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Review

How Is Transportation Sector Low-Carbon (TSLC) Research Developing After the Paris Agreement (PA)? A Decade Review

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Abstract: The Paris Agreement (PA), an authoritative political document on emissions reduction and low-carbon initiatives, requires the transportation sector to take decisive action toward achieving low-carbon objectives. This study uses CiteSpace to conduct a bibliometric analysis of 746 transportation sector low-carbon (TSLC) research articles published since the PA. The analysis reveals that China, the United States, and the United Kingdom are the leading contributors, with Tsinghua University being the most prolific institution. *Sustainability*, the *Journal of Cleaner Production*, and *Transportation Research Part D* are the most influential in terms of publication volume. This study reviews recent studies of TSLC from the perspective of renewable energy and technology applications, the evolution of intelligent transport systems, policy support, and public participation. Then, an in-depth interpretation of the potential impacts of low-carbon policies on the circulation of transport commodities, the energy system, the transportation system, and socioeconomic development is conducted. Finally, a knowledge map is presented, illustrating pathways for achieving TSLC targets under the guidance of the PA, laying a foundation for future research and policy efforts in sustainable transport.

Keywords: transportation sector; low carbon; Paris agreement; systematic review

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Academic Editor: Giovanni Leonardi

Received: 3 January 2025
Revised: 22 February 2025
Accepted: 27 February 2025
Published: 5 March 2025

Citation: Zhao, X.; Han, J. How Is Transportation Sector Low-Carbon (TSLC) Research Developing After the Paris Agreement (PA)? A Decade Review. *Sustainability* **2025**, *17*, 2261. https://doi.org/10.3390/su17052261

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1. Introduction

With the increasing severity of the global climate change problem, low carbon has become the most important and urgent topic of global governance, attracting worldwide attention and efforts. Based on the practice of the Kyoto Protocol, the Paris Agreement (PA) adopted in 2015 emphasizes the same goal of climate change governance and strengthening global cooperation [1], and has become an authoritative document and international constraint for guiding the global response to climate change. The PA aims to limit global temperature rise to below 2 °C above pre-industrial levels, with efforts to keep it within 1.5 °C. This landmark agreement set ambitious and binding targets to reduce greenhouse gas emissions [2–4] and spurred numerous initiatives and research across sectors, including transportation [5,6]. The transportation sector is a major contributor to global carbon dioxide emissions [7–9], accounting for 23% of total global greenhouse gas emissions worldwide. This sector also has the lowest energy diversity, relying almost exclusively on petroleum products [10–12]. Therefore, the transportation sector is considered to be one of the most challenging sectors for achieving low-carbon targets [13]. Conventional modes of transport, such as fuel-powered vehicles and air travel, not only consume large amounts of fossil fuels but also release significant amounts of carbon dioxide and other greenhouse gases, raising widespread concerns about energy consumption and climate change [14]. To meet the goal

of limiting warming to 1.5 °C or well below 2 °C, the transportation sector must transition to a low-carbon model as swiftly as possible.

Given this critical situation, low-carbon initiatives in transportation have become an essential part of global climate action strategies [15]. The PA explicitly requires countries to take robust actions to cut emissions, making the transformation of the transportation sector an urgent task for achieving global climate goals [16,17]. The agreement has driven countries to focus on the research, development, and implementation of low-carbon transportation technologies, fostering the rapid advancement of electric vehicles, renewable energy, and intelligent transportation systems. In particular, fuel cells, as an advanced clean energy technology, have demonstrated significant potential in balancing energy security, economic growth, and environmental protection, leading to a new wave of technological innovation in TSLC [18]. The European Union has set a carbon neutrality target for the transportation sector by 2050 through its "Sustainable and Smart Mobility Strategy" and has strongly promoted electric vehicles and hydrogen technologies. China has regarded the transportation sector as crucial to achieving its 2060 carbon neutrality goal, actively promoting new energy vehicles, with electric vehicle sales accounting for over 40% of global sales in 2020. India is driving the adoption of electric vehicles through the "National Electric Mobility Mission Plan", focusing on electric two-wheelers and the electrification of public transport, with the target of achieving 30% electric vehicle penetration by 2030. In line with the requirements of the PA, countries are vigorously promoting the green and clean transformation of the transportation sector, resulting in a noticeable increase in low-carbon research within the sector following the PA. Some studies have made academic contributions from the perspectives of clean energy and smart transportation technologies in achieving the goals of the PA within the transportation sector. Another body of research evaluates the social changes induced by the PA and the potential implementation challenges from an economic and social perspective. Undoubtedly, substantial progress in emissions reduction and energy conservation within the transportation sector has been made, as evidenced by a significant body of research. However, the introduction of the PA provides an opportunity to review and organize low-carbon research in the transportation sector from the previous phase and offer forward-looking guidance for future research.

We aim to provide a comprehensive overview of low-carbon research outcomes in the transportation sector since the PA, identifying key scientific issues and strategic needs for low-carbon development and exploring future research directions. Through a systematic review and analysis of the progress and trends in TSLC research post-PA, we examine how the transportation industry can achieve sustainable development under the influence of policy, technology, and social factors. By employing bibliometric analysis, this study reveals current research hotspots, major contributors, and future directions, offering valuable references for academia and policymakers. Additionally, we aim to identify gaps and challenges in low-carbon transportation research, guiding subsequent studies. By delving into these issues, we hope to provide an empirical basis for a more comprehensive low-carbon transportation strategy, promoting the global transition to low-carbon transportation and supporting sustainable development goals. Section 2 provides an overview of the classic literature. Section 3 describes the research methodology. Section 4 discusses the bibliometric visualization results. Section 5 systematically discusses the latest research developments and the profound impact of the PA, developing the knowledge map. Section 6 summarizes the conclusions of this study.

2. Literature Review

As climate change intensifies, low-carbon transportation research has become a priority for scientists and policymakers alike. Some scholars have begun reviewing the literature on low-carbon transportation (Table 1).

Table 1. Previous literature reviews of TSLC research.

Perspective	Methodology	Main Content	References
Transportation carbon emissions	Bibliometric	This review employs CiteSpace to perform a bibliometric analysis of traffic carbon emission papers published between 1991 and 2022, focusing on measurement methods, mechanism analysis, and low-carbon pathway strategies.	[19]
Transportation supply chain	Bibliometric	Based on the carbon-neutral goals in the transportation sector, this review conducts a bibliometric analysis and highlights the increasing importance of hydrogen and biomass energy.	[20]
Transportation green development	Systematic	This review systematically summarizes research progress in the green development of the transportation sector, covering three key areas: performance evaluation, impact mechanism analysis, and the exploration of development pathways.	[21]
Regional research	Systematic	Focusing on carbon emissions in the Asian region, this review surveys research in four key areas: sustainable energy, water resources, transportation, and low-carbon emission technologies.	[22]
Cybersecurity technology	Systematic	This review provides an overview of cybersecurity technologies in low-carbon transportation, discussing current challenges and future development directions from a holistic perspective.	[23]
Railway transportation	Systematic	This review evaluates the development and transportation of clean energy in China's railway sector, emphasizing the vast potential of China's energy resources.	[24]
Hydrogen storage and transportation	Systematic	This review explores low-carbon technologies in the transportation sector from a hydrogen storage perspective, discussing various carrier methods in terms of availability, energy efficiency, water demand, and their applicability to power generation, shipping, truck transportation, and aviation, with a comprehensive safety review.	[25]
Transportation low-carbon fuel policies	Systematic	This review compares carbon policies for transportation fuels, considering economic efficiency, fuel price impacts, greenhouse gas emission reductions, and innovation incentives.	[26]

As climate change intensifies, TSLC research has become a key focus for scientists and policymakers. Over the past decade, with the emergence of numerous TSLC studies, several scholars have conducted literature reviews on TSLC research (Table 1). From a technical perspective, as pioneers in clean transportation, research on new batteries and

other sustainable fuels in sustainable energy conversion and storage systems has received significant attention and has been thoroughly reviewed [14,27–29]. Additionally, the development of algorithms for traffic air pollutants has also garnered significant attention. These reviews consolidate research on clean technologies and emission reduction strategies, providing continuous updates to provide direction for the technological advancement of TSLC research. Previous literature reviews have explored research developments across various transportation modes, including automotive energy demands and carbon emissions [30], the emergence of electric vehicles (EVs) [31,32], the rise of electric bicycles [33], and railway transportation energy [24]. Alongside the review of clean technologies and applications, emerging fields in transportation, such as green logistics [20], urban sustainable and smart transportation [34,35], and shared transportation [36], have also become key topics in literature reviews. Meanwhile, literature reviews from the perspectives of the transportation sector and social development are also contributing valuable insights. Some literature reviews focus on policy assessment and selection, collaborative institutions, and future directions from the perspectives of the transportation sector and government [37]. Other literature reviews aim to summarize progress in regional transportation sustainability goals and social efforts [22,38], offering support and guidance for regional low-carbon initiatives. Additionally, some literature reviews focus on the impact of TSLC aspects on individual-level factors, such as the effects of traffic emissions on human health [39] and the practitioners of low-carbon travel [40]. In terms of research methodology, most literature reviews in the TSLC field are systematic reviews. Meanwhile, some literature reviews utilize bibliometric methods for systematic organization. For example, a bibliometric analysis of carbon emissions research in the transportation sector is conducted [41], while a bibliometric method is used to summarize carbon emission measurement, mechanism analysis, and low-carbon pathway analysis in the transportation field [19]. These literature reviews have made significant contributions to summarizing, organizing, and guiding TSLC research within their respective subfields.

Although previous studies have outlined some of the research on TSLC progress, there are still some research gaps. (i) Previous literature reviews have mostly focused on specific transportation issues, such as sustainable fuels for transportation, transportation supply chains, etc., have weak contributions and connections to the topic of TSLC, and lack reviews and guidelines summarizing low-carbon technologies, low-carbon policies, and public participation at the macro level. (ii) Previous literature reviews have mostly focused on emission reduction technologies, carbon emission algorithms, regional development, and other perspectives, which can help researchers to a certain extent, but there is a lack of observation and summary from low-carbon policy, legal, social, and economic perspectives contributing to the coordination and sustainability of the overall development of TSLC research. (iii) Many use a single research method. Few reviews combine systematic and bibliometric methods to summarize research significantly and comprehensively. Following the entry into force of the PA, there has been an urgent need for "carbon reduction" and "zero-carbon" actions [42]. Given the impact of the PA on global emissions reductions, a systematic and bibliometric review of TSLC research 10 years after the PA is essential.

3. Data Collection and Methodology

3.1. Data Collection and Screening

We extracted the data from the Web of Science (WoS) Core Collection, following a detailed process of retrieval, collection, and cleaning through the following steps: (i) The start date for literature retrieval was set to 1 January 2016, aligning with the PA's effective date. (ii) To ensure that the literature focuses on the themes of "transportation" and "low carbon", the initial search formula was as follows: TI = (transport* OR traffic*)

AND TI = (low-carbon OR low carbon OR zero-carbon OR zero carbon OR decarboni* OR emission reduction OR net-zero emission* OR carbon neutral* OR clean OR CO_2 mitigation* OR carbon mitigation* OR CO_2 capture OR carbon capture). We chose to search by title rather than keywords to minimize interference from unrelated studies in fields such as physics, chemistry, biology, or materials science. (iii) To further ensure the accuracy of the data, we excluded any potentially confounding research areas. (iv) Document types were limited to articles, excluding previous literature reviews, to ensure that all selected texts are research papers. (v) Only English-language papers were included, eliminating language inconsistencies. This process ultimately yielded 746 publications, identified as the core bibliometric sample for TSLC study. The specific data processing steps are outlined in Figure 1.

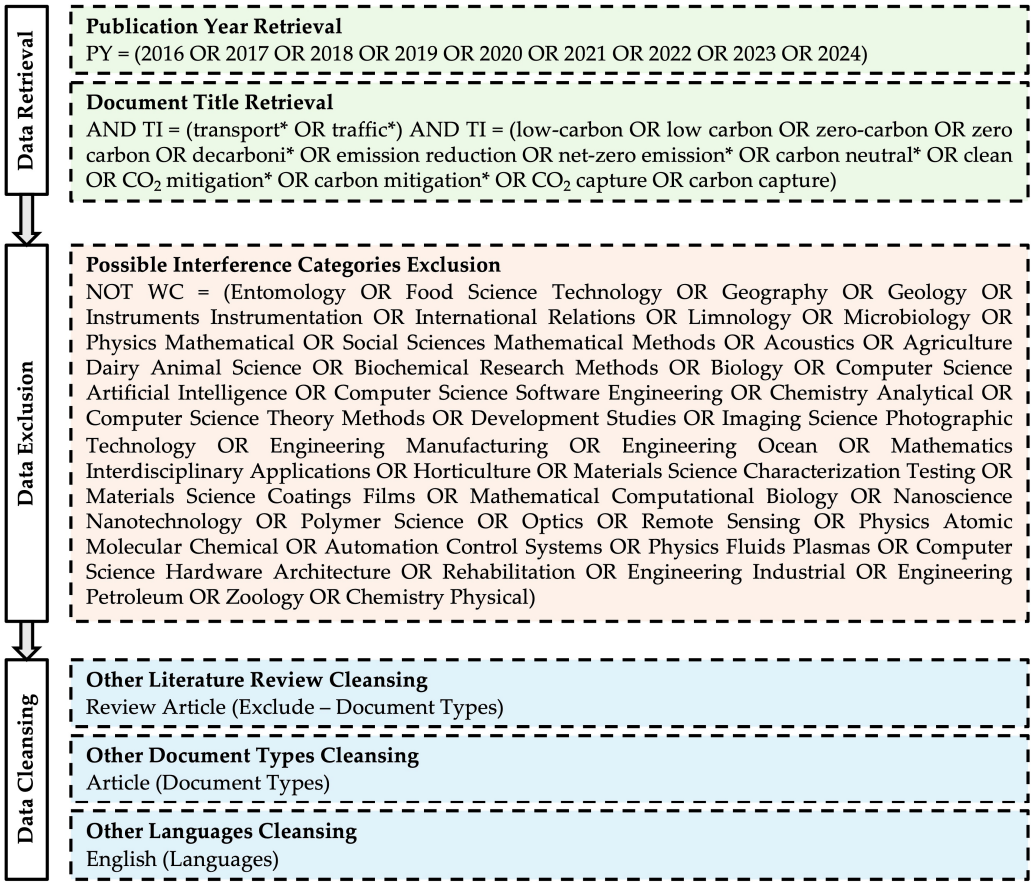

Figure 1. Flow chart of literature data collection and screening for TSLC research.

