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Literature Trend Identification of Sustainable Technology Innovation: A Bibliometric Study Based on Co-Citation and Main Path Analysis

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Abstract: In the past 20 years, there have been increasingly more studies on sustainable technology innovation (STI), possessing a significance for sustainable development. This paper aims to provide a research landscape, since the systematic understanding of STI is still inadequate. Through bibliometric analysis, it explores the literature distribution characteristics and the literature citation network. Based on the relevant literature data in the Web of Science (WOS), the study visually analyzes the development trend, topic distribution, burst literature, and co-citation network of the research literature, and extracts the evolution path of literature citation by using the main path analysis method. Through the analysis of co-citation and main path, 13 clusters in the co-citation network are found, which are further extracted as the main path network containing 82 nodes. Furthermore, this paper summarized the bibliometric landscape and discussed the frontier STI research topics. The comprehensive framework contributes to the understanding of STI themes and identifying future research agenda.

Keywords: sustainable technology innovation; literature citation network; bibliometric analysis; co-citation network; main path analysis

1. Introduction

With climate change accelerating, sustainable technology innovation (STI) is attracting more attention than ever before. Recent extreme and unusual weather conditions, such as high temperatures in the Arctic Circle, have raised concerns about the ecological environment. Although the current development of technological innovation has little impact on the process of tackling climate change [1], it will take long-term research and development efforts to see tangible results. Therefore, how to realize the sustainable development of society has become a common issue concerned by the whole society. Driven by the demand for sustainable development, the concept of STI has been formed and developed, which is a transdisciplinary research field, different from traditional technology innovation. STI needs to change the market structure through disruptive technology [2], otherwise there are very few opportunities to implement emission reduction.

STI is a challenge to the mainstream markets and industries [3], thus it faces the fierce competition from traditional technologies. Compared with traditional technological innovation, the STI research field pays more attention to the rational utilization of resources, ecological and environmental protection, and socially sustainable development [4]. Traditional technological innovation takes economic benefit maximization as the main goal and does not consider the adverse consequences caused by sacrificing the ecological environment. There are still many uncertain challenges on how to achieve reliable and sustainable technological innovation, and how to apply the innovative output to economic and social development in a substantial way. Some existing studies [5–7] highlight the important role of sustainable technology in addressing climate change. However, the full information has not yet been excavated from the prior research's text, which shows a mass of research issues and a vast potential for STI. For the motivation, this study intends to explore STI related studies based on bibliometrics analysis, promoting further progress and more interdisciplinarity research in this field.

Furthermore, there are numerous understandings, making it possible to produce puzzles for STI. This paper intends to identify the hotspot distribution and topic evolution trend based on the bibliometrics analysis methods, aiming to provide a systematic understanding for STI and some enlightenments for tackling climate change. Specifically, there are mainly two research problems to be solved. First, what are the core research topics and mainstream literature in this field? Second, how does the research process evolve in the field? By solving the former problem, the aim of the paper is to explore and identify the most relevant literature, which provides a solid knowledge base for future theoretical or empirical research. Moreover, by solving the latter problem, this study aims to summarize the research evolution path in the STI research field, which can provide a reliable inspiration to identify new research perspectives.

The structure of this research is organized as follows. Section 2 introduces the literature data source and bibliometric methodology. Section 3 presents the primary distribution and trend of STI literature. Section 4 presents the bibliometric analysis results of burst literature detection, co-citation network analysis, and main path analysis. Section 5 discusses the research progress based on the three frontier directions. Finally, Section 6 summarizes the findings of bibliometric research and discusses future research agenda.

2. Data Source and Methodology

Web of Science (WOS), Scopus, or PubMed are usually the main data source for bibliometric analysis [8]. To retrieve the related articles as much as possible, this study chose the WOS database as the data source. The search strategy was decided as "Topic = Sustainable Technology Innovation", and the time-span was 1985–2020. The retrieving process was performed on 16 July 2020. Some search restrictions were made for data acquisition, such as the document type limited as "article". The specific scope was limited in the sub-databases of WOS including SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, and IC. Finally, 3431 results were generated.

This paper adopted a series of bibliometrics research methods based on the analysis module of Citespace software (version 5.7 R1) and the main path analysis module of Pajek. By presenting the key information in the literature in visualization, it systematically identified the research evolution trend and specific academic hotspots [9]. In the related research on the bibliometric analysis, the commonly used research methods are citation analysis, keyword analysis [10], and collaborative analysis. In addition, there are many effective tools to visualize the bibliometric analysis results, including VOSviewer [11], Netdraw, and Gephi, which can directly show the knowledge evolution path in specific research fields. These bibliometrics tools and methods play an important role in identifying key articles and research development trends. Based on the prior methods, this study integrated the knowledge base and knowledge evolution path to form a systematic literature review.

Co-citation analysis is a core feature of Citespace, which includes multiple analysis modules. The co-citation network can be generated from literature, authors, or journals. Among the modules, the co-citation network of literature is usually constructed by the nodes of cited literature. The co-citation relationship means that two cited papers are connected since they are cited by the same literature, and the citation network will expand with the increase of relevant literature. Frequent co-citations indicate the existence of the same or similar research topics between the two cited papers [12]. The citation of scientific literature shows the characteristic of unbalanced distribution. Therefore, the importance of the literature can be judged from the sparsity of the citation network, in which the node with high frequency of co-citation has an important position. These nodes can be identified as the core literature, and the potential research topics can be further explored based on the contribution from the core literature.

The co-citation network can reflect the hot topics in the research field, but it cannot show the evolution of the research topics. However, this deficiency can be remedied by main path analysis on scientific literature, which is to discover the basic path of knowledge growth along with time. The main path analysis can be a supplementary bibliometric method for citation network analysis. According to the node position of literature in the direct citation network, the routes of knowledge flowing in specific research fields can be identified, indicating a transitive relationship between prior knowledge and new knowledge. Besides, the main path analysis extracts the core routes of literature evolution from the citation network and then presents the evolution citation chain of literature in a visual way. In this study, the main path analysis can illustrate the evolution of mainstream theories and research frontiers in the STI research field, which can provide a reference for further research effectively. Nevertheless, it is noted that main path analysis is not the core function supported by Citespace software, and it is necessary to combine Citespace with other software to carry out analysis, such as Pajek.

Based on the above prior research methods, the bibliometric research methods and analysis procedures used in this paper are as follows. First, the literature distribution analysis aims to explore the growth trend and bibliometric distribution according to preliminary statistics of literature data. Second, the co-citation analysis is conducted by importing literature data into Citespace software, which then identifies core articles based on the burst literature identification. Third, the main path analysis extracts the citation evolution routes from the direct citation network, identifying the mainstream venation of knowledge diffusion by the visualized citation chain. Finally, the paper discusses the hot research topics, summarizes the research directions, and proposes future research themes.

3. Literature Distribution Analysis

3.1. Literature Development Trend

The concept of STI is formed in a specific economic and social background, which has been updated and expanded in long-term literature research. As shown in Figure 1, the annual distribution of relevant literature demonstrates an overall steady growth trend from 1997 to 2020. From 1997 to 2006, there was little research literature. However, after 2007, the rate of literature growth accelerated with the maximum publication quantity of 650 in 2019. The literature during 2015 and 2020 has a higher growth rate than that before 2015, indicating that the STI research has received widespread attention. Correspondingly, as shown in Figure 2, the overall literature citation quantity is also increasing annually. The citation trend indicates that research topics have received more extensive attention, and there is a need to extend the knowledge system to multiple disciplines, promoting the STI research field.

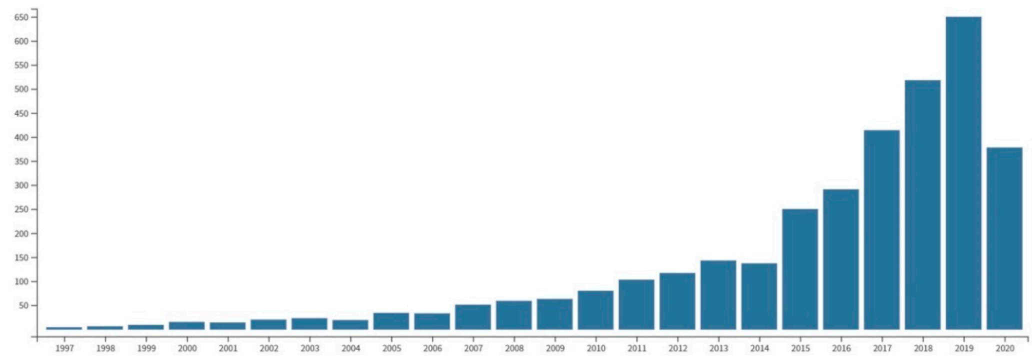

Figure 1. Annual literature distribution in the sustainable technology innovation (STI) research field.

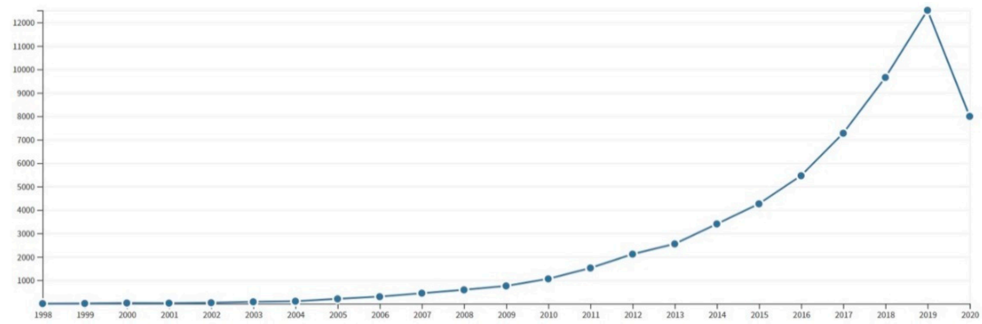

Figure 2. Annual citation distribution in the STI research field.

Figures 1 and 2 indicate that the STI research field is in a growth stage rather than an aging stage according to the increasing trend of literature and citation. The trend further illustrates that more and more attention is paid in the field of STI. Besides, the annual quantities show a steady growth trend, and this study speculates that future research of STI has enough potential. However, the annual trend can only provide a simple interpretation on the literature development. Knowing what the research focuses are and how research evolves are also the main goals of literature distribution analysis. Therefore, subsequently, this study explored the structure of the STI field through research area and subject category analysis, and further detected the citation process based on the dual-map overlap analysis.

3.2. Research Area and Subject Category

STI related literature shows explosive growth in more than 20 years according to the literature development trend. This research field involves various research topics, which can be illustrated by a wide range of research areas and subject categories. Especially in the field of industrial manufacturing, the concept of STI is extended to multiple segments of the economic and social system. In the bibliometrics analysis of this paper, the research area and subject category were used to describe the knowledge structure characteristic of the STI research field. These two classification regimes were according to Clarivate's InCites (http://help.incites.clarivate.com/). The research area is an important bibliometric indicator for benchmarking the peer publications and has approximately 250 components in the WOS. Scholars can be evaluated according to the citations in the same research area. Moreover, the subject category is also a bibliometric indicator but a narrower classification scheme. The subject category reflects the corresponding knowledge attribute of a research theme. For the 3431 items of literature data, there are 118 research areas and 184 subject categories in total. Table 1 presents the top 20 ones respectively.

Table 1. Top 20 research areas in WOS.

Research Area	Records	Research Area	Records
Environmental Sciences Ecology	1216	Operations Research Management Science	83
Business Economics	946	Development Studies	75
Science Technology Other Topics	878	Information Science Library Science	71
Engineering	654	Materials Science	66
Public Administration	224	Geography	64
Energy Fuels	220	Chemistry	62
Agriculture	157	Public Environmental Occupational Health	51
Social Sciences Other Topics	113	Construction Building Technology	48
Computer Science	103	Urban Studies	46
Education Educational Research	83	Water Resources	46

The relevant studies are mainly distributed in four research areas, "Environmental Sciences Ecology", "Business Economics", "Science Technology Other Topics", and "Engineering". Among them

"Environmental Sciences Ecology" has the most literature records, while the quantities of the other three areas decrease stepwise. In addition, for the other research areas regardless of the above four ones, the corresponding literature quantity is relatively less. The situation indicates that "Environmental Sciences Ecology" is the main research area in the STI field originally, but with the research development, there is a shift to other areas. In terms of the literature distribution quantity, there are obvious characteristics of imbalance among different research areas. However, this feature also indicates that there is still much space for exploration in the STI research.

In addition, the statistical results of the top 20 STI subject categories are shown in Table 2. The relevant research papers concentrate in the categories of "Environmental Sciences", "Green Sustainable Science Technology", and "Environmental Studies". In contrast, there are moderate research literature distributions in subject categories such as "Management", "Business", "Engineering Environmental", and "Economics", while the quantities of articles distributed in other subject categories are less than the above categories. The statistical results of Tables 1 and 2 together indicate that the STI research has an emerging, comprehensive, and intersected development trend. They can provide a primary understanding for STI by ranking the hotpot classifications. The first classification indicates that STI usually concerns environment issues, which involve social science and nature science. Therefore, the classifications of business, economic, and management can be seen in the forefront of the ranking. The engineering classifications show that the STI theme has relation with a series of industrial sectors.

Table 2. Top 20 subject categories in WOS.

Subject Category	Records	Subject Category	Records
Environmental Sciences	969	Multidisciplinary Sciences	92
Green Sustainable Science Technology	781	Operations Research Management Science	83
Environmental Studies	686	Agriculture Multidisciplinary	75
Management	463	Development Studies	75
Business	343	Education Educational Research	71
Engineering Environmental	328	Information Science Library Science	71
Economics	303	Engineering Multidisciplinary	64
Energy Fuels	220	Geography	64
Regional Urban Planning	191	Engineering Chemical	63
Engineering Industrial	94	Social Sciences Interdisciplinary	59

3.3. Journal Citation Distribution

Dual-map overlap analysis is a characteristic function of Citespace software, mainly used to analyze the citation relationship of journals in specific research fields [13]. Through portfolio analysis of citing journals and cited journals, the analytical outcomes can intuitively show the journal distribution and the corresponding research categories, and the knowledge flow process among different disciplines can be further indicated from the distribution of citation links. In the outcome figure, nodes of citing journals are presented only when the number of corresponding articles is higher than 5, and journal titles are displayed only when the number of corresponding articles is higher than 50. Besides, the average citation frequency is the threshold that decides whether the cited journals can be showed. If the frequency is higher than 10, nodes of cited journals will be showed. If the frequency is higher than 15, journal titles will be displayed.

Therefore, the dual-map overlap outcome is mainly composed of graph elements such as citing journal nodes, cited journal nodes, and links connecting nodes with titles of research categories. The research category mentioned here is derived from the cluster analysis result of Citespace software, which adopts a different classification standard compared with the research area of WOS. In general, the left area of the figure is for the nodes of citing journals, while the right area is for the nodes of cited journals. In addition, the ellipse size represents the development scale of the corresponding research category, where the vertical axis length of the ellipse represents the number of papers published, and the horizontal axis length of the ellipse represents the corresponding number of authors.

Through the Z-score function in Citespace software which simplifies the reference relationship between journals, the result of the dual-map overlay analysis in the STI research field is generated as Figure 3. It shows that the main category of citing journals is “7. Veterinary, Animal, Science”, and the main categories associated with the above category include “2. Environmental, Toxicology, Nutrition”, “12. Economics, Economic, Political”, and “7. Psychology, Education, Social”. The second major category of citing journals is distributed in “6. Psychology, Education, Health”, and the main categories of cited journals linked to the prior category include “12. Economics, Economic, Political” and “7. Psychology, Education, Social”. The third major category of citing periodicals is “10. Economics, Economic, Political”, and the main categories of cited journals linked to the category before include “12. Economics, Political” and “7. Psychology, Education, Social”. These associations reveal that the knowledge domain mainly concentrates in the above-mentioned research categories, which have become the core components of STI literature. In addition, the results also show that the knowledge flow process is in a cyclic stable state. Most knowledge flow activities are performed within the same research category, while a small amount of knowledge flows to different research categories and generates interactions.

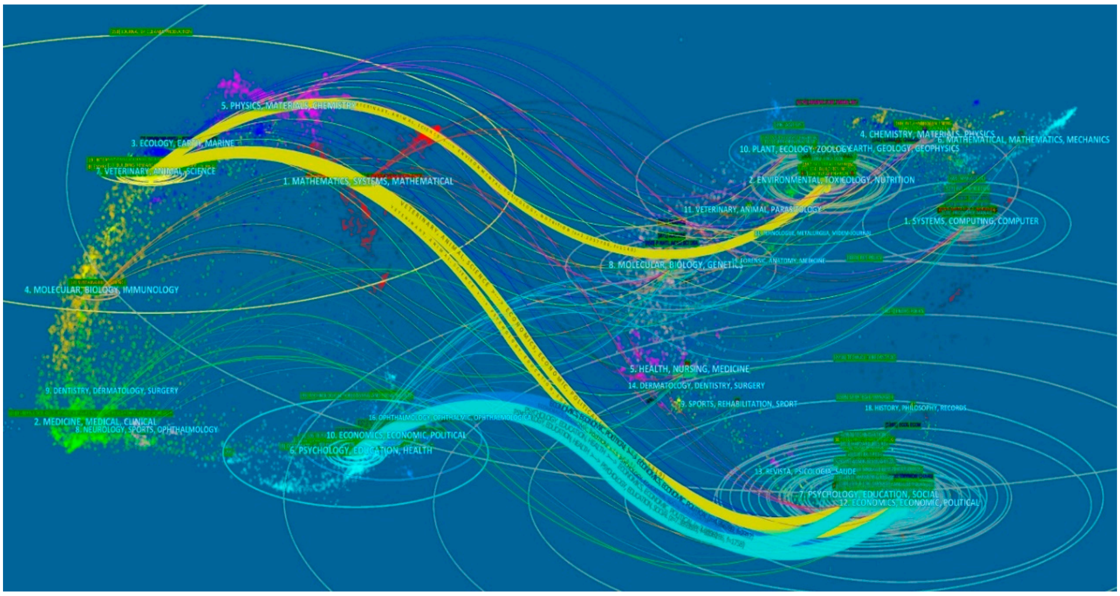

Figure 3. Journal citation dual-map overlap of STI research.

4. Bibliometric Analysis

4.1. Burst Literature Exploration

Through the exploration of Citespace software, the preliminary result shows that the time-span of forming a non-null network in the original literature dataset is 1997–2019, with 3027 corresponding literature records in the analytic dataset. In this study, Citespace software is used to identify and summarize the articles with the top 20 burst strength, and Table 3 presents the descriptions of the 20 articles from a total of 67. The time interval of these 20 articles is roughly 2000–2010. In Citespace [14], the burst literature means that the cited frequency of the literature has a jumping trend in a period, and the burst strength is a quantitative index measuring the rate of citation surge for the literature. The burst trend can be detected based on the Kleinberg’s algorithm [15], which helps to find the core literature as pioneer of a new research area [16].

Table 3. Top 20 burst literature identification.

References	Year	Strength	Begin	End	1997–2019
Smith, A., 2005, RES. POLICY	2005	15.4629	2007	2013	
Geels, F.W., 2007, RES. POLICY	2007	14.9539	2008	2015	
Geels, F.W., 2002, RES. POLICY	2002	14.3395	2007	2010	
Schot, J., 2008, TECHNOL. ANAL. STRATEG.	2008	13.7349	2011	2015	
Hekkert, M.P., 2007, TECHNOL. FORECAST SOC.	2007	11.7165	2008	2015	
Geels, F.W., 2004, RES. POLICY	2004	9.4914	2008	2012	
Jacobsson, S., 2004, IND. CORP. CHANGE	2004	8.7404	2007	2012	
Rockstrom, J., 2009, NATURE	2009	8.6319	2014	2017	
Bergek, A., 2008, RES. POLICY	2008	7.7048	2008	2016	
Smith, A., 2007, TECHNOL. ANAL. STRATEG.	2007	7.5099	2013	2015	
Geels, F., 2006, TECHNOL. ANAL. STRATEG.	2006	7.4865	2008	2014	
Hodson, M., 2010, RES. POLICY	2010	7.4825	2012	2014	
Shove, E., 2007, ENVIRON. PLANN. A	2007	7.3273	2013	2015	
Smith, A., 2010, RES. POLICY	2010	7.2931	2012	2016	
Markard, J., 2008, RES. POLICY	2008	7.0507	2009	2014	
Seyfang, G., 2007, ENVIRON. POLIT.	2007	6.7916	2013	2015	
Horbach, J., 2008, RES. POLICY	2008	6.6571	2014	2016	
Unruh, G.C., 2000, ENERG. POLICY	2000	6.5157	2007	2008	
Loorbach, D., 2010, GOVERNANCE	2010	6.371	2017	2019	
Carrillo-Hermosilla, J., 2010, J. CLEAN. PROD.	2010	6.17	2016	2019	

Note: The dash lines represent the years in 1997–2019, and the red part represents the burst period of literature.

The 20 articles that have burst strength in Table 3 generally reflect the main knowledge in the STI research field. From the burst literature, bibliometric information can be summarized for further research, including research background, key research issues, core theoretical models, and mainstream research methods. As seen in Table 3, studies have formed a theoretical research basis, such as the research of Geels et al. [17–20]. Moreover, the study of Smith et al. [21] having the highest burst strength, mainly analyzed the quasi-evolutionary model of social technological system and expounded the selected situations during the transformation process of the system. Bergek et al. [22] having the longest burst duration, mainly studied the functional dynamic evolution process of the innovation system and provided a practical reference for policymaking. The earliest published article is by Unruh et al. [23], which indicated that innovation in sustainable technologies is mainly caused by fossil-fuel-based energy pathway dependence, and the dependence scale drives the co-evolution of technology and institutions.

Based on the historical background of energy transformation, the above studies regarded the development process of energy technology as a grand and complex system and put forward the theoretical framework of sociotechnical system, which focuses on the relevant mechanisms in the process of technology transformation. This theoretical framework is integrated with the technology evolution from a systematic perspective, and subsequent studies further formed new research perspectives, such as multilevel framework [24], radical innovation [25], and strategic niche [26]. The knowledge base literature emphasizes that technology innovation in energy industry is closely related to the level of social and economic development and forms a development system similar to an ecosystem. In addition, it can be seen that the energy transformation starts from the sustainable development demand of the society, then forms the sustainable innovation of new energy technology, and finally develops the competitive advantage of strategic emerging industries.

4.2. Literature Co-Citation Analysis

Co-citation network of literature is constructed by applying Citespace, as shown in Figure 4. To visualize the important nodes in the limited space, the software provides the g-index criterion to select nodes. The criterion means that the citation frequency of the selected node should be less than the square of citation ranking in all nodes, represented by g-index. Through the analysis, the literature co-citation network in the STI research field is obtained. The result shows that the literature co-citation network has a total of 1056 nodes, 3662 links, and the network density is 0.0066. The network density is the ratio of actual connections to potential connections, used as an index to describe the occupation of connections between nodes in the network. Clustering analysis can be carried out by combining the literature text content corresponding to the literature nodes.

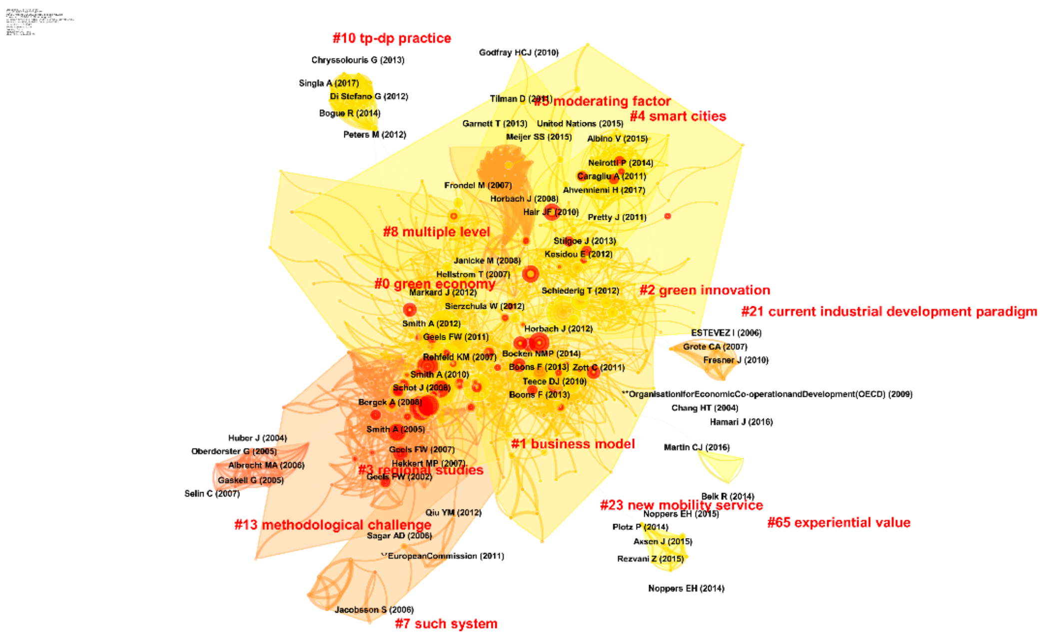

Figure 4. Cluster diagram view of literature co-citation analysis.

Figure 4 reflects the theme relationships of the STI literature. The red text represents the cluster number and cluster label, and the corresponding shaded area is the literature nodes corresponding to the cluster category. The clustering result also shows the core co-citation network divided into 13 clustering categories, among which the largest five are "#0 Green Economy", "#1 Business Model",

"#2 Green Innovation", "#3 Regional Studies", and "#4 Smart Cities". Through transforming the perspective of bibliometric analysis, the literature co-citation network with cluster labels can be visualized in terms of timeline, as shown in Figure 5. Compared with the cluster diagram in Figure 4, the timeline diagram mainly shows the time interval distribution of the co-citation relationship in each cluster category. For example, the co-citation time interval of cluster category #0 is 2006–2017, while the co-citation time interval of cluster category #3 is 1999–2012.

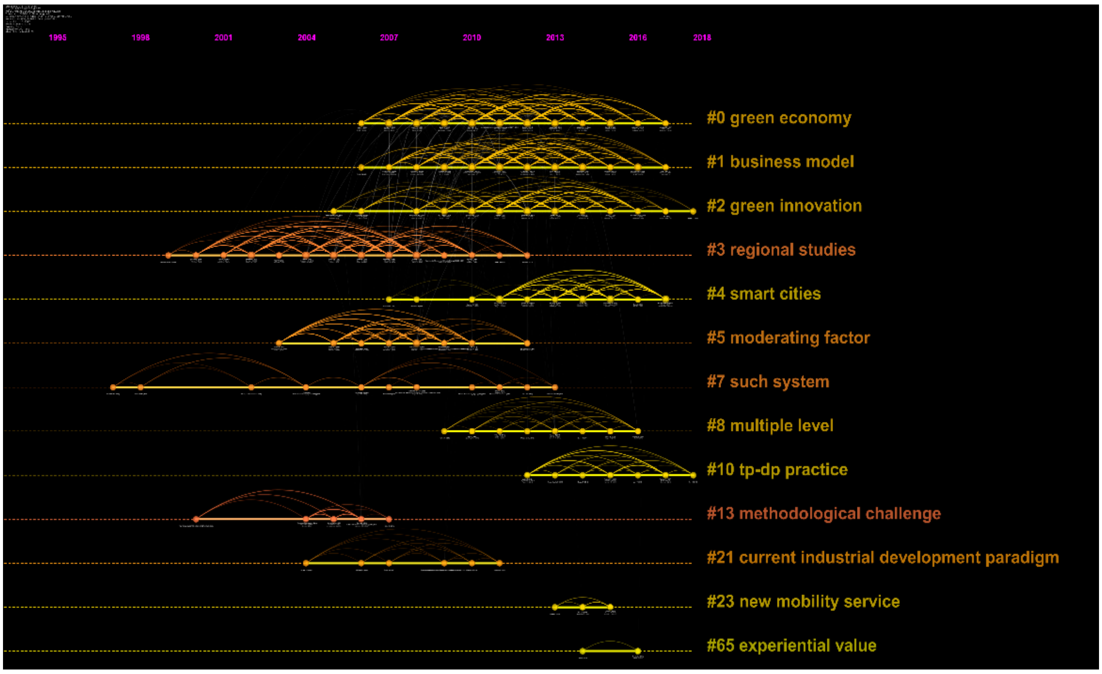

Figure 5. Timeline diagram view of literature co-citation analysis.

It is seen from the cluster diagram that the network size of the other eight cluster categories is significantly smaller than that of the first five main categories. In the eight categories of the clustering, burst exploration analysis results indicate a small amount of burst literature. For example, Horbach [27] investigated the related influence factors of environmental innovation based on Porter's hypothesis and argued that environmental regulation and organizational change promote environmental innovation. This is the only one burst literature in the eight clustering categories, which is subordinate to the clustering category "#5 Moderating Factor" and has a burst strength of 6.6571. Apart from all 13 clustering categories, the burst exploration result shows that there are also a small number of burst articles in the non-mentioned cluster categories. The articles outside the 13 cluster categories reflect underlying research themes which can be the knowledge base of subsequent studies. For example, the studies of Wustenhagen et al. [28] and Chesbrough [29] have burst strengths of 3.4142 and 4.4238, respectively. The previous study focused on technological innovation in renewable energy, examining the impact of social acceptance on technological innovation. Additionally, the following research mainly discussed an issue related to the open innovation mode, proving how the business mode takes full advantage of the information and how the world-renowned companies operate the intellectual property rights.

The clustering results show five main clustering categories. The silhouette value [30] is used to evaluate the literature clustering effect in this study, and the value close to 1 indicates the nodes having an ideal clustering result. "#0 Green Economy" is the largest clustering category in the literature co-citation network and the silhouette value of this cluster is 0.863. The network of cluster #0 contains 124 literature nodes, and there are 17 nodes presenting burst strength. Truffer et al.'s [31] paper is the most actively cited in cluster #0. It explored the sustainable transformation process from innovation perspective and examined the spatial factors in a regional innovation system. The second-largest clustering category is "#1 Business Model" with a silhouette value of 0.896, and there are 113 literature nodes including 15 burst nodes in the cluster. The article of Boons et al. [32] is the most active citer literature in cluster #1, which discussed the sustainable innovation issue and summarized the theoretical framework of sustainable business model. "#2 Green Innovation" is the third largest clustering category with a silhouette value of 0.854, and the cluster contains 103 literature nodes and 10 burst literature nodes. The study of Kiefer et al. [33] is the most active citer literature in cluster #2. The paper identified the influencing factors related to ecological innovation and evaluated the promoting and hindering effects of the factors examined. The silhouette value of the clustering category "#3 Regional Studies" is 0.896. Cluster #3 is the fourth clustering category in the literature co-citation network containing 93 literature nodes and 18 burst nodes. The article of Alkemade et al. [5] is the most active citer literature in cluster #3. It discussed sustainable innovation and argued that the competition challenge of emerging technology comes from the social expectation rather than technological performance. "#4 Smart Cities" is the fifth clustering category in the literature co-citation network. There are 39 literature nodes and four burst nodes in cluster #4, and the silhouette value of this cluster is 0.975. The research of Mora et al. [34] is the most active citer literature in cluster #4. It mainly discussed the sustainable innovation issue on the smart city construction and summarized the strategic principles for promoting smart city development through four European city case studies.

Through the analysis of burst literature exploration and co-citation analysis with cluster, this paper summarizes the knowledge base and topic hotspots in the STI research field. The results indicate that subsequent research will further explore new research directions from the prior studies. With the deepening of the research process, research accumulation can lead to the transformation and evolution of the research topics. Therefore, according to the burst year rather than the publication year, this paper roughly divides the topic development of the STI research into four periods, which describe the evolution process of knowledge base and research topic hotspots. They are 2007–2009, 2010–2012, 2013–2015, and 2016–2017.

At the first stage (2007–2009), the corresponding research promoted the research process from a systematic perspective, such as energy technology system [35], innovation system [36], and energy economy system [37]. Most literature nodes of this stage were subject to cluster #3. At the second stage (2010–2012), the multilevel theoretical framework emerged. The corresponding research aimed to explain and support sustainable technological innovation. Studies explored the application of the multilevel framework in an energy transformation process, such as technology change policy assessment [38], energy transformation management [39], and impact factors on the environment innovation [40]. More literature nodes belonged to cluster #0, and a small number of literature nodes distributed in the cluster #2. At the third stage (2013–2015), researchers took interest in the public policy of sustainable innovation. More research contributed to the concept system of sustainable innovation, including grassroots innovation [41], strategic niche evolution [42], and business model [43] among others. Relevant research articles were mainly distributed in cluster #0 and cluster #1. The research in the fourth stage (2016–2017) tended towards diversification, with research topics related to sustainable innovation further evolving to risk minimization of sustainable innovation [44], diversity factors of sustainable innovation [45], and innovation system framework [46]. In addition, there were some emerging research topics such as responsible innovation [47], green supply chain [48], and smart-city construction [49]. At this stage, many related articles distributed in cluster #2, while others were evenly distributed in cluster #0, cluster #1, and cluster #4.

Based on the above co-citation analysis, the early STI studies focused on research topics related to energy system transformation, mainly because the crisis of fossil fuel use then attracted wide attention from the international community. Besides, the concept of sustainable innovation at that time was not fully developed, and public policy was urgently needed to guide the transformation of the energy system [50]. Subsequently, research topics were formed related to sustainable innovation, and STI research made significant progress from the theory perspective [51]. In the recent progress of the STI research, the emergence of topics, such as smart cities [52], indicated that the basic theories are relatively mature, and there was more attention paid the impact of emerging technologies on sustainability.

4.3. Main Path Analysis

Main path analysis can reflect the mainstream and relevant literature in the overall citation network, as well as highly cited papers in specific research fields [53]. The arc path in the visualization results reflects the evolution of the research topic and methodology. In this study, we applied Pajek to perform the main path analysis, and visualized the result through VOSviewer. As shown in Figure 6, the main path network has a total of 82 nodes and 120 directed arcs, and the density of the overall network is 0.018. The arc linking nodes has a direction. In addition, there are 12 layers in the main path network. The bottom layer is the sink vertex containing one paper, whereas the top layer is the source vertexes containing three papers in total. In a non-cyclic network, the sink vertex represents the node with an output degree value of 0, having no outgoing arcs to other nodes. The source vertex represents the node with an input degree value of 0, having no ingoing arcs to other nodes. For the literature node of sink vertex, Kemp et al. [54] proposed a theoretical framework for strategic niche management of emerging technologies, which aims to realize the transition to a sustainable technology innovation mechanism. Besides, the literature node is the only sink vertex in the main path network, reflecting that this literature is the core knowledge base in the STI research field.

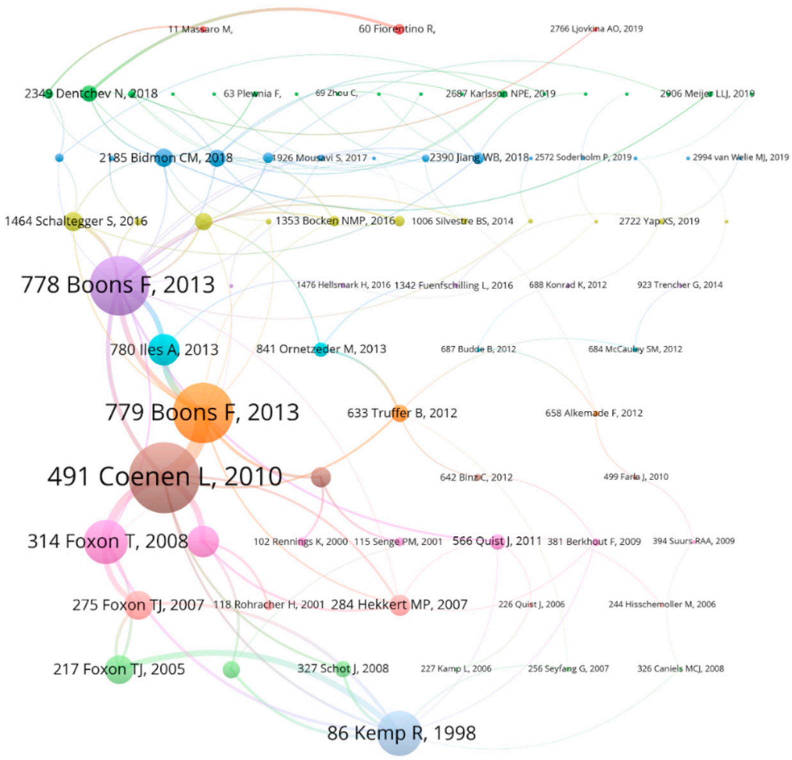

Figure 6. Main path network visualization of the STI research field.

According to the attribute value ranking of arcs, the first 30 arcs in the main path network are presented in Table 4. The attribute value is the traversal weight of citation, referring to the proportion of citation arc or literature node in all paths between source vertexes and sink vertexes. Besides, the attribute value reflects the dependence of the knowledge diffusion process on the citation arc or literature node in a specific discipline. As seen from Figure 6 and Table 4, literature nodes related to research teams of Boons, Kemp, Coenen, Ritala, Hekkert, Foxon, or Quist demonstrate a more significant network centrality than other nodes in the main path network. Network centrality indicates the association situation of a specific node, which will be more important if the node has more links with others. We found two papers published by Boons et al. [7] occupy the most core positions from the main path network, playing a transition role in the STI research and expanding the emerging research field of sustainable business model.

Table 4. Top 30 arcs in the main path network.

Rank	Line	Value	Line-Id	Rank	Line	Value	Line-Id
1	39.28	0.31134	779 Boons, F., 2013→491 Coenen, L., 2010	16	14.1	0.05982	165 Brown, H.S., 2003→86 Kemp, R., 1998
2	28.22	0.18174	491 Coenen, L., 2010→314 Foxon, T., 2008	17	22.15	0.05883	314 Foxon, T., 2008→217 Foxon, T.J., 2005
3	40.39	0.14354	780 Iles, A., 2013→779 Boons, F., 2013	18	22.1	0.05883	314 Foxon, T., 2008→86 Kemp, R., 1998
4	28.27	0.1363	491 Coenen, L., 2010→397 Hekkert, M.P., 2009	19	27.13	0.04869	397 Hekkert, M.P., 2009→118 Rohracher, H., 2001
5	15.1	0.1268	217 Foxon, T.J., 2005→86 Kemp, R., 1998	20	27.14	0.04869	397 Hekkert, M.P., 2009→165 Brown, H.S., 2003
6	22.2	0.11766	314 Foxon, T., 2008→275 Foxon, T.J., 2007	21	27.21	0.04869	397 Hekkert, M.P., 2009→284 Hekkert, M.P., 2007
7	38.39	0.11413	778 Boons, F., 2013→779 Boons, F., 2013	22	41.32	0.04788	841 Ornetzeder, M., 2013→633 Truffer, B., 2012
8	38.4	0.11413	778 Boons, F., 2013→780 Iles, A., 2013	23	28.24	0.04543	491 Coenen, L., 2010→327 Schot, J., 2008
9	38.28	0.08779	778 Boons, F., 2013→491 Coenen, L., 2010	24	28.1	0.04543	491 Coenen, L., 2010→86 Kemp, R., 1998
10	50.38	0.07078	1464 Schaltegger, S., 2016→778 Boons, F., 2013	25	28.21	0.04543	491 Coenen, L., 2010→284 Hekkert, M.P., 2007
11	24.1	0.06308	327 Schot, J., 2008→86 Kemp, R., 1998	26	38.31	0.0439	778 Boons, F., 2013→566 Quist, J., 2011
12	39.29	0.06227	779 Boons, F., 2013→496 Hockerts, K., 2010	27	29.11	0.04082	496 Hockerts, K., 2010→102 Rennings, K., 2000
13	5.63	0.06118	60 Fiorentino, R., →2349 Dentchev, N., 2018	28	29.12	0.04082	496 Hockerts, K., 2010→115 Senge, P.M., 2001
14	20.1	0.06082	275 Foxon, T.J., 2007→86 Kemp, R., 1998	29	32.28	0.04073	633 Truffer, B., 2012→491 Coenen, L., 2010
15	20.15	0.06082	275 Foxon, T.J., 2007→217 Foxon, T.J., 2005	30	54.38	0.03747	1723 Baldassarre, B., 2017→778 Boons, F., 2013

The knowledge diffusion venation of the STI research field can be further identified from the main path analysis results. As seen in Figure 6, 10 knowledge diffusion branches are derived from the sink vertex "86 Kemp R, 1998", which further spread and eventually connect with the source vertex literature. For the corresponding literature of three source vertexes, Fiorentino (2020) et al. [55] and Massaro et al. [56] analyzed the impact of intelligent technology and blockchain technology on the sustainable business model. Ljovkina et al. [57] studied innovative resource management from the ethical perspective of sustainable development. Moreover, these articles cited a single prior literature respectively, including Peralta et al. [58], Dentchev et al. [59], and Calabrese et al. [60], which are the only way to connect the three source vertexes in the main path network. Due to the limitation space, other knowledge diffusion paths are not reported in this section.

5. Discussion

The bibliometric analysis explored the inner relationships of the STI literature. The results also enlighten some research directions for STI. The co-citation analysis indicates 13 main categories and the main path analysis further presents the mainstream trend of 82 core articles. There are several subject topics showing emerging research potential according to the bibliometric analysis. Nevertheless, our study choses three subject topics of STI for discussion, including sustainable business model, smart-city construction, and sustainable transformation governance.

5.1. Sustainable Business Model

The main path analysis shows that the sustainable business model (SBM) study is a main research trend in recent years. Lozano [61] summarized the concept of SBM based on existing literature and proposed the theoretical framework containing organizational method, corporate system, stakeholders, change, and sustainability. SBM reflects the competitive advantages that an enterprise can continuously acquire through product or design innovation [62], service process innovation, and dynamic capability. These competitive advantages can help an enterprise continuously create and apply value [63], and SBM performance is influenced by the value of the corresponding competitive advantage. On the one hand, SBM has the core resources or capabilities not easily imitated and forms a path-dependent effect [3] through key products or services. On the other hand, as a non-static mechanism, SBM can quickly adapt to market dynamics and promote innovation.

Due to the rapid change of market environment, enterprises need to follow a sustainable development path to business values in response to the uncertainty. By exploring the evolution of "prosumer" in the renewable energy system, Brown et al. [64] found that the development of emerging technologies produces new value propositions. For example, the emerging business model formed by lithium battery secondary use (B2U) technology has the character of shared value creation [6] based on the situation of cross-sector and multistakeholder. Some literature review studies indicated that social system dimensions [65] and sustainability integration [66] can potentially become new themes of SBM. Luedeke-Freund [67] explored how business models achieve sustainability by balancing sustainable innovation with business cases and summarized two research perspectives, namely the agency and system perspectives.

SBM is influenced by various elements, such as sociotechnical system boundary [68], design of value proposition [2], and identification of business model innovation [69]. These factors cannot be separated from the participation and promotion of incumbents in the new business model [70,71]. Bohnsack et al. [72] discussed sustainable product innovation from the perspective of "enterprise in industrial cluster", and identified the main factors as coercive, normative, and mimetic, which supported the fact that electric vehicle technology is the core strategy of the automobile industry. Mature SBM provides feedback to the industrial environment and promotes the widespread adoption of emerging energy technologies [73]. Bolton et al. [74] discussed the impact of business model innovation on the sociotechnical system and summarized the value-capture path to improve resource utilization of sustainable technology deployment.

5.2. Smart-City Construction

Cluster #4 in the co-citation analysis indicates that smart city is also an emerging topic of STI. Through the Internet and advanced communication technology, smart cities integrate relevant information of urban core modules, quickly responding to various demands of urban service, environmental protection, public safety, and commercial activities based on intelligent system processing, which finally realizes sustainable urban development. By exploring the supply chain of a smart city, Neirotti et al. [75] found that the evolution of a smart city is highly dependent on the city factors at the local background. Ruhlandt et al. [76] discussed the components of a smart city and summarized the governance of a smart city, which showed conceptual differences involving environmental factors, measurement technology, and implementation result. However, especially for developing countries, Tan and Taeihagh's research [77] argued that the smart-city framework of developing countries had a stricter construction requirement for components. Additionally, Guo et al. [78] provided a comprehensive view for smart city by the bibliometric analysis, finding that emerging technologies such as artificial intelligence and Internet of Things have been discussed more in the smart city studies.

The upgrading of information technology pushes the research on smart cities. Ismagilova et al. [79] discussed the relationship between smart city and sustainable development based on a literature review. Appio et al. [80] illustrated the new connotation of smart cities by integrating prior research, emphasizing the impact of technology and society. However, differences still exist in the understanding of smart cities in academic and practical fields, regarding the conceptual framework and driving factors. Mora et al. [81] summarized two main development paths of the smart city through bibliometrics analysis. One is the overall development perspective promoted by European universities, and the other one is the technology-centered perspective supported by the American business community. Yigitcanlar et al. [82] highlighted community, technology, and policies as the driving factors of a smart city and proposed a framework to integrate these factors with construction vision.

Due to the uncertainty in the world, studies are carried out to predict the future of smart cities, including the smart energy system [83] and the sustainable city model [84]. Lim et al. [85] summarized the role and challenges of big data technology in the transformation process of smart cities. Fernandez-Anez et al. [86] proposed a theoretical model to discuss the transition of smart city construction from strategic to project level. The other side of a smart city has gradually attracted academic attention, and studies began to explore the impact of smart city development on the residents. Yigitcanlar et al. [87] explored the relationship between broadband Internet and sustainable commuting patterns, revealing that the popularity of Internet access promotes the fragmentation of daily work. As the smart-city construction integrates the opinions from various stakeholders, standardized evaluation systems are required to meet the diversified construction needs. Ahvenniemi et al. [88] argued that smart cities and sustainable cities have great differences by proposing a series of urban assessment tools, and the two concepts can be integrated to meet the future development need. Huovila et al. [89] proposed a set of evaluation systems for the sustainability of the smart city, which provided corresponding standards for the implementation of construction methods and sustainable development in various stages of city construction.

5.3. Sustainable Transformation Governance

Sustainable transformation governance (STG) is a rapidly developing branch of STI research, aiming to explain the evolution process of sociotechnical system and provide relevant governance countermeasures. Blythe et al. [90] discussed the concept definition of sustainable transformation, analyzed the origin, development, and trend of this term, and highlighted the main potential risks in different contexts. In the development process of sustainable transformation, elements such as public policy [91] and governance organization [92] play an important role. Loorbach [4] discussed the transformation management method and proposed a theoretical framework to distinguish governance activities and roles, dealing with the complex and long-term transformation process. The main reason for the rapid development of sustainable transformation research is the severe challenge of climate change, and increasingly more research began to focus on identifying the factors related to sustainability. Fazey et al. [93] emphasized the important role of complex social factors in transformation management. From an action-oriented perspective, Fazey et al. [94] also stressed the importance of transforming knowledge production and knowledge application.

Many articles have summarized and analyzed prior research on STG, showing that advanced research has a transition between the macro- and the micro-levels, and extending from the energy field to other industrial sectors. Köhler et al. [95] summarized the core research themes for the future research agenda of STG through reviewing multiple research directions, respectively. There are studies to explore the motivations, drivers, and barriers of governance by analyzing the texts of prior research comprehensively [77]. Cross-disciplinary and cross-sectoral communication activities contribute to the sustainable transformation process. El Bilali et al. [96] summarized five heuristic theoretical frameworks applied to STG through a literature review on agro-food sustainability transitions. Sustainable transformation is characterized by significant elasticity, which enables organizations to adapt and evolve in dynamic environments. Olsson et al. [97] emphasized the role of theoretical framework combination from sustainable transformation elasticity aspect, which includes social–ecological–technological systems, patterns of transformation, and agency and transformation. Gillard et al. [98] pointed out two major research agendas in sustainable transitions through a systematic literature review, which are sociotechnical transitions and social-ecological resilience.

However, according to the current research progress, the concept of STG is still vague without unified definition. Patterson et al. [99] conducted a discussion on the conceptual approach of sustainable transitions and compared four approaches, indicating that the transformative process has attracted the attention of governance. Luederitz et al. [100] discussed related issues of sustainable transformation assessment and proposed an exploratory evaluation mechanism, which demonstrated key features such as generic, comprehensive, operational, and formative. From the social governance perspective, the participation of citizens and organizations is the key element of STG, in which the interaction effect [101] and mediation effect [102] between individuals play an important role. Chilvers et al. [103] explored the issue related to public and social participation in the STG and proposed a sociotechnical system framework to explore specific manifestations of the participation process. However, it is noted that social conflicts and differences are inevitable in the process of STG, and the existing mechanism needs to improve the understanding of the general social conflicts about public interest boundary, including the aspects of direction, speed, and way of the transformation process [104].

6. Conclusions

Based on the literature data collected from the WOS database, this study fully utilized the co-citation analysis, text mining, clustering, information visualization, and other functions of Citespace software, which analyzes the hotspot distribution and the evolution trend of STI topics. Besides, it further identified the core evolution paths through the main path analysis, providing in-depth understanding of potential research directions. The bibliometric research was conducted from three aspects: first, the panoramic layout of the STI research field was explored through the literature distribution analysis. Second, the knowledge base and hotspots were identified through burst literature exploration and co-citation analysis. Third, the research evolution process and mainstream research were summarized by applying the method of main path analysis based on previous analytical results. The paper contributes to the STI knowledge structure exploration, and provides a comprehensive framework for understanding this theme and planning for future studies.

The results of bibliometrics analysis show a steady evolution process of STI-related research hotspots in the past 30 years, and knowledge flow frequently appears in multiple research fields. Among a flood of literature, 67 burst studies constitute the knowledge foundation, and 13 main categories and 82 main path articles visualize the research distribution and trend of the STI research. The burst studies are cited by other mainstream literature for continuous development and evolution, forming a diversified knowledge structure centering. Some theoretical models, such as sociotechnical system, multiperspective model, and innovation ecosystem, frequently appear in some popular articles recently. In addition, new research topics are becoming emerging research hotspots, specifically from the aspects of sustainable business model, smart-city construction, and sustainable transformation governance. Nevertheless, more case and empirical analyses are needed to promote further progress and provide substantial supports for the policy making. Finally, this paper conducted a systematic literature review of hotpot articles on three emerging subject topics, which can potentially enlighten future research.

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