sustainable development. The magnitude and complexity of challenges faced by Chinese cities make the implementation of effective measurement systems essential to assess and guide progress [46, 47]. In a bibliometric analysis of scientific publications on SDGs with an emphasis on good health and well-being, it was reported that China is among the top-five most productive countries in SDGs research [48]. Similarly, another bibliometric analysis covering sustainable development literature from 1993 to 2019 found that China is among the top-five most productive countries in this field [49]. However, in a bibliometric analysis for urban sustainability assessment, China was reported as the most productive country [50]. Additionally, a bibliometric analysis of the scientific landscape of smart and sustainable city literature

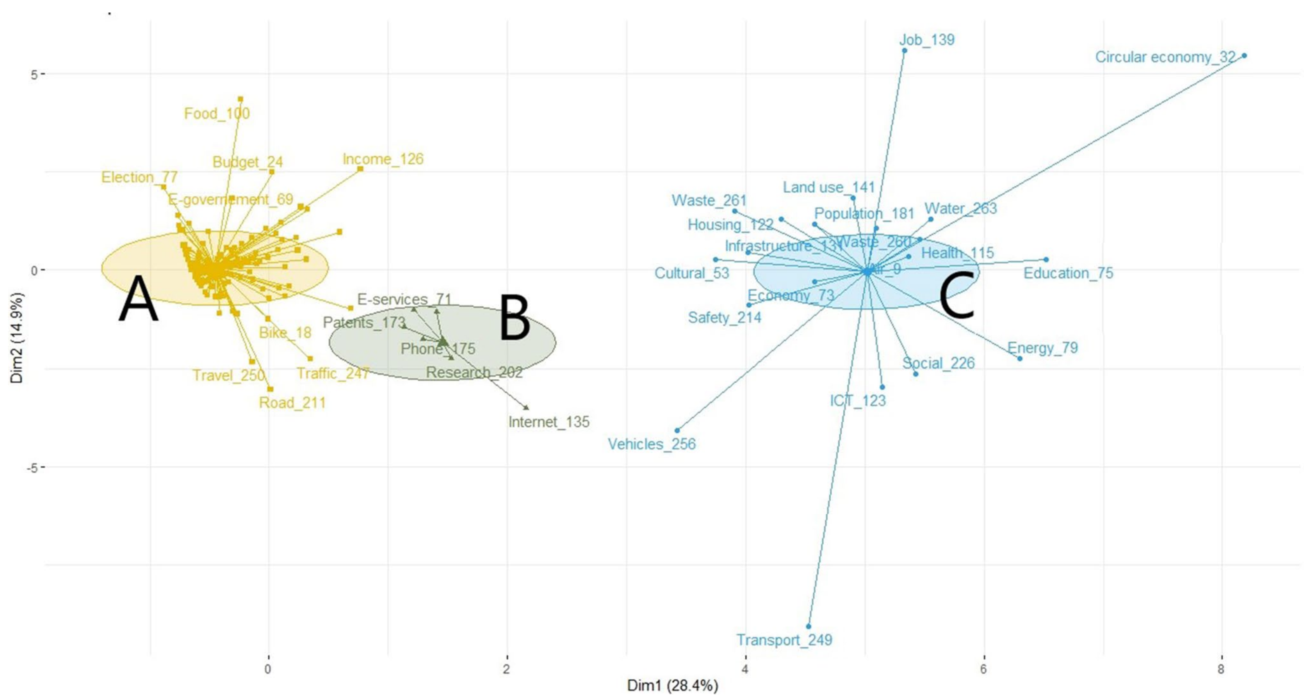

Fig. 9 The k-means analysis reveals 3 clusters (**A**, **B**, **C**) with distinctive indicator compositions, illustrating their roles in economic, governance, and transport (**A**), technology and innovation (**B**), and environmental and social aspects (**C**), with performance indicators distributed across all clusters

indicated that China is the most productive country in smart city research [36]. Furthermore, another bibliometric diagnosis and analysis of smart cities also confirmed that China leads in productivity in this domain [51].

China emerges as a central player in formulating SSCI, offering valuable lessons and innovative solutions that resonate on an international scale. The country's impact in these fields underscores the need for global collaboration to address common challenges related to sustainability and intelligent urban development. In a total of 191 papers analyzed, 134 of them were related to China. Its commitment to reducing emissions and transitioning to clean energy sets an example for other nations and contributes to global efforts to combat climate change [52, 53]. China's policy decisions, such as urbanization strategies and environmental regulations, have global significance, and successful policies can serve as models for other countries facing similar challenges [54, 55].