3.2. Research Methodology

In our study, we used a combination of bibliometric methods and systematic reviews. The bibliometric approach can provide an objective quantitative analysis of a group of studies, avoiding selection bias which can arise in traditional literature reviews. This approach has become central to multidisciplinary literature analysis. CiteSpace 6.3, one of the most popular bibliometric tools [43], offers visualization of various co-occurrence networks and insights into network structures, including collaboration, author co-citation, and citation dynamics over time [44]. It also identifies research frontiers and emerging trends [45]. Therefore, we chose CiteSpace as the bibliometric tool for our study. Additionally, we used descriptive analysis to interpret the visualized results and systematically mapped the development trajectory of TSLC studies following the PA. This bibliometric analysis was conducted on 30 July 2024. Based on the bibliometric results, we aimed to con-

struct a systematic framework of TSLC research, covering recent developments and future implications. Therefore, a systematic review was used in the second half of our study.

4. Results Analysis

4.1. Annual Change in Publication

Analyzing publication volume trends helps identify the topic's attention and development trajectory. Figure 2 shows the annual changes in publication volume for TSLC research post-PA, revealing a general upward trend. Publications were expected to exceed 140 articles by 2024. TSLC research growth can be divided into two phases: (i) 2016–2020, where annual publications increased from 39 to 77, with a cumulative 281 articles, marking the first growth phase after the PA; (ii) 2021–2024, when annual publications consistently surpassed 100 and increased yearly. The year 2020 marks a clear turning point, likely linked to policy directions, including China's carbon neutrality targets set in September 2020. Additionally, from 1 January 2020, the European Union enforced stringent vehicle CO_2 emissions standards, capping new car emissions at 95 g per kilometer. These policies spurred renewed interest in TSLC research and directly propelled the second growth phase of research.

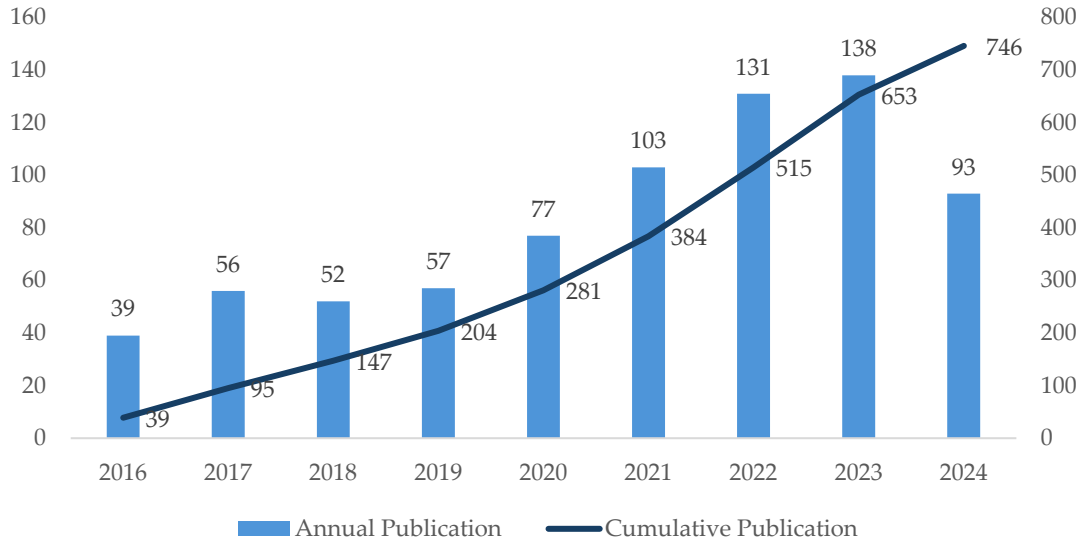

Figure 2. Distribution of publications in TSLC research after PA.

4.2. Country Analysis

Based on the data from the WoS Core Collection, we analyzed 85 countries or regions involved in TSLC research. Information on the top 10 countries by publication volume is presented in Table 2. Overall, publication output varied widely among these countries. China led TSLC research in publication volume, reflecting a high degree of interest likely influenced by national policies. Countries listed in Table 2 are primarily concentrated in Asia, Europe, and North America.

Figure 3 shows the country collaboration network generated by CiteSpace, displaying countries with publication volumes exceeding 10. The larger the node, the higher the publication volume; lighter colors indicate more recent research; denser connections signify stronger collaboration. The high-centrality nodes marked in red, such as China, the United States, the United Kingdom, India, Sweden, and Spain, reflect substantial and influential collaborative research. The darker color of the U.S. node in the figure indicates its early contributions, often leading in areas like renewable energy applications in low-carbon transport [46,47]. By contrast, China's lighter-colored node suggests more recent research

outputs, influenced by policies focusing on "carbon peaking" and "carbon neutrality". Notable Chinese studies include carbon-neutral highway strategies [48], technology paths for carbon-neutral freight transport [49], and the impact of spatial and temporal carbon emission patterns on carbon neutrality [50].

Table 2. Top 10 countries in TSLC research in terms of publications.

Rank	Country	Publications	Percentage
1	China	261	34.99%
2	United States	107	14.34%
3	United Kingdom	69	9.25%
4	Germany	50	6.70%
5	Italy	39	5.23%
6	India	32	4.29%
7	Japan	31	4.16%
8	Sweden	28	3.75%
9	Spain	27	3.62%
9	Canada	27	3.62%

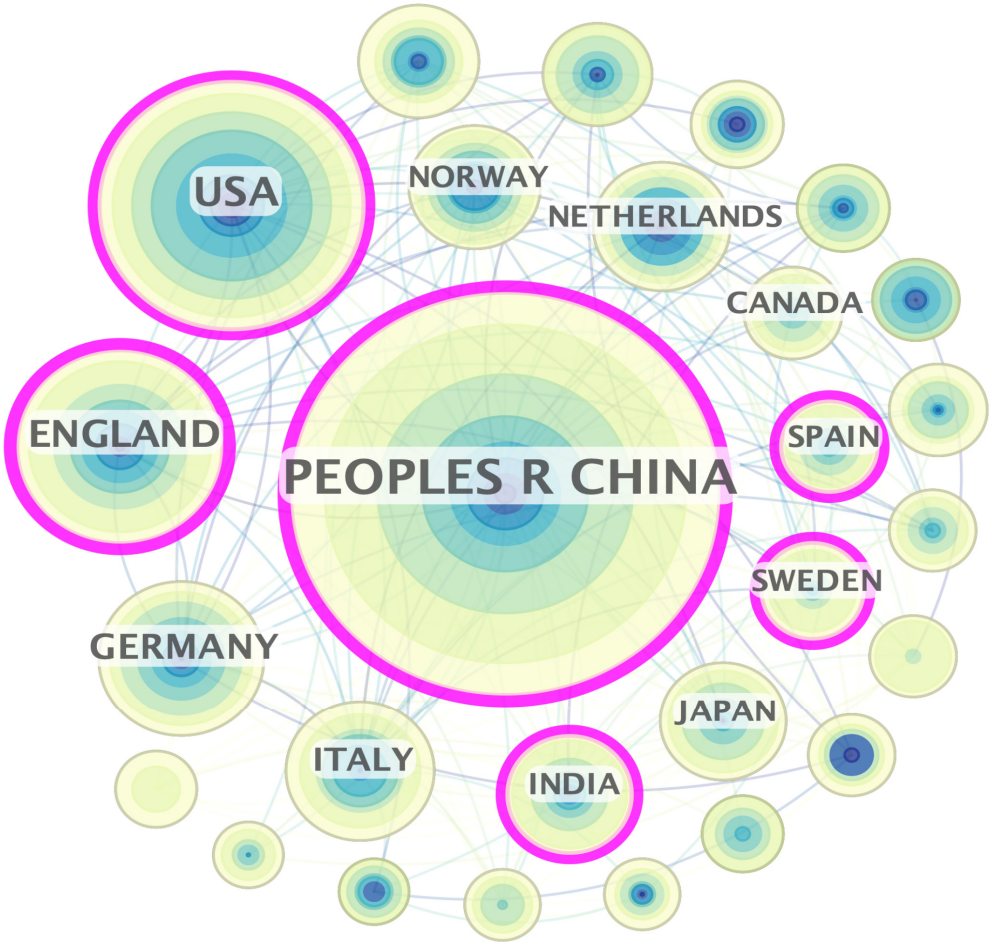

Figure 3. Snapshot of country cooperation network.

4.3. Institute Analysis

Table 3 lists the top 10 research institutions by TSLC publication volume. These include three institutions in China (totaling 7.24% of publications), three in the United Kingdom (4.16%), two in the United States (4.16%), two in Switzerland (2.94%), and one in India. This distribution highlights China's leading role and strong commitment to TSLC research.

Table 3. Top 10 institutes in TSLC research in terms of publications.

Rank	Institute	Country	Publications	Percentage
1	Tsinghua University	China	23	3.08%
2	Chinese Academy of Sciences	China	22	2.95%
3	University of California System	United States	19	2.55%
4	United States Department of Energy (DOE)	United States	12	1.61%
4	University of London	United Kingdom	12	1.61%
6	Swiss Federal Institutes of Technology Domain	Switzerland	11	1.47%
6	ETH Zurich	Switzerland	11	1.47%
8	Imperial College London	United Kingdom	10	1.34%
9	Indian Institute of Technology System (IIT System)	India	9	1.21%
9	University of Leeds	United Kingdom	9	1.21%
9	Central South University	China	9	1.21%

Using CiteSpace, we visualized institutional collaboration (Figure 4), focusing on institutions with more than four publications. Four high-centrality nodes—Tsinghua University, Chinese Academy of Sciences, the University of California System, and the University of London—are highlighted in red, reflecting their productivity and collaborative networks in TSLC research. Notably, the darker color of the Chinese Academy of Sciences node indicates early engagement in TSLC research, with early studies focusing on CO_2 emissions modeling and forecasting [51,52].

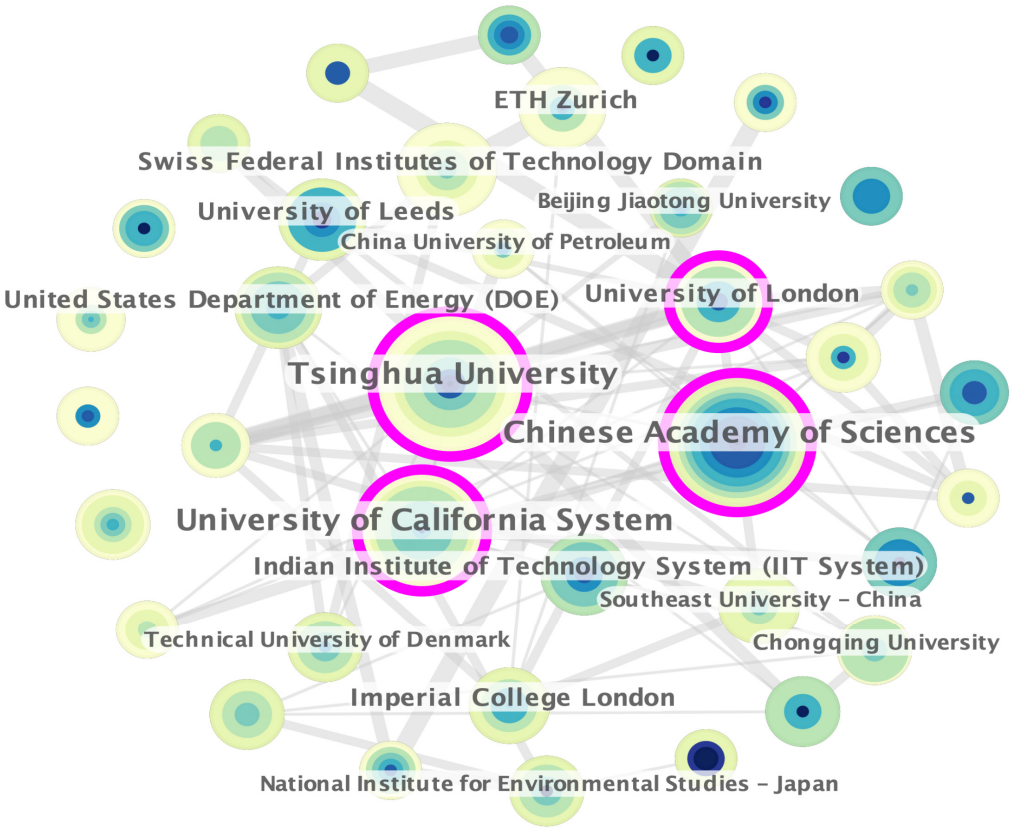

Figure 4. Snapshot of institute cooperation network.

4.4. Journal Analysis

We analyzed 490 journals that published TSLC-related research, with the top 10 journals in terms of publication volume listed in Table 4. Although these journals lead in publication numbers, none account for over 10% of the total publications. Table 4 also includes the impact factors (IF 2023) of these journals, among which *Applied Energy* (IF 2023 = 10.1) is considered the most authoritative.

Table 4. Top 10 journals in TSLC research in terms of publications.

Rank	Journal	Publications	Percentage	Co-Citation	IF 2023
1	*Sustainability*	51	6.84%	192	3.3
2	*Journal of Cleaner Production*	42	5.63%	332	9.7
3	*Transportation Research Part D-Transport and Environment*	34	4.56%	304	7.3
4	*Energies*	32	4.29%	157	3
5	*Applied Energy*	30	4.02%	333	10.1
6	*Energy*	21	2.82%	285	9
7	*Energy Policy*	21	2.82%	4	9.3
8	*International Journal of Greenhouse Gas Control*	17	2.28%	75	4.6
9	*Environmental Science and Pollution Research*	12	1.61%	89	0.99
10	*Transport Policy*	11	1.47%	7	6.3

To further investigate the contributions of these journals, we used CiteSpace to generate a journal citation network (Figure 5). By setting a threshold of citation ≥50, a total of 47 journal nodes appear in the figure. *Energy Policy* (citation = 359), *Applied Energy* (citation = 333), and the *Journal of Cleaner Production* (citation = 332) are the three largest nodes, indicating that they have the highest citation counts in TSLC research. By combining Table 1 and Figure 5, we observe that the *Energy Policy* node is darker, reflecting an earlier focus on regional carbon emissions and decarbonization path analysis in areas like Malaysia [53], the EU [54], and China [55]. The lighter-colored node of *Environmental Science and Pollution Research* shows its relatively recent focus on multidisciplinary TSLC studies, such as environment–law [56], environment–finance [57], and environment–policy intersections [58].

4.5. Author Analysis

We also analyzed prolific TSLC authors, and Table 5 shows eight authors with publications ≥5. D'amore F., a leading researcher in this field, collaborated with Bezzo F. on a mixed-integer linear programming framework for optimizing Europe's large-scale carbon geological storage supply chain to achieve low-carbon targets [59]. This study has been cited 64 times in WoS, marking a significant contribution. Notably, all five of Bezzo F.'s studies were in collaboration with D'amore F., indicating a strong connection in TSLC research. Zhang R. S., with five studies and 161 citations, is the most cited author. He focuses on interdisciplinary TSLC topics, such as economics and policy [60].

Figure 6 shows the CiteSpace-generated co-citation network (co-citation ≥ 10), highlighting key contributors to TSLC research. Frequently cited publications from authoritative institutions such as the IEA, European Commission, and IPCC underscore the significance of these references, although these organizations are omitted from the figure to avoid skewing the analysis. According to Figure 6, Creutzig F. (co-citation = 41), Brand C. (co-citation = 39), and Hao H. (co-citation = 36) are the three main nodes, indicating that

their research is widely recognized in the TSLC field. The node for Ang B. W., highlighted in red, signifies his status as an influential contributor.

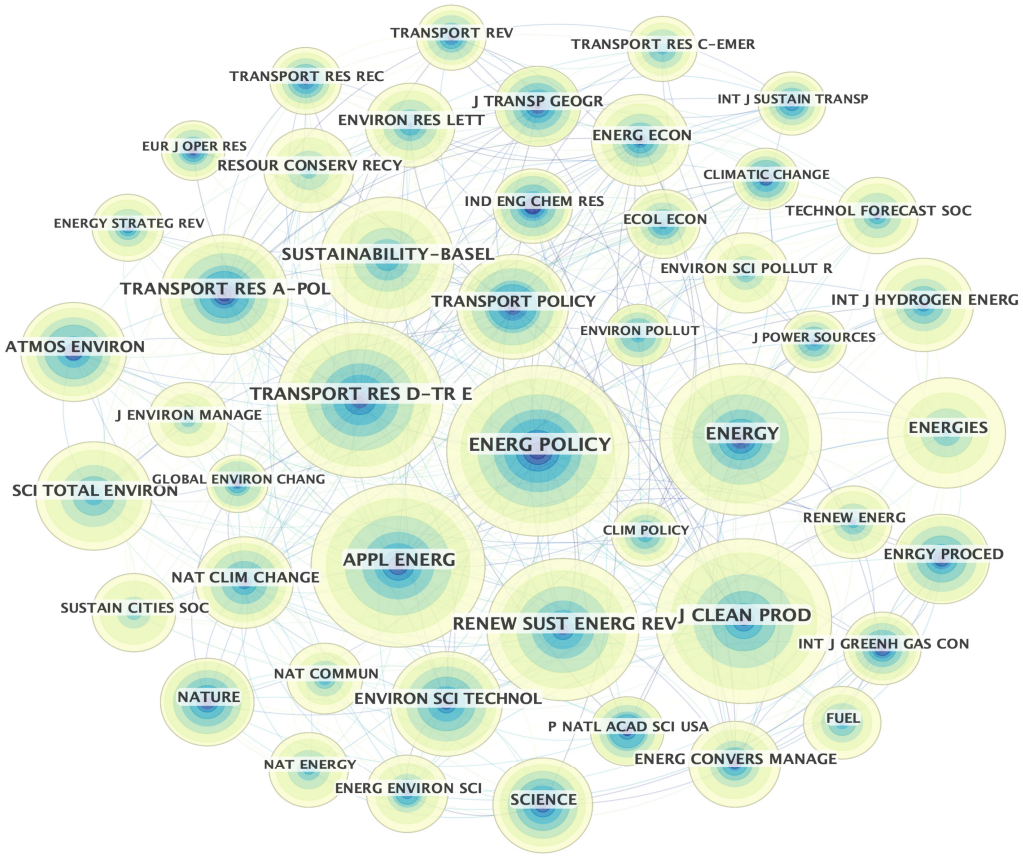

Figure 5. Snapshot of journal co-citation network.

Table 5. Top authors in TSLC research in terms of publications.

Rank	Author	Publications	Total Citations in TSLC Research	Most Cited Studies in WoS
1	D'amore F.	6	156	Economic optimisation of European supply chains for CO_2 capture, transport and sequestration [59]
2	Bezzo F.	5	150	Economic optimisation of European supply chains for CO_2 capture, transport and sequestration [59]
2	Li W. X.	5	97	Assessing the transition to low-carbon urban transport: A global comparison [61]
2	Wang S.	5	50	High reduction of ozone and particulate matter during the 2016 G-20 summit in Hangzhou by forced emission controls of industry and traffic [62]

Table 5. *Cont.*

Rank	Author	Publications	Total Citations in TSLC Research	Most Cited Studies in WoS
2	Yang Y.	5	107	Assessment of Osculating Value Method Based on Entropy Weight to Transportation Energy Conservation and Emission Reduction [63]
2	Zhang H. Y.	5	51	Emission reduction mode of China's provincial transportation sector: Based on "Energy+" carbon efficiency evaluation [64]
2	Zhang R. S.	5	161	Long-term pathways to deep decarbonization of the transport sector in the post-COVID world [60]
2	Zhang X.	5	72	Hollow microsphere-infused porous poly (vinylidene fluoride)/multiwall carbon nanotube composites with excellent electromagnetic shielding and low thermal transport [65]

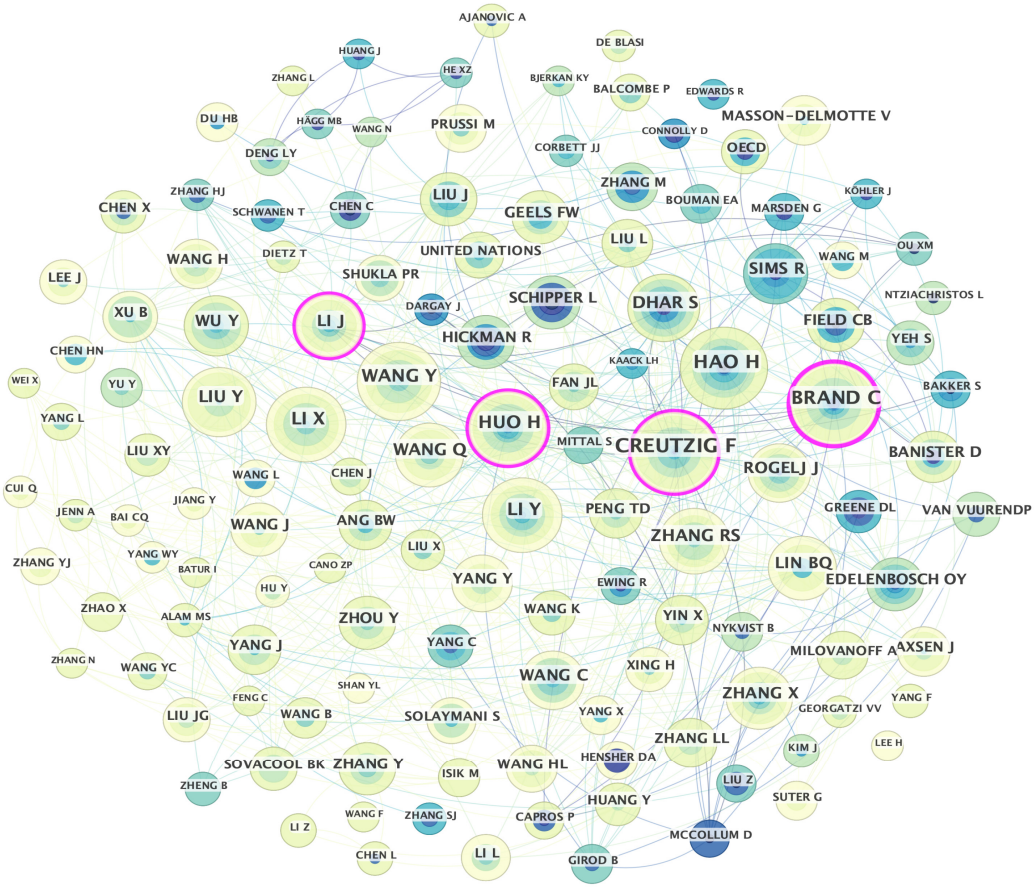

Figure 6. Snapshot of author co-citation network.

4.6. Literature Analysis

4.6.1. Crucial Research

We counted the number of citations of TSLC studies, and Table 6 shows the top seven studies (co-citation ≥ 9). Among them, studies on the factors influencing passenger carbon emission pathways [66] and the vehicle electrification goal [67] are considered the most important, with each being cited 13 times. While the co-citation counts of these two studies indicate their importance in TSLC research, their citation count in WoS is lower than that of many other studies, suggesting that they are more important in TSLC research but may not apply to the whole field of low-carbon research. The four significant studies shown in Table 6 are from *Nature* publications, reinforcing the journal's authority in TSLC research.

Table 6. Top 7 co-cited references of TSLC research.

Rank	Co-Citation	Citation in WoS	Reference	Title	Source (IF 2023)
1	13	89	[66]	Decomposing passenger transport futures: Comparing results of global integrated assessment models	*Transportation Research Part D-Transport and Environment* (IF = 7.3)
1	13	127	[67]	Electrification of light-duty vehicle fleet alone will not meet mitigation targets	*Nature Climate Change* (IF = 29.6)
3	12	—	—	Transport	*Climate Change 2014: Mitigation of Climate Change*
4	11	465	[68]	Towards demand-side solutions for mitigating climate change	*Nature Climate Change* (IF = 29.6)
4	11	130	[69]	Development and application of China provincial road transport energy demand and GHG emissions analysis model	*Applied Energy* (IF = 10.1)
4	11	152	[70]	Regional differences and driving factors analysis of carbon emission intensity from transport sector in China	*Energy* (IF = 9)
7	9	136	[71]	Crafting strong, integrated policy mixes for deep CO_2 mitigation in road transport	*Nature Climate Change* (IF = 29.6)
7	9	63	[72]	Transportation emissions scenarios for New York City under different carbon intensities of electricity and electric vehicle adoption rates	*Nature Energy* (IF = 49.7)
7	9	77	[73]	Peaking CO_2 emissions for China's urban passenger transport sector	*Energy Policy* (IF = 9.3)

4.6.2. Literature Co-Citation

Co-citation analysis reveals the key features and relationships among critical research in this area [74]. Figure 7 shows the co-citation network generated in CiteSpace with G-index = 35, including 1882 links. We extracted 13 of the largest clusters, categorized into three primary modules as follows:

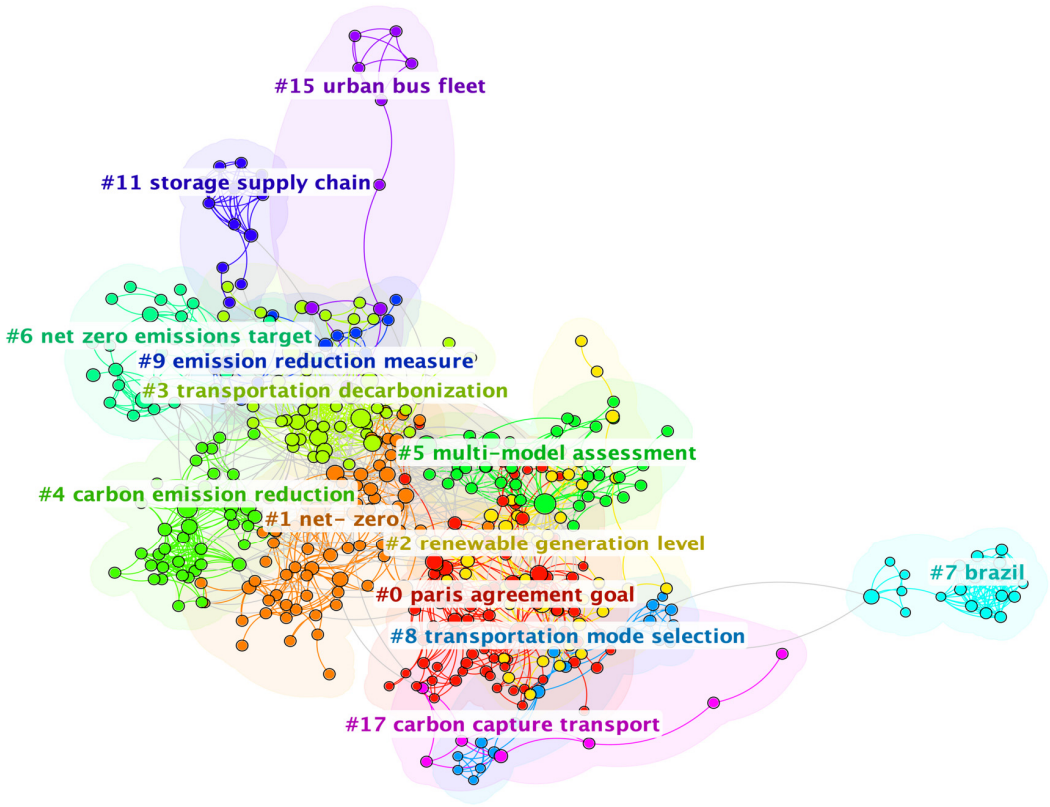

Figure 7. Snapshot of network of literature co-citation.

(i) Low-Carbon Policy and Targets: Cluster #0 and Cluster #6. These studies illustrate the substantial impact of the PA on TSLC research. Cluster #0 contains 80 papers, with the key paper [75] assessing the decarbonization efforts in China's transportation sector. Cluster #6 includes 26 studies. A study discussing how the transportation sector can achieve Türkiye's 2053 net-zero target became the focal point of the cluster [76]. This module's research is closely linked to PA targets, with scholars often evaluating the impact of policy goals on transportation across various regions.

(ii) Emission Reduction Technologies and Measures: Cluster #4, Cluster #9, and Cluster #17. The research in this group focuses on emission reduction in the transport sector and its impacts. Among these, the study on carbon dioxide emissions and low-carbon planning strategies in Beijing's transportation sector received the most citations in this cluster [77]. This module builds TSLC-focused emission reduction strategies from multiple angles, including regional differences [70,78], energy system efficiency [79,80], and carbon reduction policies [81,82].

(iii) Clean Energy and Sustainable Transportation: Cluster #2, Cluster #8, and Cluster #15. Cluster #2, containing 50 studies, emphasizes clean energy applications in transportation [83]. Cluster #8, containing 19 studies, examines low-carbon transportation mode selection [84]. Cluster #15 includes nine studies, contributing insights into sustainable urban bus fleet development [85,86].

4.7. Research Trend Analysis

4.7.1. Summary of Hotspot

Table 7 displays the top 10 high-frequency keywords and their centrality values identified by CiteSpace from 411 keywords. In TSLC research, the most popular keywords are CO_2 emissions (frequency = 93, centrality = 0.06) and emissions (frequency = 93, centrality = 0.05). Many studies explore the relationship between greenhouse gas emissions and

environmental pollution [87] and propose pathways to low-carbon development [88–90]. Energy occupies a significant position in TSLC research, with high frequencies for keywords such as energy (frequency = 59, centrality = 0.04) and energy consumption (frequency = 54, centrality = 0.04). Numerous researchers focus on clean, sustainable energy applications in low-carbon transport [22,91]. Although performance (frequency = 42, centrality = 0.13) and technology (frequency = 39, centrality = 0.12) have lower frequencies, their high centrality values suggest that these concepts are core to TSLC research.

Table 7. Top 10 high-frequency keywords of TLC research.

Rank	Keywords	Frequency	Centrality
1	CO_2 emissions	93	0.06
2	emissions	90	0.05
3	energy	59	0.04
3	impact	59	0.08
5	electric vehicles	56	0.05
6	greenhouse gas emissions	54	0.05
6	energy consumption	54	0.04
8	model	47	0.06
9	performance	42	0.13
10	technology	39	0.12

4.7.2. Hotspot Co-Occurrence

To analyze the relationships among these key research hotspots, we constructed a research hotspot co-occurrence network (Figure 8), which reveals the thematic configurations in the TSLC research field [92]. Figure 8 presents 10 major keyword clusters calculated based on document titles in CiteSpace with the G-index set to 35, representing different directions in TLC research. These clusters are described as follows:

Cluster #0 is the largest cluster, containing 97 keywords. Research here focuses on decarbonization in passenger transport [93]. Key terms include "emissions" (co-occurrence = 90), "electric vehicles" (co-occurrence = 56), and "greenhouse gas emissions" (co-occurrence = 54). For example, total CO_2 emissions have been estimated from urban transport with a focus on passenger transport decarbonization [61], while a multi-objective optimization model has been proposed for the urban passenger transport structure to support low-carbon urban planning [94]. Passenger transport is recognized as one of the primary contributors to carbon emissions in the transport sector [95], making the keywords within this cluster core topics in TSLC research.

Cluster #1 comprises 57 keywords, focusing on optimizing traffic efficiency through adaptive traffic signal systems [96]. The main keywords include "system" (co-occurrence = 33) and "design" (co-occurrence = 17). A representative study in this cluster discusses a smart sensor network with adaptive traffic lights which can reduce carbon emissions from vehicles at traffic intersections and support the sustainable development of low-carbon smart cities [97].

Cluster #2 includes 56 keywords, with a strong focus on emissions reduction strategies. The term "China" appears 33 times, indicating China's significant focus in this field, with multiple studies targeting low-carbon development in Chinese cities. Notable examples include low-carbon emissions reduction strategies [98,99] in Beijing [55,100], Shenzhen [101], and Harbin [102].

Cluster #5 includes 50 keywords. Although overlapping somewhat with Clusters #0 and #2, this cluster places a greater emphasis on sustainability within the TSLC field [103]. Key research topics include "CO_2 emissions" (co-occurrence = 93), "energy consumption" (co-occurrence = 54), and "carbon emissions" (co-occurrence = 30). Scholars have analyzed

the effects of global and regional low-carbon policies on TSLC development [56] and examined factors, mechanisms, and pathways for low-carbon development [104,105].

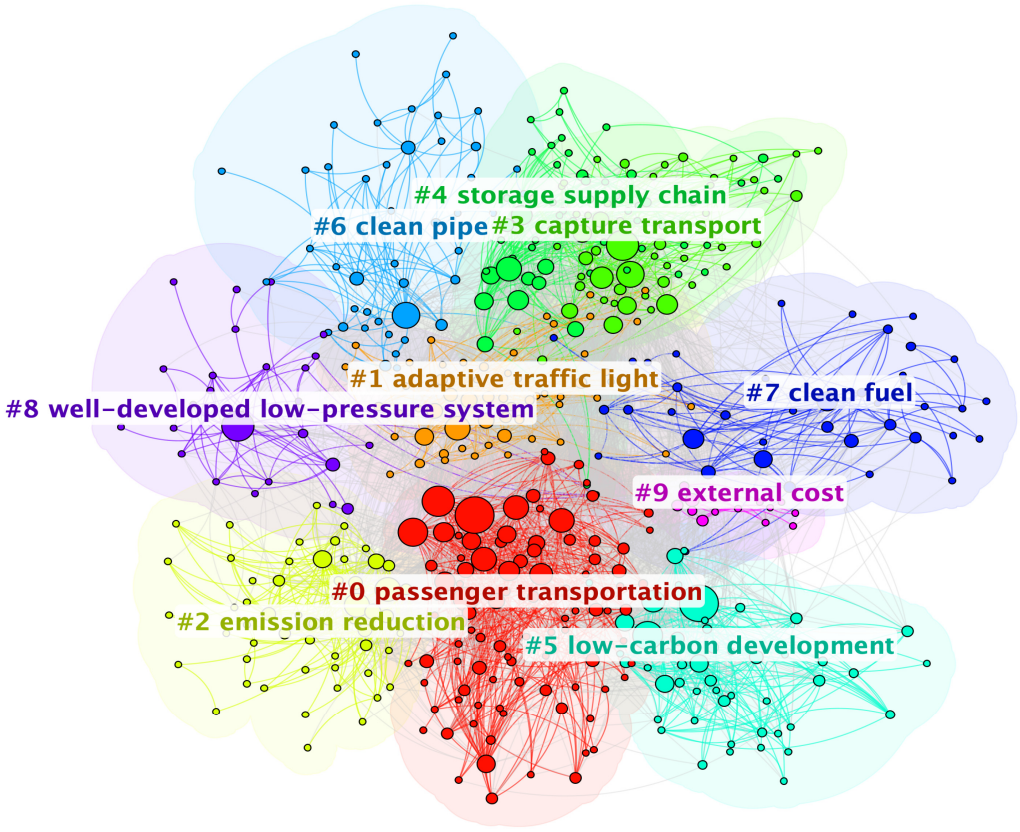

Figure 8. Snapshot of network of keywords co-occurrence.

Clusters #8 and #9 are smaller clusters. Cluster #8 includes 26 keywords, mainly discussing variations in carbon emissions under low-pressure climate conditions [106]. Common keywords in this cluster are "impact" (co-occurrence = 59) and "simulation" (co-occurrence = 10). Cluster #9 includes 13 keywords, exploring the external costs and benefits of clean fuels in TSLC initiatives [107] and predicting future carbon reduction potential. Common keywords in this cluster include "sustainable transport" (co-occurrence = 8), "barriers" (co-occurrence = 6), and "incentives" (co-occurrence = 5).

4.7.3. Emerging Hotspot

We analyzed bursts in TSLC research to uncover emerging and declining themes in the field [108]. Table 8 presents the top 15 burst terms. Red line segments indicate the time span of each burst [109]. These keywords are arranged in chronological order. The earliest bursts were observed for behavior and reduction. This suggests that after the PA came into effect, scholars initially focused on two themes: first, the influence of behavior on TSLC systems, including individual, corporate, transportation sector, and social behaviors; and second, the relationship between carbon reduction and TSLC systems, covering the calculation, prediction, and pathways for carbon reduction. "Electric vehicle" is the latest burst term, continuing from 2022 to the present, becoming a crucial component in building a low-carbon transport system [110,111]. This hotspot extends beyond traditional energy-saving and emissions-reducing research to political discussions [112]. The terms with the highest burst strengths in Table 8 are "cost" (strength = 3.29), "electric vehicle" (strength = 3.28), and "simulation" (strength = 3.2), indicating intensive research interest in these topics over a short period.

To investigate the latest trends in TLC research and provide guidance for future studies, we identified 28 new keywords emerging in 2024 and their frequencies (see Table 9). Among these, "transportation sector" (frequency = 3, degree = 13) appears with the highest frequency and intensity. Low-carbon development of the transportation sector is critical to achieving peak carbon emissions [113]. Recent research in this area involves carbon emission model construction [114], decarbonization policies [115], and sector development [116–118]. Additionally, the frequent occurrence of "supply chain" (frequency = 3, degree = 10) underscores its importance in commercial carbon emissions, particularly in relation to delivery methods and TSLC linkages [119].

Table 8. Top 15 keywords with the strongest bursts in TSLC research.

Rank	Keywords	Strength	Begin	End	2016–2024
1	behavior	3.12	2016	2019	
2	reduction	2.36	2016	2018	
3	cost	3.29	2017	2020	
4	climate change	3.09	2017	2020	
5	hybrid	2.77	2017	2018	
6	travel	2.69	2017	2021	
7	dioxide	2.49	2017	2018	
8	design	2.48	2017	2018	
9	scenarios	2.64	2018	2021	
10	greenhouse gas emissions	2.49	2019	2020	
11	sustainable development	2.65	2020	2021	
12	particulate matter	2.42	2020	2022	
13	simulation	3.2	2021	2022	
14	PM 2.5	2.39	2021	2022	
15	electric vehicle	3.28	2022	2024	

Table 9. Latest keywords of TSLC research emerging in 2024.

Keywords	Frequency	Degree	Keywords	Frequency	Degree
transportation sector	3	13	acceptability	1	5
logistics	2	12	deep reinforcement learning	2	5
energy storage	2	11	products	2	5
green hydrogen	2	11	net -zero	2	5
generation	2	10	co benefits	2	5
supply chain	3	10	perspective	2	4
prospects	2	10	perovskite solar cells	2	3
net zero	2	9	formulation	2	3
emission	2	8	drivers	2	3
stirpat model	2	8	carbon electrodes	2	3
adaptive signal control system	1	8	fabrication	2	3
waste	2	7	sustainable transportation	2	3
socioeconomic factors	2	6	CGE	2	2
carbon peak	2	6	ab initio	1	2

5. Discussion and Knowledge Mapping

5.1. The Latest Development in TSLC Research Since the PA

TSLC research has progressively developed in line with society's focus on sustainable development. As one of the most important and cutting-edge low-carbon policies in the world, the PA has largely guided the direction of research in this field. The PA's carbon

reduction requirements have spurred the exploration of emissions reduction technologies in transportation, including advances in zero-carbon fuels and the application of new low-carbon technologies. A significant body of new research emphasizes carbon reduction from a digital technology perspective, aiming to optimize transportation emissions reduction strategies through data-driven solutions. Additionally, cutting-edge studies on low-carbon policies and societal acceptance have deepened the application and implementation of policies like the PA. We will next review the latest developments in TSLC research post-PA from three perspectives to provide a systematic overview for future research.

5.1.1. Renewable Energy and Technology Applications

Since the PA came into effect, addressing high carbon emissions from traditional fuels in the transportation industry has driven rapid advancements in sustainable energy research, notably hydrogen fuel cells and technologies for electric vehicles (EVs) powered by renewable energy sources. Among them, hydrogen energy is a key enabler to achieve the goals of the PA, especially in less electrified sectors, and ammonia–hydrogen hybrid fuels have been shown to deliver significant carbon reductions in heavy-duty transportation [120]. Recent studies have demonstrated the gradual deepening and refinement of renewable energy applications in transportation. Forecasting hydrogen energy demand for regional transport is at the forefront of attention. Assessing the economic and environmental benefits of hydrogen fuel in transport is also a hot research topic. Recent studies have shown that hydrogen produced from methane is the most economically viable for transportation applications [121]. Other renewable energy technologies have also become prominent research topics. For example, biomass resources can significantly reduce energy costs in the transportation sector [91]. Biofuels and electro fuels derived from biomass resources are viable clean energy alternatives to traditional fuels [122].

Advances in onboard battery technology have driven the widespread adoption of EVs [123]. According to data from the International Energy Agency (IEA), global electric vehicle sales exceeded 10 million by 2020. Integrating renewable energy into EV charging infrastructure is crucial for achieving environmental benefits. Government policies promoting EVs have played a pivotal role in advancing low-carbon goals [124]. Consequently, since the PA, academic discussions on EVs have expanded across various aspects, including low-carbon policy incentives, low-carbon fuel technologies, and the integration of EV applications [125].

5.1.2. Evolution of Intelligent Transport Systems

The development of intelligent transportation systems (ITSs) has become a central topic in low-carbon transportation research following the implementation of the PA. ITSs aim to enhance the efficiency of transportation networks through advanced digital technology, promoting sustainable transportation. The urgency for transportation system transformation, as outlined in the PA, has accelerated the rapid advancement of ITS technologies.

Recent studies emphasize ITSs' substantial role in increasing energy efficiency and reducing urban carbon emissions. For instance, ITSs' contribution to emission reduction in road transportation has been quantified [126,127], thus advancing the shift toward low-carbon mobility. The integration of artificial intelligence (AI) has further amplified ITSs' emission reduction impact. Research shows that big data and machine learning have also been introduced in ITS research and development [128]. Furthermore, as noted in Section 4.7.2, new ITS applications like adaptive traffic lights have made remarkable progress post-PA, demonstrating a reduction in urban vehicle carbon emissions.

In addition, Vehicle-to-Grid (V2G) technology, which enables electric vehicles to interact with the power grid, is regarded as a promising technology for advancing clean trans-

portation and improving EV utilization efficiency [87]. And V2G-integrated shared hubs provide optimal ITS services, significantly enhancing emission reduction [129]. As a key component of ITSs, V2G is making a substantial contribution to low-carbon development.

5.1.3. Developments of TSLC Policies

The global impact of the PA, one of the most important global low-carbon policies in recent years, continues to deepen. Moreover, the latest TSLC research continues to focus on the deep impact of the PA on the transport sector globally, especially in developing countries and countries and regions with critical carbon emission situations, such as Pakistan [130], Glasgow [131], Zimbabwe [132], etc. The implementation of the PA targets in these regions has been a hot topic of recent research. Under the guidance of the PA, government departments and transportation sectors in each region are committed to developing TSLC policies relevant to local conditions in order to achieve the PA goals. As a result, with the proliferation of TSLC policies in each region, the number of studies on related regional policy assessments and recommendations has also increased. The Chinese government has emphasized carbon peaking and carbon neutrality policies, and China's transport choices under its constraints and key urban transport governance have received attention [55,56]. The Indian government has proposed to achieve 30% penetration of electric vehicles to increase the use of green energy and meet the PA goals. Recent studies have focused on the likelihood of realizing this policy and how it will be implemented, and have highlighted the direction of future policy interests of the Indian government [133]. