A Scientometric Analysis and Overview of Research on Infrastructure Externalities

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Abstract: There is a growing level of concern regarding infrastructure externalities globally. However, most of the previous relevant reviews were undertaken manually and few of them covered all infrastructure systems. This study conducted a scientometric analysis and overview of the research on externalities of all infrastructure systems. The analysis results of 743 articles that were rigorously selected first showed the increasing trend of research interest in infrastructure externalities. Moreover, the results demonstrated productive and influential journals, scholars, and institutions, and their collaboration networks. Furthermore, research on the spillover effects of the infrastructure on economic growth, airport-related externalities, road transport-related externalities, and externalities of ecosystem services and energy systems were identified as the four main research domains. The evolution of the research is reflected in the focus change from economic aspects to environment aspects, from government governance to assessing and pricing by the market, and from airport to other infrastructure systems. Additionally, this study identified the scientific knowledge base supporting each research domain. Finally, this study pointed out research gaps and future research directions in the aspects of knowledge base, multi-dimensional evaluation, and multiple governance strategies. The results could cultivate deeper and more carefully focused research into this field in the academic community, and assist policymakers and practitioners in research planning and funding efforts.

Keywords: infrastructure; externalities; science mapping; literature review

1. Introduction

Hansen [1] pointed out that the push of the national economy needs to initiate a large number of interdependent infrastructure projects. As public goods, infrastructures are not excludable and have significant external effects. Externality as a code word for external effects has been used after the studies of Coase [2], Pigou [3], and Hardin [4]. Because of the complexity and various manifestations of externalities, there is still no consensus on the definition of externalities. From the cost perspective, externalities can be defined as unintentional and unbalanced losses or gains in the welfare of a party resulting from the activity of another party [5]. From the market perspective, externalities can be defined as a type of missing market and encompass the unpriced effects of one agent's activity on the welfare of another agent [6,7]. Considering the distinctiveness of infrastructures and to precisely define the scope of this research, this study extended the above definitions and defined infrastructure externalities as unintentional and unbalanced losses or gains caused by infrastructures that are not reflected by the market price.

Economists today have almost reached a consensus that externalities and public goods are the leading causes of market failure, holding the utmost level of relevance in environmental economics. Since the last century, practical problems caused by infrastructure

externalities have attracted great attention from scholars worldwide. For example, Firman and Dharmapatni [8] revealed that the development of infrastructure in Jakarta promoted economic growth while also causing negative externalities to the environment. Tomkins et al. [9] analyzed the bad effects of an airport such as noise and traffic congestion. Lera-López et al. [10] investigated citizens' willingness to pay to reduce noise and air pollution caused by road transportation. In the academic field, there has been a burgeoning of academic research in this field [11–13].

The research on infrastructure externalities involves various types of infrastructure. Besides airports and roads, the involved infrastructures also include ecosystem services [14], health care [15], and sewage treatment [16], etc. The research on infrastructure externalities also covers multiple concerns and topics such as economic impacts and assessments [17], social benefits and costs [18], costs/benefits evaluation methods [10,19], and internalization measures [20].

With a large number of emerging research activities, a literature review is helpful to obtain a deep understanding of a research field. However, the existing literature reviews on the external effects of infrastructures have some significant limitations. First, the majority of research focused on reviewing the externalities of a specific type of infrastructure category. For example, Ranieri et al. [21] and Wang et al. [22] reviewed the externalities of urban logistics infrastructure and the impacts of transportation infrastructure, respectively. Second, other relevant research simply focused on a specific field of infrastructure externalities. For example, Carmona [23] and Cai and Zhou [24] reviewed the supervision measures and evaluation methods of externalities of the transportation infrastructure, respectively. From the systematic point of view, all infrastructure externalities are not generated separately but have internal connections. It is very necessary to make a systematic and holistic review of externalities research covering all types of infrastructure. Moreover, despite its undoubted value, manual reviews generally have a narrow perspective and generalize findings from only a small portion of available publications, which is subject to bias [25]. Indeed, the volume of research on infrastructure externalities now available makes it difficult to manually evaluate its exact knowledge nature, impact, and contribution, and specifically, to identify pivotal areas that remain neglected [25].

To fulfill this research gap, this study aimed to conduct a scientometric analysis and overview of externalities of all infrastructure systems. The scientometric analysis quantitatively measures and analyzes the literature outputs to generate a comprehensive and objective portrait of the state of research knowledge in a specific topic [25]. The specific objectives of this study include: (1) analyzing the state of the art of the research on infrastructure externalities; (2) identifying mainstream research domains, their evolution, and scientific knowledge base for each research domain; and (3) identifying research gaps and proposing future research directions. The findings of this study could enrich the body of knowledge of sustainable infrastructure development from the perspective of infrastructure externalities. Moreover, the findings of this study could provide a platform for both researchers and practitioners to retrieve the latest developments and trends in infrastructure externalities.

2. Methodology and Data Presentation

The scientometric analysis can quantify the relationships in disciplines, fields, specialties, and documents or authors [26]. In addition, it can identify the knowledge structure and capture the development of science. Using scientometric analysis and visualization software, this study can conduct in-depth analyses of retrieved bibliographic data, identify systematic patterns in the research field of infrastructure externalities, and visualize the scientific networks.

To conduct a rigorous literature review, this study divided the reviewing process into four stages: bibliographic search, data preprocessing, scientometric analysis, and qualitative discussions, as depicted in Figure 1. Because the goodness of a review depends

on the quality of bibliographic data, data preprocessing is given great attention in this study. The data preprocessing method has been confirmed by Jin et al. [27] and Hosseiniet al. [25].
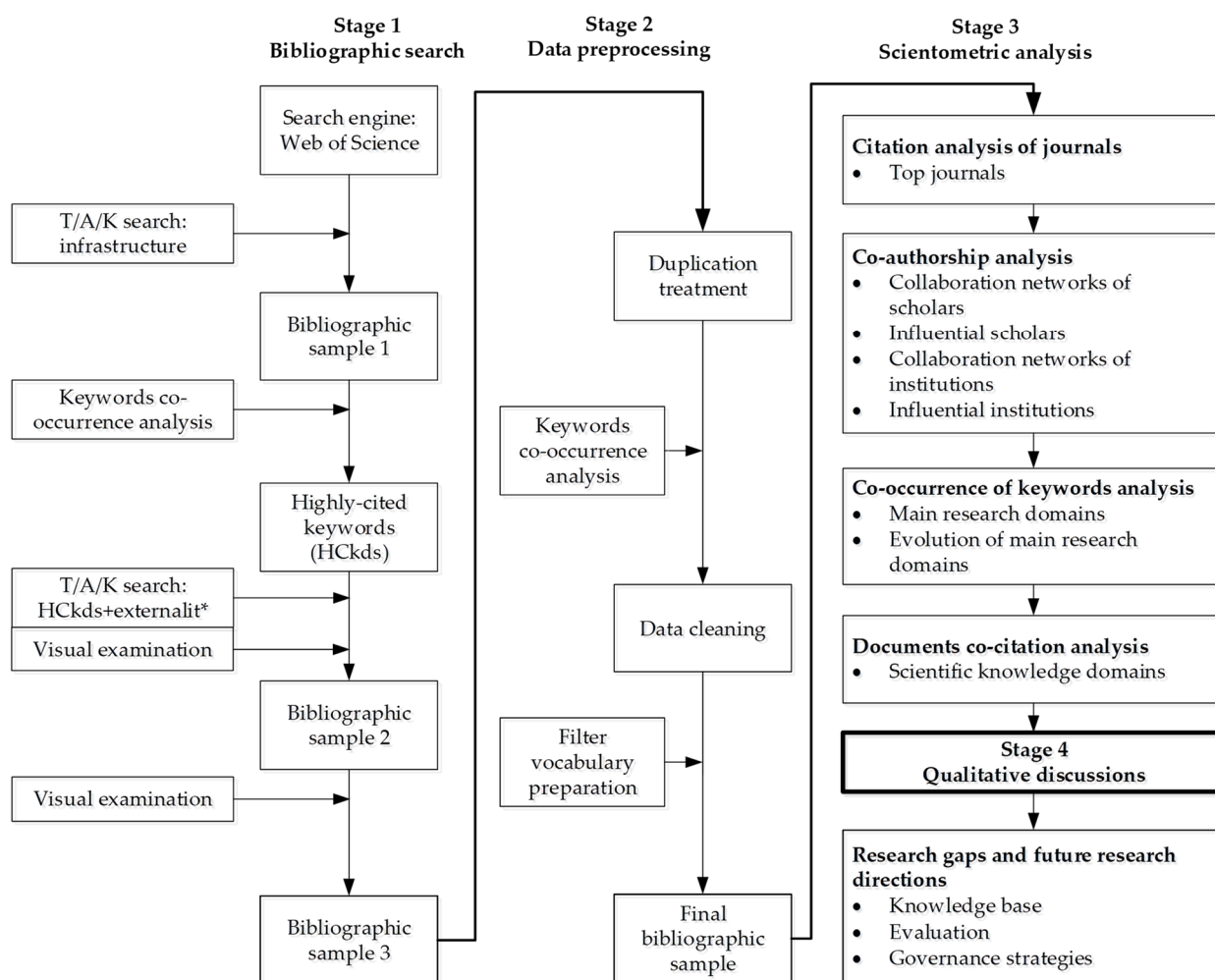

Figure 1. Flow chart of the four-stage literature review process.

2.1. Selection of Search Engine and Analysis Software

To make the literature sample comprehensive enough, this study chose Web of Science (WoS) as the search engine because it has strong coverage and covers journals with higher impact articles [28,29]. In addition, this study chose the popularly used analysis software of VOSviewer and CiteSpace. The bibliographic sample downloaded from WoS can be directly analyzed by VOSviewer and CiteSpace without conversion and information loss. VOSviewer offers text mining functionality that can be used to efficiently analyze, construct, and visualize bibliometric networks [30]. CiteSpace can be used to remove duplicated records from the bibliographic sample. This study used CiteSpace and VOSviewer (Version 1.6.17, Universiteit Leiden) in combination to complement each other and obtain the best analysis results.

2.2. Bibliographic Search and Data Preprocessing

Infrastructure is a generalized word and has many categories. Moreover, different countries have different classifications of infrastructure. To avoid missing a host of studies that do not use "infrastructure externalities" to discuss the same kind of concerns, this study first explored the key substitute words of infrastructure using the following three-step methods.

In the first step, this study used "infrastructure" as the keyword to perform a search under the TITLE-ABS-KEY (T/A/K) field using WoS without timeframe limitation. As the initial impressions of a research article, authors correctly, accurately, and meticulously write the T/A/K fields. Searching keywords in T/A/K fields is the most effective method to grasp the most accurate information. Moreover, the literature type was defined as "article". As of 16th September 2021, a total of 146,083 bibliographic records were searched and downloaded from the WoS ^{TM} Core Collection, forming bibliographic sample 1. Using this sample, this study conducted a co-occurrence of keywords analysis using VOSviewer with default settings and manually screened the analysis results to select the initial key alternative vocabularies to infrastructure (HCkds). The selection was based on two criteria: with the highest frequency of co-occurrence and with the nature of infrastructure. Moreover, after a pre-search using externality, this study identified that research using the most relevant keywords of externality, such as spillover effects and external effects, could also be searched, implying that externality is used as a code word in this research field.

In the second step, this study used the combination of each HCkds and externalit* as the keyword to perform a search under the T/A/K field using WoS. The use of an asterisk (*) in a word when searching for a document means that any character group can be represented. For example, using "externalit*" as a keyword can retrieve "externality" and "externalities". Through this round of search, this study identified new key alternatives to infrastructure and found inaccuracies of some initial key alternatives. For example, when performing the search using "water infrastructure externalit*", new key alternatives, such as "wastewater treatment" and "water supply", were identified as being closely related to the water infrastructure and added into the initial key alternative vocabulary table. Through replacing and updating the keyword pronouns in time and conducting the bibliographic search using the combination of each HCkds and externalit*, this study finalized 25 key alternatives of infrastructure and obtained the bibliographic sample 2.

The third step was implemented together with the second step aiming at screening the retrieved bibliographic records. This study deleted irrelevant articles mainly by manually studying their titles, abstracts, and keywords in detail. In this step, articles that just included any of the keywords in their T/A/K but did not focus on infrastructure externalities were excluded. Ultimately, a total of 1189 journal articles were selected forming the bibliographic sample 3. The final key substitutes of infrastructure and the statistic of bibliographic sample 3 were shown in Appendix A to increase the transparency and reproducibility of this study. Bibliographic sample 3 may have two types of flaws: repetition in the sample literature and keywords with the same meaning but different expressions or generic terms. To preprocess bibliometric sample 3, this study first used the remove duplicates function in CiteSpace to remove duplicated records from the bibliographic sample 3 [31]. Finally, a total of 743 sample documents were retained, forming the final bibliographic sample. Moreover, this study compiled a synonym file (thesaurus file) for keywords aiming at increasing the effectiveness of the co-occurrence of keywords analysis using VOSviewer. Semantically consistent keywords, such as cost-benefit-analysis and cost-benefit analysis, technology and technologies, were merged. Moreover, generic terms, such as country names and some terms that are more versatile but lack research value, were omitted.

2.3. Scientometric Analysis and Qualitative Discussion

Using VOSviewer, this study first conducted citation analysis and co-authorship analysis to obtain the network maps of the cooperation among journals, scholars, and institutions on infrastructure externalities. This study further conducted co-occurrence of keywords analysis and documents co-citation analysis to reveal network structure maps of the main research areas and knowledge bases of this research field. Based on the keyword analysis, documents co-citation analysis as well as articles analyzed in the prior step, this study made a comprehensive qualitative discussion aiming at providing an enhanced understanding of the mainstream research areas, research gaps, as well as potential future research directions.

3. Scientometric Analysis Results

3.1. Wave of Research on Infrastructure Externalities

The first study on infrastructure externalities within the dataset turned out to be the study by Poon [32] published in "Land Economics" in 1978. Poon [32] estimated the economic costs of railway pollution by studying its influence on housing prices. The variations in the total number and annual growth number of publications on infrastructure externalities over the period 1978–2021 are shown in Figure 2. Because the publications span over 44 years, this study displayed the distribution of the articles by taking every two years as a unit. Moreover, the data retrieval was performed in September 2021 and the number of documents in 2021 is relatively small.
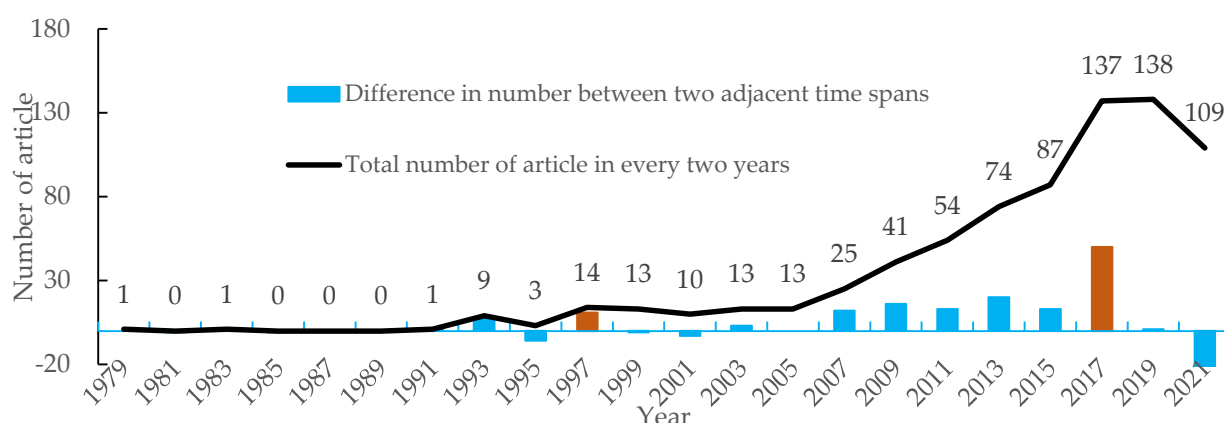

Figure 2. Variations in the number of articles on infrastructure externalities (1978–2021).

The results demonstrated that the research interest in infrastructure externalities has increased notably since 1997. The results also showed two sudden spikes in 1997–1998 and 2017–2018. An in-depth investigation revealed that infrastructure development was used as a means of stimulating economic growth during the economic crisis in 1998, which may have led to the growing interest in infrastructure externalities [33]. Since 2016, with global increasing urbanization, global environmental change, and the rise of global megacities, research on environmental and social externalities of urban systems has become increasingly prevalent [34,35]. The publication trend and the severe externality problems related to the infrastructure suggest that this research field will remain active in the future.

3.2. Top Research Journals

The quality of a journal is often used to estimate the worth of original research articles and reviews [36]. The results of direct citation analysis of journals reflect the relevance of various journals and disciplines. By setting the minimum number of documents of a source and the minimum number of citations of a source at 5 and 0 in VOSviewer, respectively, a network comprised of 22 journals and 29 links was created and visualized by weights of documents, as shown in Figure 3. VOSviewer uses a node and a link to represent an item and a connection between two nodes in a graph, respectively [37].

To better understand the impact of the identified journals, this study also provided a more quantitative measurement of the influence of journals in infrastructure externalities research in Table 1. The following table listed eleven journals whose average normalized citation (ANC) was above 1.0. ANC is an indicator revealing the performance of an article compared with the performance of other articles where the higher number indicates better performance.
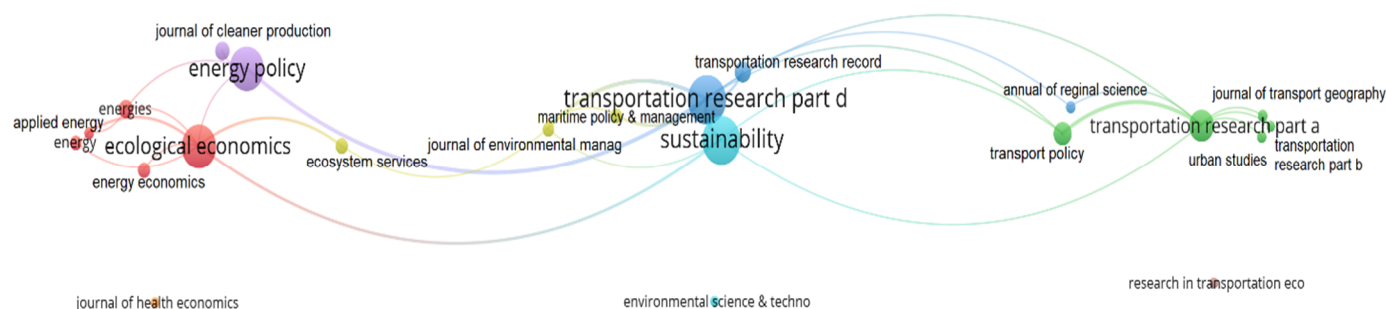
Figure 3. Network of prominent journals for publication in infrastructure externalities research.

Table 1. Quantitative summary of journal impacts in infrastructure externalities research.

Journal	Number of Articles	Total Citation	Norm. Citation	Avg. Pub. Yr. [a]	Avg. Citation	Avg. Norm. Citation [b]
Applied Energy	6	347	27.0	2016	57.8	4.5
Energy Policy	25	833	49.6	2013	33.3	2.0
Ecological Economics	25	1824	46.8	2014	73.0	1.9
Journal of Cleaner Production	9	78	16.1	2017	8.7	1.8
Transportation Research Part A: Policy and Practice	17	242	26.2	2010	14.2	1.5
Energy Economics	8	94	11.1	2016	11.8	1.4
Journal of Transport Geography	6	52	8.2	2017	8.7	1.4
Transportation Research Part B: Methodological	5	84	6.6	2014	16.8	1.3
Transportation Research Part D: Transport and Environment	28	368	36.4	2012	13.1	1.3
Energy	7	90	7.8	2016	12.9	1.1
Environmental Science & Technology	5	111	5.0	2012	22.2	1.0

[a] Avg. pub. yr. represents the average publication year of articles published in a given journal. [b] Avg. norm. citation (ANC) represents the average normalized number of citations received by the documents published by a journal, an author, an organization, or a country. The normalized number of citations (norm. citation) of a document equals the number of citations of the document divided by the average number of citations of all documents published in the same year. The normalization corrects for the fact that older documents have had more time to receive citations than more recent documents [37]. ANC is equal to the normalized citations divided by the number of articles.

According to the size of each node and font representing the weight of a journal in the network of prominent journals, *Transportation Research Part D-Transport and Environment* published the maximum number of infrastructure externalities-related articles, followed by *Energy Policy*, *Ecological Economics*, *Sustainability*, and *Transport Research Part A- Policy and Practice*. Moreover, the colors and connection lines in the network indicate the inter-relatedness among journals. Transport-related journals, such as *Transportation Research Part D*, *Transport Policy*, and *Transport Research Part A*, have been actively citing each other; energy-related journals, such as *Energy Policy*, *Ecological Economics*, and *Energy Economics*, have been actively citing each other. According to the value of ANC, energy-related and sustainability-related journals, such as *Applied Energy*, *Energy Policy*, *Ecological Economics* and *Journal of Cleaner Production*, published articles with the most outstanding performance.

3.3. Scientific Collaboration Networks

Co-authorship analysis aims to analyze the authors and their institutional affiliations, obtaining a deep understanding of the social structure and collaboration networks among the main scholars, research institutions, and countries [38,39]. Identifying scientific collaboration networks in a research domain could facilitate access to specialties and expertise, and help publishers to assemble editorial teams, reducing the research isolation.

3.3.1. Influential Scholars

To create a readable and manageable collaboration network of scholars, the minimum number of documents of an author and the minimum number of citations of an author

were set to be three and zero, respectively. Finally, a collaboration network of authors in infrastructure externalities research, consisting of 27 nodes and 10 links, was created and visualized by weights of documents, as shown in Figure 4. The strength of a link indicates the number of publications two researchers have co-authored.
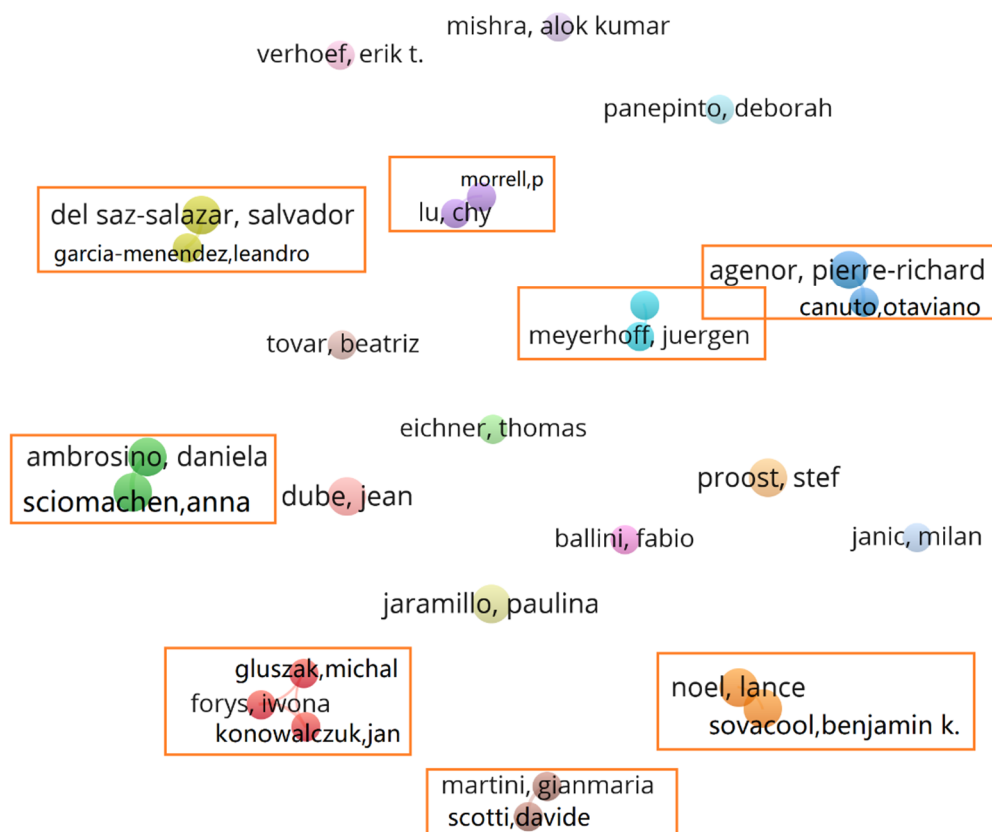

Figure 4. Collaboration network of authors in infrastructure externalities research.

This study further investigated the detailed information of the influential scholars whose ANC values were above 1.0 and provided in Table 2, serving as valuable references for individuals who are interested in infrastructure externalities research. The scholars were ranked by their ANC values.

According to the node size in the collaboration network and ANC values in the table, Lance Noel, Paulina Jaramillo, and Jean Dubé were identified as the top three both productive and influential scholars. Moreover, the distance and connection lines in the network measure the influences among scholars [27]. Scholars framed in the rectangles had a collaboration with each other. Although 15 out of the 27 identified scholars (55.6%) in the network were connected, all collaboration groups were very small consisting of only two or three scholars. In addition, a total of 1919 scholars published at least one infrastructure externalities-related paper according to the statistics of this study using VOSviewer. The result implied that 27 out of 1919 identified scholars (1.41%) were productive and kept conducting research on infrastructure externalities. The low research productivity may be caused by the lack of collaboration [25] and other reasons which deserve more in-depth studies.

Table 2. The top 11 most influential scholars in infrastructure externalities research.

Author	Institution	Country	Number of Articles	Avg. Norm. Citation
Lance Noel	Aarhus University	Denmark	4	2.3
Gianmaria Martini	University of Bergamo	Italy	3	2.0
Davide Scotti	University of Bergamo	Italy	3	2.0
Paulina Jaramillo	Carnegie Mellon University	United States	4	2.0
Beatriz Tovar	Universidad de Las Palmas de Gran Canaria	Spain	3	1.7
Erik T Verhoef	VU University Amsterdam	Netherlands	3	1.4
Jean Dubé	Université Laval	Canada	4	1.4
Anna Bartczak	University of Warsaw	Poland	3	1.1
Fabio Ballini	World Maritime University	Sweden	3	1.1
Jürgen Meyerhoff	Technische Universität Berlin	Germany	3	1.0
Peter Morrell	Cranfield University	United Kingdom	3	1.0

3.3.2. Influential Institutions

By setting the minimum number of documents of an organization and the minimum number of citations of an organization to be 5 and 0, respectively, a collaboration network of organizations consisting of 31 nodes and 22 links was created. However, 19 out of 31 identified organizations (61.3%) in the network were not connected, implying a high level of isolation in the scientific network. Therefore, this study quantitatively summarized the impacts of organizations in infrastructure externalities research instead of showing the collaboration network, as shown in Table 3. The organizations were ranked by the number of published articles. The result showed that the University of California, Berkeley published the maximum number of articles on infrastructure externalities, followed by the World Bank. From the perspective of the total link strength, the World Bank, Chinese Academy of Sciences, Carnell University, Harvard University, and Vrije Universiteit Amsterdam attached importance to cooperation, contributing to their high impact in this research field. Identifying highly influential institutions in the research field of infrastructure externalities would help authorities to make research partnership policies [25].

Table 3. Quantitative summary of institution impacts in infrastructure externalities research.

Institution Name	Total Link Strength	Number of Articles	Total Citations	Avg. Norm. Citations
University of California, Berkeley	2	16	787	1.9
World Bank	5	13	1174	1.6
Chinese Academy of Sciences	5	10	64	0.9
Delft University of Technology	1	10	388	2.2
Harvard University	4	10	366	1.2
Vrije Universiteit Amsterdam	4	10	168	1.5
University of Manchester	3	8	54	0.7
Cornell University	5	7	99	2.6
University of Maryland	3	7	57	0.6
Cranfield University	1	6	106	0.7
Technical University of Berlin	0	6	50	0.9
University of Antwerp	0	6	122	0.9
University of Cambridge	3	6	72	0.8

3.4. Main Research Domains and Evolution

3.4.1. Main Research Domains

Keywords represent the core content of an article and describe research topics within the boundaries of any domain [40]. Co-word analysis uses the most important words or keywords of documents to study the conceptual structure and the main concepts treated

by a research field [41]. This study performed the co-occurrence of keywords analysis to obtain the research hotspots and frontiers relating to the research domain of infrastructure externalities. By setting the minimum occurrence of a keyword at 5, a network comprised of 39 keywords and 117 links was created and visualized by weights of occurrence, as shown in Figure 5.
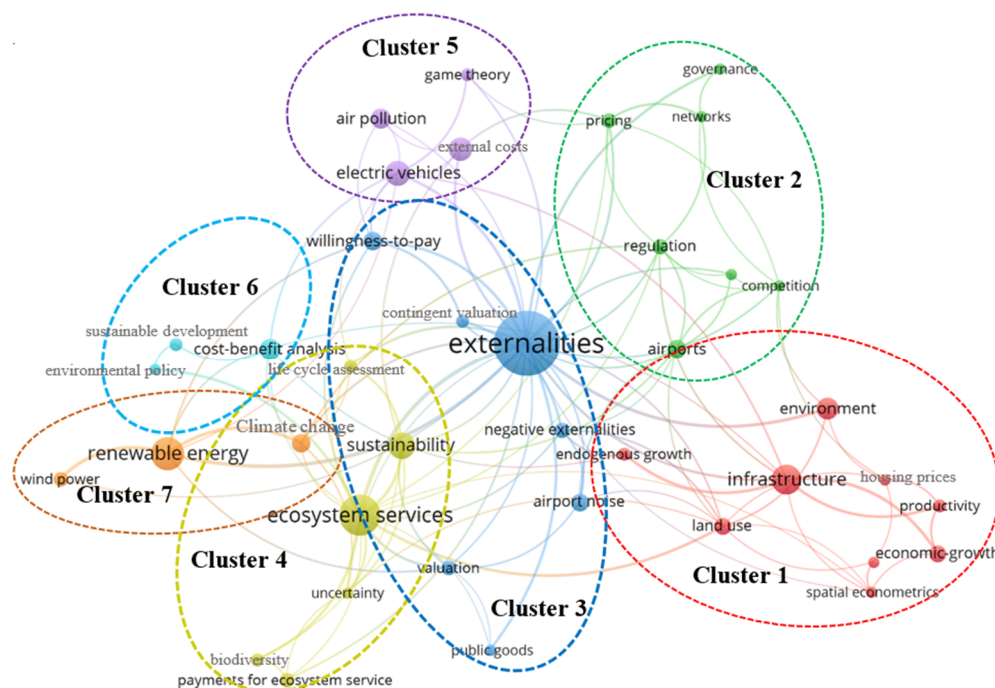

Figure 5. Main research domains of infrastructure externalities and their relatedness.

VOSviewer forms a network by considering the closeness and strength of existing links and uses different colors to indicate different clusters of topics [42]. Keywords within the same cluster have closer internal relationships. The results showed that the keywords were classified into seven significant clusters.

Moreover, to understand the meaning of these keywords and their clustering, this study further analyzed the distribution of externalities research of different infrastructure systems, as shown in Table 4. The distribution of research was based on the selected number of bibliographic records during the literature search. The results showed that a significant share of research (66.8%) focused on externality-related issues in the energy system, transportation system, and green infrastructure system. Externality-related issues in the health care system (3.8%) and other systems (5.6%) which are also important infrastructure systems in terms of their function did not draw great attention.

In combination with Figure 5 and Table 4, the following clusters of keywords represent the mainstream research domains in infrastructure externalities: (1) Cluster 1, which is the largest cluster, mainly focused on relationships among *infrastructure*, *economic-growth*, and *environment*. *Spatial economics* and *growth* theory (*endogenous growth*) are commonly used methods. (2) Cluster 2 and cluster 3, which account for a large share of the network, focused on airport-related externality issues. *Regulation* and *pricing* are commonly used *governance* methods for *airport competition*. *Willingness-to-pay* and *contingent valuation* are commonly used methods for evaluating the *negative externalities* of *airport noise* to the health of the people and creatures near the airport. (3) Cluster 5 focused on *external costs* of road transport such as *air pollution*, congestion, and noise. According to the node sizes, the occurrence of these keywords was very high. (4) Cluster 4, cluster 6, and cluster 7 were closely located to each other, representing the strong relatedness among them. Cluster 4 focused on *ecosystem services* and *payments for ecosystem services*, dealing with externality-related issues of the green infrastructure system. In this research domain, there is a significant

issue of *uncertainty*. Cluster 7 focused on externalities of energy systems. The importance of *renewable energy*, such as *wind power* and solar power, to mitigate *climate change* was emphasized. *Environmental policy* and decision making for *sustainable development* based on *cost-benefit analysis* and *life cycle analysis* were emphasized in cluster 6.

Table 4. Percentage of articles falling in different infrastructure systems.

Infrastructure System	Key Alternative Vocabularies during the Bibliographic Search	Percentage of Articles
Energy system	Energy, power, electricity, grid, renewable energy, oil and gas, hydropower	25.7%
Transportation system	Transport, airport, port, railway, logistics, electric vehicle	28.3%
Green infrastructure system	Green infrastructure, ecosystem services	12.8%
Health care system	Health-care	3.8%
Other systems	Water, communication, internet of thing, information, agriculture, waste disposal, tourism, commerce,	5.6%
* General infrastructure	Infrastructure	23.9%

Note: * General infrastructure means that relevant research did not distinguish infrastructure systems.

3.4.2. Evolution of Main Research Domains

To understand the evolution of the identified research domains, this study also showed the visualization of author keywords by the scores of average publication year (APY) in Figure 6. APY denotes the average publication year of the documents in which a keyword occurs [37], indicating the recentness of a keyword being studied. The values of APY were automatically divided into four segments based on the optimization algorithms of VOSviewer. The color of a keyword is determined by the score of its APY.
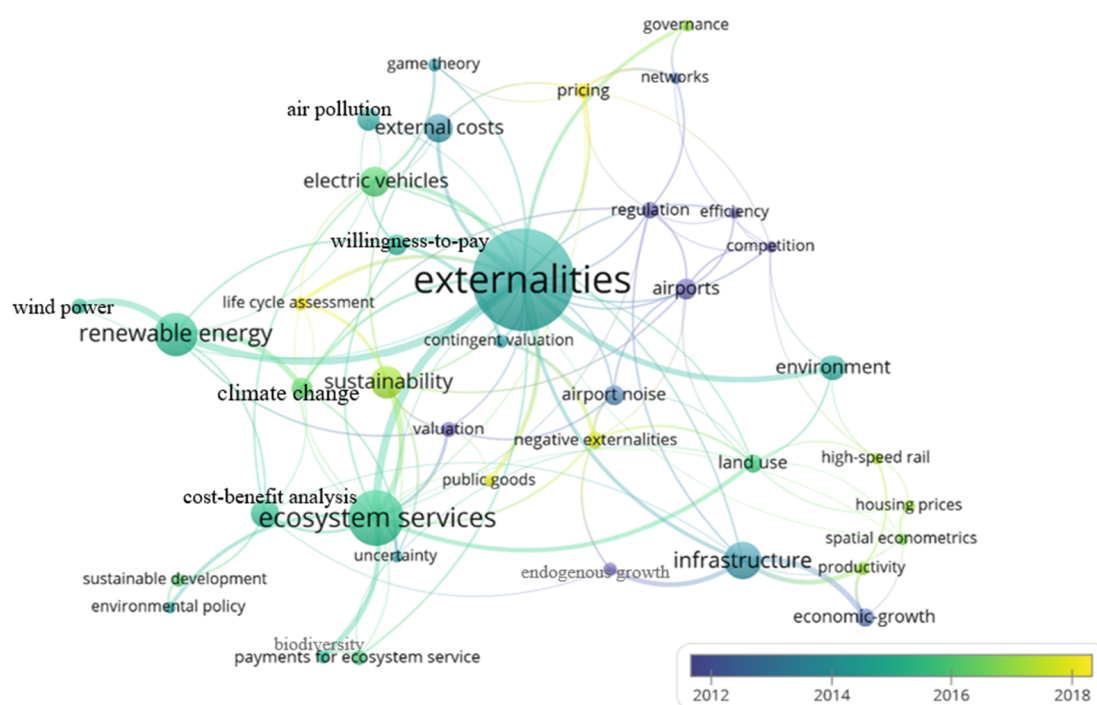

Figure 6. Visualization of author keywords evolution from 1978 to 2021.

According to the color and size of each node, the evolution of infrastructure externalities research roughly included four stages. (1) The positive spillover effects of infrastructure

on *economic-growth* (*endogenous growth*) [43,44], governance of *airport competition* [45,46], and the *valuation* of *airport noise* [47–49] were first studied. (2) Considering *climate change* and the *negative externalities* of infrastructure to the *environment*, studies later focused on external effects of *renewable energy* [50,51] and *ecosystem services* [52,53], and *external costs* such as *air pollution* and *congestion* from transport [10,54]. (3) Afterwards, from the perspective of *sustainability* and *air pollution*, studies on the *life cycle assessment* of *electric vehicles* later drew great attention [55,56]. In addition, studies investigating the relationships among infrastructure, land use externalities, and residential property values also received high attention [57,58]. (4) Recently, studies focused on the *pricing* of external costs from infrastructure such as pricing the pollutant emission right and carbon emission right. In addition, the value of commuting convenience or accessibility led by transportation infrastructures such as *high-speed rail* and *rail transit* is commonly reflected in the increase in *house prices*. Many researchers explored valuating such positive externalities through *spatial econometrics* [58,59].

3.5. Scientific Knowledge Base

Document co-citation analysis provides a network of co-cited references. Generally, the references highly cited in the selected articles provide the knowledge base of these articles [60] and were treated as concept symbols [61]. The clusters of co-cited references provide an insight into the structure of a scientific knowledge domain [25]. This study explored the underlying knowledge base of infrastructure externalities research through a co-citation analysis of cited references. By setting the minimum number of citations of a cited reference at 7, a network comprised of 56 nodes and 211 links was created and visualized by weights of citation, as shown in Figure 7. The 56 cited references were classified into 7 clusters. A node in this network represents a document that is denoted by the first author name and the publication year.
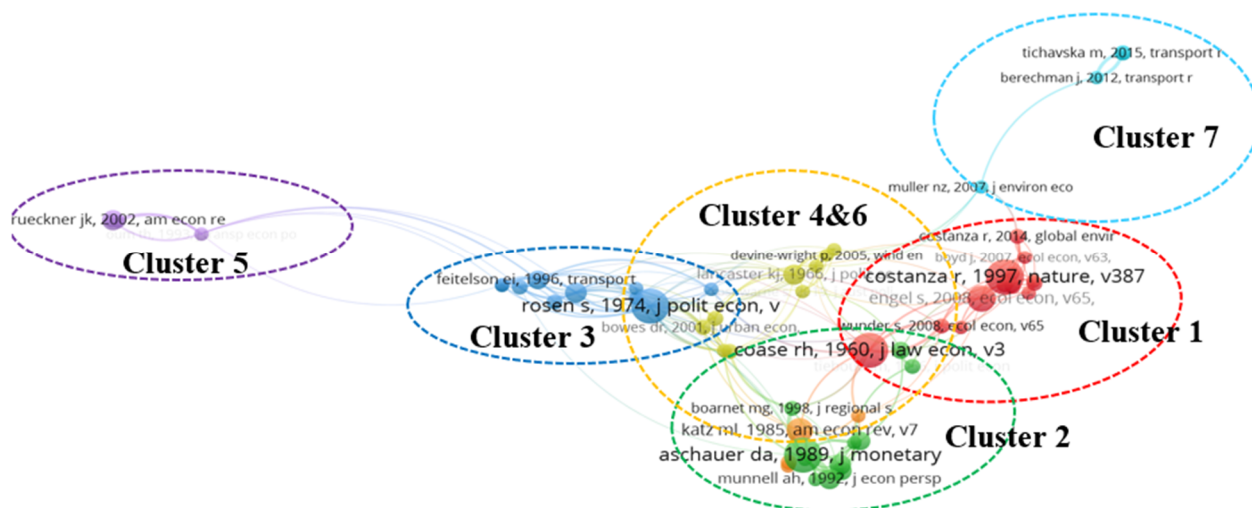

Figure 7. Scientific knowledgebase of infrastructure externalities research.

This study further quantitatively summarized the clusters of co-citation and the top highly-cited documents in infrastructure externalities in Table 5. Only documents whose number of citations was above the average number of eight were shown in the table. According to the number of co-citations, Coase [2], Rosen [62], Aschauer [63], Costanza et al. [52], Engel et al. [64], and Katz and Shapiro [65] were the top six co-cited documents, highly recognized as the fundamental bedrock of the research on infrastructure externalities.

Table 5. Summary of the most influential documents in infrastructure externalities research.

Cluster ID	Size	Citation	Influential Document	Title	Focus of the Cluster
1	13	22	Coase (1960)	The problem of social cost	Social costs; payments for environmental services; ecosystem services
		22	Costanza et al. (1997)	The value of the world's ecosystem services and natural capital	
		15	Engel et al. (2008)	Designing payments for environmental services in theory and practice: An overview of the issues	
		8	Costanza et al. (2014)	Changes in the global value of ecosystem services	
		8	De Groot et al. (2002)	A typology for the classification, description, and valuation of ecosystem functions, goods, and services	
		8	Fisher et al. (2009)	A systems approach to definitions and principles for ecosystem services	
2	12	22	Aschauer (1989)	Is public expenditure productive?	Public expenditure; economic growth; technological change
		11	Munnell (1992)	Policy watch: infrastructure investment and economic growth	
		11	Romer (1990)	Endogenous technological change	
		10	Lucas (1988)	On the mechanics of economic development	
		10	Romer (1986)	Increasing returns and long-run growth	
		9	Samuelson (1954)	The pure theory of public expenditure	
3	10	22	Rosen (1974)	Hedonic prices and implicit markets: product differentiation in pure competition	Airport noise; evolution of impact; hedonic prices; willingness to pay
		11	Nelson (1980)	Airports and property values: a survey of recent evidence	
		10	Feitelson et al. (1996)	The impact of airport noise on willingness to pay for residences	
		8	Mitchell et al. (1989)	Using surveys to value public goods: The contingent valuation method	
		8	Pennington et al. (1990)	Aircraft noise and residential property values adjacent to Manchester International Airport	
4	9	11	Lancaster (1966)	A new approach to consumer theory	Impacts of rail transit on house prices
		8	Bowes et al. (2001)	Identifying the impacts of rail transit stations on residential property values	
		8	McMillen (2004)	Reaction of House Prices to a New Rapid Transit Line: Chicago's Midway Line, 1983–1999	
5	4	11	Brueckner (2002)	Airport congestion when carriers have market power	Airport congestion; pricing
6	4	14	Katz and Shapiro (1985)	Network externalities, competition, and compatibility	Network externalities; estimation;
		8	Hawkins et al. (2012)	Comparative environmental life cycle assessment of conventional and electric vehicles	
7	4	8	Tichavska et al. (2015)	Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port	Externalities from transport emissions
		8	Tzannatos (2010)	Ship emissions and their externalities for the port of Piraeus—Greece	

In combination with Figure 7 and Table 5, the following clusters of co-cited documents represent the main scientific knowledge base in infrastructure externalities:

(1)   Ecosystem services have positive externalities to the health of human beings and the environment. Cluster 1 provides the knowledge base for the research on externalities of ecosystem services. The well-known theory of social cost by Coase [2] provided the basis for research in this domain. Research on the definition [66], classification [67], valuation [52,67,68], and designing payments [64] of ecosystem services provided a systematic knowledge base for research in this domain.

(2)   With the attribute of public goods, the development of infrastructure is generally through public expenditure. Cluster 2 is a collection of theories for public expenditure [63,69], economic growth [70–72], and the spillover effects of the development of infrastructure on economic growth [43].

(3) Cluster 3 and cluster 5 provide the knowledge base for estimating the market value of airport noise and congestion, respectively. The well-known theory of hedonic prices by Rosen [62] provided the basis for estimating the externalities of airports on property values [48,73]. To estimate the negative impacts of airport noise on the health of human beings and other creators, the contingent valuation method was introduced to this research field [47,74]. The location of cluster 5 is far from the main knowledge domains. It provides the knowledge basis for congestion pricing for transport [75].

(4) Urban transportation externalities, such as congestion, noise, and emissions, are a key development challenge. Cluster 4, cluster 6, and cluster 7 provide the knowledge basis for the research on externalities of the transport system. The well-known theory of consumer behavior by Lancaster [76] and the theory of network externalities by Katz and Shapiro [65] provided the basic approaches for analyzing transport-related issues. Congestion externality has been successfully priced and internalized by the market through congestion tolls. The estimation of the environmental cost of emissions from transport provides the basis for pricing or internalizing these externalities [77,78]. Electric vehicles coupled with low-carbon electricity sources offer the potential for reducing greenhouse gas emissions. The life cycle assessment of electric vehicles provides the basis for the valuation of transport emissions [56]. As valued by the market, residential property values provided the basis for estimating the positive externalities of transport infrastructure [79,80].

4. Qualitative Discussions

This study made qualitative discussions of the research on infrastructure externalities mainly from three perspectives: knowledge base, three-dimensional evaluation, and governance strategies of infrastructure externalities. Within each perspective, this study summarized current research status, gaps in the current body of knowledge/research, and future research directions.

4.1. A Systematic and Solid Knowledge Base

According to the scientometric analysis results, previous studies focused more on the externalities of a few infrastructure systems, including the energy system (electricity), transport system (surface transportation and airports), and green infrastructure system (ecosystem services). The knowledge base in these fields is relatively solid and systematic. For example, there is a systematic and solid knowledge base for the definition, classification, estimation, and pricing of externalities in ecosystem services. In addition, there are handbooks on the external costs of transport, and relevant institutions constantly update it [81,82]. Along with the global increasing attention to climate change and sustainable development, it can anticipate that externality-related research in these infrastructure systems will still be hot and prosperous in the future.

Moreover, it is worth noting that rapid urbanization worldwide is adding tremendous pressures to urban infrastructure systems [83,84]. Diverse infrastructure externality-related problems and concerns have become more evident and are now considered important issues for urban planners and decision makers. According to the theory of urban carrying capacity, the more overloaded the infrastructure, the more likely it is to cause serious externality-related problems [83,84]. For instance, as the urban population increases, the quantities of municipal solid waste in many cities have been beyond the capacity of solid waste treatment infrastructure, leading to serious water, air, and land pollutions [83,85]. In addition, the building of new solid waste incineration facilities also has "not in my backyard" issues because nearby residents believe such facilities negatively affect their health [86,87]. However, the studies on the externalities of other infrastructure systems are relatively small and the knowledge base for such research is relatively not obvious and systematic. According to Table 4, the percentage of articles on the externalities of other infrastructure systems only accounts for 5.6%. In addition, there is no significant cluster representing the knowledge base for such research in Figure 7.

Furthermore, according to Figure 4 and Table 3, there is a high level of isolation of scholars and institutions in infrastructure externalities research. According to the analyses of the main research domains and the scientific knowledge base, the high research productivity and solid knowledge base of the energy system, transport system, and green infrastructure system indicate that a solid and systematic knowledge base greatly contributes to the high research productivity. Therefore, various researchers and institutions focusing on a specific infrastructure system need to make great efforts to build a solid system knowledge base for that category of infrastructure, which at least includes the classification, estimation, pricing, or making public policies for externalities, reducing research isolation and improving research productivity. Famous scholars or industry associations can play a leading or organizational role in establishing a conceptual framework and guiding research of externalities in a specific category of infrastructure. In addition, researchers are also encouraged to borrow and validate applicable theories and findings from studies outside their research domain.

4.2. Three-Dimensional Evaluation of Infrastructure Externalities

Infrastructure externalities are gradually considered in decision making [88]. The quantitative evaluation of the external effects of the infrastructure is the precondition for proposing public policies or internalization mechanisms. Scholars worldwide attempted to estimate the externalities of infrastructure externalities from three dimensions: the economic, environmental, and social dimensions. According to the scientometric analysis results, the majority of the previous evaluations of infrastructure externalities were performed from the economic and environmental perspectives [51,89]. Only a handful of scholars focused on the evaluation of infrastructure externalities from the social aspect [18]. The infrastructure development comes from the needs of the economy, society, and environment, and conversely, has impacts on these three aspects. The lack of externalities evaluation of any dimension will pose a hindrance to exploring the formation mechanism of infrastructure externalities, leading to government failure or market failure for the governance of infrastructure externalities. The typical example is that the car purchase restriction policy aiming to reduce traffic emissions leads to the increase in car ownership because of the lack of consideration and analysis of the social costs and inconvenience that the people need to bear [90,91].

From the economic perspective, scholars quantified the spillover effects of the infrastructure on a region's development using classic economic growth theory and spatial econometrics [44,89], and on property value using hedonic price models [92,93]. With a rich knowledge base, the improvement of computing power, and the accumulation of panel data, such evaluations become mature and have been considered in policy decision making. The typical example is the transportation-oriented development considering the spillover effects of the transport system [94]. From the environmental perspective, both negative and positive environmental externalities of the infrastructure have been evaluated. The main evaluation methods included carbon emissions measurement and material flow analysis [95–97]. For example, a vast number of scholars estimated the positive effects of ecosystem services on the environment [67] and the air pollution of road transport [98]. In addition, there were many studies on the ecological impacts of the infrastructure in different topics such as balancing environmental and ecosystem services by protecting biodiversity [99], optimizing ecosystem services [100], and adopting payments for ecosystem services [101]. According to the results of keywords analysis, a great challenge for the evaluation of environmental externalities of the infrastructure is "uncertainty" such as uncertain climate change [102] and the uncertain parameters in the development of carbon sink forests projects [103]. This should be considered with great efforts made to overcome this challenge in future research.

It is worth noting that researchers need to leverage information technologies to evaluate infrastructure externalities. According to classical theories of externalities, the costs for information collection and difficulties in information transparency were among the

reasons for the government failure; the existence of positive transaction costs was one of the reasons for the market failure [3]. Gupta, et al. [104] pointed out that the Internet is making a significant transition from a network of desktop computers to a network of varieties of connected information devices. The advancement of information technologies and infrastructure increases the possibilities of the internalization of externalities because of the convenience of information collection and decreased transaction costs [105]. For instance, the evolution of main research domains identified by this study showed that the spillover effects of the transport system, which are mostly represented by the housing prices, are increasingly quantified and internalized because they can be easily quantified with the help of spatial econometrics and advanced information technologies.

4.3. Multiple Governance Strategies for Infrastructure Externalities

The two classical strategies for the governance of externalities follow the principles set by Pigou [3] and Coase [2]. Pigou [3] and Coase [2] suggested solving externalities through government interventions and market transactions, respectively. From the government's perspective, regulation, public policy, and taxation are commonly used governance practices. The popular research methods include network theory and game theory. For instance, Santos et al. [106] held the view that a sustainable land-use policy could allow public transport as well as walking and cycling to be at the core of urban mobility, improving general health and reducing tailpipe emissions. Glaister and Smith [107] elaborated that through government interventions, a reformed charging regime designed to deal with road congestion would also help with the carbon emission problem.

The identified evolution of main research domains implied that the governance strategies for infrastructure externalities are shifting from the government to the market. "Willingness-to-pay", "contingent valuation", "life cycle assessment", "payments for ecosystem services", and "pricing" are hot keywords used by most recent research, implying the emphasis of the quantification and internalization of infrastructure externalities. Along with the increasing awareness of infrastructure externalities, industry organizations and practitioners also start to bring these issues into their decision making [97,108].

It is noteworthy that if the internalization of infrastructure externalities through pricing or compensation only uses marginal social costs, it would lead to increased transaction costs and market failures. The hindrance to the emissions trading system for wastewater and the carbon sink forest trading are good examples [103,109]. As shown in the results of keywords analysis, "renewable energy", "wind power", and "electric vehicles" were hot keywords mentioned in research of infrastructure externalities. Energy innovation and high-tech investment to reduce or offset infrastructure externalities, especially negative externalities such as pollutions to the environment, are increasingly emphasized. For example, Mirkouei et al. [110] proposed a mixed biomass-based energy supply chain and a multi-criteria decision-making framework to address the challenges of supply uncertainties. As recently released, Germany is expecting to end nuclear power in 2022 and sway to clean energy.

The world has reached a consensus that fostering sustainable development to address climate change and socio-environmental crises is the main theme of the world in the future. The existing proposed solutions for the governance of infrastructure externalities still pays more attention to the end treatment towards specific external effects of a certain infrastructure system or project. Sustainable solutions should be directed to the mutual transformation, exchange, or compensation among the environmental, social, and economic externalities of the infrastructure in large scope and in a long-term optimization perspective by efforts from both the government and the market [14,97,111].

5. Conclusions and Recommendations

This study conducted a scientometric analysis and overview of the research on externalities of all infrastructure systems. The analysis results first showed that the research interest in infrastructure externalities has increased notably since 1997 and had two sudden

spikes in 1997–1998 and 2017–2018. The results further showed that *Transportation Research Part D-Transport and Environment*, *Energy Policy*, *Ecological Economics*, *Sustainability*, and *Transport Research Part A-Policy and Practice* were the top five most productive journals; Lance Noel and the University of California, Berkeley were the most productive scholars and institutions, respectively. Despite a large number of studies, there was a high level of research isolation among scholars and institutions. This study also identified four main research domains that are the research on the spillover effects of the infrastructure on economic growth, airport-related externalities, road transport-related externalities, and externalities of ecosystem services and energy systems. The evolution of these research domains is mainly reflected in the focus changes from the economic aspect to environment aspect, from government governance to life cycle assessment and pricing by the market, from airport to other infrastructure systems. Additionally, this study identified the scientific knowledge base for each main research domain. The knowledge base for the research on externalities of ecosystem service, which includes the definition, classification, valuation, and designing payments of ecosystem services, is most solid and systematic. Finally, through an analysis from a macro perspective, this study identified research gaps in the current body of knowledge and proposed future research directions from three perspectives. From the knowledge base perspective, except the ecosystem service, transport system, and energy system, the research on externalities of other infrastructure systems is relatively small and the knowledge base is not solid and systemized; researchers and institutions need to make great efforts to construct a solid and systemized knowledge base for each specific infrastructure system to reduce research isolation and improve research productivity. From the evaluation perspective, the majority of the previous evaluations of infrastructure externalities were performed from the economic and environmental perspectives; three-dimensional evaluation of the economy, society, and environment should be paid more attention to. From the governance strategies perspective, multiple governance strategies including government intervention, market evaluation and transaction, and the mutual transformation, exchange, or compensation among the environmental, social, and economic externalities should be considered. The enhanced understanding of infrastructure externalities research could cultivate the academic community in a deeper and more carefully focused research into this field, and aid policymakers and practitioners in research planning and funding efforts. Although the objectives of this study have been fulfilled, some limitations still exist. For instance, the use of highly-cited keywords as key substitute words of the infrastructure to obtain the bibliographic sample could still omit some relevant literature due to keyword limitations.

Data Availability Statement: Data generated or analyzed during the study are available from the corresponding author by request.

Appendix A

Table A1. Keywords for bibliographic search and collected bibliographic records.

Infrastructure System	Keywords for Bibliographic Search	Number of Articles
Energy system	Energy infrastructure externalit *	71
	Power infrastructure externalit *	19
	Electri * infrastructure externalit *	32
	Grid infrastructure externalit *	12
	Renewable energy externalit *	157
	Oil and gas infrastructure externalit *	8
	Hydropower infrastructure externalit *	7
Transportation system	Transport * infrastructure externalit *	137
	Airport externalit *	64
	Port externalit *	53
	Railway externalit *	30
	Logistics infrastructure externalit *	11
	Electric vehicle externalit *	41
Green infrastructure system	Green infrastructure externalit *	11
	Ecosystem services externalit *	141
Health care system	Health care externalit *	45
Other systems	Water infrastructure externalit *	27
	Communication infrastructure externalit *	4
	Internet of things externalit *	10
	Information infrastructure externalit *	2
	Agriculture infrastructure externalit *	8
	Waste disposal infrastructure externalit *	7
	Tourism infrastructure externalit *	5
	Commerce infrastructure externalit *	3
* General infrastructure	Infrastructure externalit *	284
Subtotal		1189

Note: * General infrastructure means that relevant research did not distinguish infrastructure systems.

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