The analysis showed a significant growth in the number of articles published on SSCI over the years. In 2015, nine articles were published, while in 2022, 35 articles were published, marking a substantial increase of 288% over eight years. The highest number of publications occurred between 2020 and 2022. The rapid growth in recent years can be attributed, in part, to the emergence of the coronavirus disease in 2019 (COVID-19). The swift and widespread outbreak of the novel COVID-19 had devastating effects on countries worldwide, introducing new challenges to ensure the sustainability of cities [56, 57].

In the wake of COVID-19, cities are prioritizing resilient and sustainable urban development, with a strong emphasis on integrating smart technologies and data-driven solutions [58, 59]. Efforts are directed towards ensuring equitable access to essential services, green spaces, and digital infrastructure [60, 61]. Recovery strategies are centered on sustainable transportation, including pedestrian-friendly infrastructure and enhanced public transit networks [62, 63]. Collaborative partnerships with academic and private sector stakeholders are driving innovation to address urban challenges such as climate change adaptation and public health resilience [64, 65]. Inclusive governance frameworks empower local communities in decision-making processes, fostering a sense of ownership and collective responsibility [66, 67]. This post-pandemic era presents a pivotal moment for cities to build more resilient and livable urban environments, prioritizing the well-being of all residents in preparation for future challenges [68, 69].

The SSCI has taken significant steps in the post-COVID-19 pandemic era. The global crisis caused by the pandemic has brought forth new priorities and challenges that have directly impacted the development of smart cities and how we measure their sustainability [59, 70]. One of the most notable changes has been the emphasis on resilience. Out of 191 papers, 13 talked about resilience in different scenarios: urban resilience (7), climate change resilience (3), community resilience (1), environmental resilience (1), and disaster resilience (1).

In [71], they developed an urban resilience index using indicators of urban sustainability for environmental, economic, infrastructure, and social dimensions. They found that the primary factors influencing urban resilience in Chinese cities were the proportion of actual use of foreign capital in the GDP and carbon emissions per 10,000 CNY of GDP, both having negative impacts [71]. On the other hand, GDP per square kilometer, the proportion of urban pension insurance coverage, the proportion of the population with higher education, and expenditures on city maintenance and construction had positive impacts [71]. Futhermore, [72] developed a tool for assessing low-carbon and disaster-resilient housing for communities, with the aim of encouraging the implementation of climate mitigation and adaptation strategies at the community level with vulnerable groups.

The pandemic has highlighted the importance of cities being able to adapt quickly to shocks and stresses, such as pandemics, natural disasters, and economic crises [73, 74]. Therefore, indicators now consider resilience as a key element in assessing urban sustainability [75, 76]. Resilience is a critical aspect of sustainability in smart cities, acknowledging the challenges posed by climate change and other uncertainties. The integration of resilient infrastructure, disaster preparedness measures, and adaptive urban planning enhances the city's ability to withstand shocks and disruptions while ensuring the well-being of its inhabitants [74, 77].

"Sustainable development", "sustainability" and "urban development" were the principal keywords in the analysis; they had the most occurrences among the keywords, with more than 47 occurrences each. They are crucial elements when considering the transformation of urban spaces into smart cities. These concepts hold immense importance across various dimensions.

Sustainable development in smart cities represents a paradigm shift in urban planning and governance. It involves the harmonious integration of technology, social equity, economic viability, and environmental responsibility [78, 79]. The transition to smart cities requires a holistic approach that not only leverages cutting-edge technologies but also prioritizes long-term ecological balance and community well-being [78, 80]. In the context of smart cities, sustainable development extends beyond the conventional focus on economic growth. It encompasses the efficient use of resources, reduction of environmental impact, and enhancement of the overall quality of life for urban residents [9, 81].

Sustainability is an essential pillar that underpins the very essence of smart cities. It is an interwoven principle that guides urban planners, policymakers, and city dwellers towards creating urban environments that are not only technologically advanced but also environmentally responsible, socially inclusive, and resilient [82, 83]. Establishing sustainability in smart cities relies heavily on the integration of robust environmental systems. These systems play a pivotal role in ensuring that urban centers can effectively balance growth and development with environmental conservation and resilience [83–85].

Urban development is a dynamic and complex process that responds to the evolving needs of a growing urban population. As more people migrate to urban areas in search of better opportunities, cities must adapt and expand to accommodate this influx [86]. Proper land use planning is fundamental to ensuring efficient utilization of space, preventing urban sprawl, and promoting compact, well-designed urban environments [87, 88]. Holistic urban planning that integrates environmental responsibility, social inclusivity, and technological advancements is essential for creating cities that are not only sustainable but also smart and resilient [83, 89]. The choices made today in urban development will shape the cities of tomorrow, influencing the quality of life for urban residents and the overall well-being of the planet [90, 91].

For the key themes, stakeholders wield indicators as potent instruments to propel smart, sustainable cities forward and achieve the SDGs [92, 93]. Citizens serve as agents of change, embracing eco-conscious behaviors and advocating for policies conducive to sustainability [94, 95]. Businesses emerge as engines of innovation, embedding sustainable practices within their operations and aligning with global sustainability imperatives [96, 97]. Government agencies play pivotal roles in monitoring progress and enacting evidence-based policies to foster sustainable urban development [98, 99]. Simultaneously, civil society organizations champion equity and environmental justice, amplifying the voices of marginalized communities and spearheading grassroots initiatives [100, 101]. Through collaborative efforts fueled by indicators, stakeholders synergize their actions, unlocking new pathways for progress towards a more sustainable future [102, 103].

According to [104], in a 35-year bibliometric analysis of urban sustainability concepts, "sustainability" and "sustainable development" emerged as the most frequently used terms. In bibliometric analyses involving the terms "sustainable development", "sustainability", and "urban development", the most frequently used term for urban development was "sustainable urban development". This indicates a spatial planning approach to cities that incorporates sustainability as a guiding principle [104–106]. Futhermore, in a bibliometric analysis of the Sustainable Development journal spanning twenty-seven years from 1993 to 2019 revealed that the most commonly used keywords in publications during this period were "sustainable development" and "sustainability" [49]. This suggests that between 2010 and 2019, there was a focus on environmental sustainability and its role in global economies [49].

Clustering analysis with k-means for our indicator dataset revealed three different clusters: A, B, and C. In Cluster A, the interaction between economics, governance, and transportation within the SSCI framework creates a synergistic environment that drives smart city success [107–109]. A robust economy generates employment, attracts investment, and fosters innovation [109]. Effective governance ensures fair resource distribution and transparent decision-making, benefiting businesses and communities [110]. The integration of these pillars with transportation enhances urban mobility, supports economic activities, and reduces environmental impact [111, 112]. Accessible public transportation promotes inclusive economic participation and helps in urban planning, sustainability, and social inclusivity [113]. This interdependence forms a virtuous cycle, fostering sustainability and prosperity in smart cities [114].

In Cluster B, technology and innovation indicators stand out, playing a crucial role in SSCI. The integration of cutting-edge technologies is a driving force behind improved efficiency, reduced environmental impact, and overall sustainability enhancement [115]. These interventions aim not only to optimize resource utilization but also to create a more responsive and sustainable urban environment [116]. The innovation ecosystem, fostering collaborations between technology firms, research institutions, and local governance, propels continuous technological advancements, offering solutions to intricate sustainability challenges and shaping the evolution of smart urban landscapes [117, 118]. Despite challenges, such as potential exclusions, the ongoing evolution of technology holds promise for effectively addressing future sustainability challenges.

In Cluster C, the central theme revolves around the intersection of social and environmental factors within the context of SSCI. The symbiotic connection between social and environmental dimensions takes precedence, emphasizing that community well-being is closely tied to environmental health and sustainability [119–121]. This dynamic interaction underscores the need to consider social aspects alongside environmental initiatives for comprehensive smart city development [13, 122]. Social initiatives contribute to positive environmental outcomes, and vice-versa. This may include community engagement in environmental initiatives, awareness campaigns, and participatory approaches that involve residents in sustainable practices [123, 124]. Conversely, environmental conditions influence social aspects, such as the positive effects of a cleaner environment on residents' health and overall quality of life [125, 126]. This recognition reinforces the importance of integrated strategies that embrace both social and environmental considerations, steering us towards a future of resilient, inclusive, and sustainable smart cities.

The interconnectedness of these clusters ensures that advancements in one area support and enhance outcomes in others, creating a synergistic effect across urban development. For instance, smart governance practices enable efficient resource allocation and policy implementation, which directly supports technological innovations like smart transportation and energy-efficient infrastructure. These advancements not only drive economic growth by attracting investment and improving operational efficiency but also promote social inclusivity by making urban services more accessible and equitable. At the same time, technological innovations contribute to environmental conservation by reducing carbon emissions and improving waste management systems. Social initiatives, such as community engagement and the development of green spaces, further reinforce these benefits by fostering a sense of community and enhancing the quality of urban life. This holistic approach ensures that cities can achieve the SDGs, where economic vitality, social equity, and environmental health are not pursued in isolation but as interconnected objectives. By leveraging the strengths of each cluster, cities can create resilient, livable environments that are prepared to meet the challenges of the future.

Circular economy was the category with the highest number of indicators and demonstrated its importance in cultivating a harmonious relationship between social and environmental factors in the SSCI topic. Initiatives such as community engagement in recycling programs, job creation through repair and refurbishment, and the promotion of sustainable consumption contribute to both social and environmental well-being [127–129]. Circular economy principles empower communities, reduce waste, and enhance overall quality of life, serving as a unifying force in the pursuit of comprehensive and sustainable urban development within the SSCI.

The symbiotic relationship between these elements is essential to creating resilient, resource-efficient, and environmentally conscious urban environments. Within the realm of smart cities, a focus on circular economy indicators introduces a holistic approach to resource management [130]. By emphasizing the reduction, reuse, and recycling of materials, smart cities can optimize resource utilization, minimize waste generation, and contribute to the establishment of closed-loop systems [131, 132]. On sustainability, the circular economy indicators present metrics such as material efficiency, waste diversion rates, and product life extension as integral components of a comprehensive sustainability framework within the smart city paradigm [133, 134].

As smart cities continue to evolve, the integration of indicators of the indicators of the circular economy stands out as a transformative force. The key lies in recognizing that circularity is not merely a component but a fundamental ethos that underpins the smart and sustainable cities of the future [128–130]. This interplay between the circular economy, smart cities, and sustainability indicators represents a forward-looking approach where technological innovation converges with environmental stewardship to create urban environments that are not only smart but also enduring and regenerative.

5 Conclusion

In conclusion, our study highlights the imperative for specific planning and policy recommendations aimed at optimizing the use and better integration of smart city and sustainability indicators. The synthesis of data and analysis underscores the critical role that these indicators play in shaping urban development strategies for a more sustainable future. Moving forward, policymakers and urban planners should prioritize the integration of these indicators into decision-making processes to ensure that cities are effectively moving towards sustainability goals. Specific recommendations could include the development of comprehensive urban planning frameworks that incorporate both smart city technologies and sustainability principles. Additionally, there is a need for greater collaboration between government agencies, academic institutions, and industry stakeholders to foster innovation and knowledge exchange in this field. By leveraging smart city technologies and sustainability indicators in tandem, cities can achieve more efficient resource management, enhance quality of life for residents, and build resilient urban environments capable of addressing future challenges. Ultimately, the adoption of targeted planning and policy measures will be instrumental in guiding cities towards a more sustainable and prosperous future.

In addition to providing specific planning and policy recommendations, it's essential for conclusions to explicitly address the limitations of the study. One limitation is the scope of our data collection, which may not encompass all relevant studies or indicators in the field. Additionally, the analysis may be subject to biases inherent in the selection and interpretation of data. Furthermore, the generalizability of our findings may be limited by the geographical and temporal scope of the studies included in our review. Finally, the dynamic nature of urban development and technological innovation means that our conclusions may not fully capture the most recent advancements or trends in the field. By acknowledging these limitations, we can provide a more nuanced and balanced interpretation of our findings, as well as guide future research efforts in addressing these gaps.

Encouraging further research to delve into emerging challenges and opportunities in sustainable urban development, particularly by integrating resilience-focused indicators and innovative solutions, is paramount. By examining how cities adapt and thrive amidst evolving challenges like climate change, resource scarcity, and population growth, researchers can identify strategies to enhance urban resilience. This entails exploring the role of technology, community engagement, and governance frameworks in fostering resilience and sustainability. Additionally, investigating the socio-economic and environmental impacts of these strategies can provide valuable insights into their efficacy and potential trade-offs. Ultimately, such research can inform policy decisions and urban planning efforts geared towards crafting more resilient and sustainable cities for future generations.

Author contributions LST Conceptualisation, Methodology, Investigation, Software, Formal analysis, Writing—Original Draft, Writing—Review & Editing. EVC Methodology, Investigation, Software, Formal analysis, Writing—Original Draft, Writing—Review & Editing, Supervision. WTM Methodology, Investigation, Formal analysis, Writing—Review & Editing YM Methodology, Investigation, Formal analysis, Writing—Original Draft, Writing—Review & Editing, Supervision. All authors reviewed the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. This study was funded by Fundação Araucária Superior (PD&I 151/2021).

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests The authors declare no competing interests.

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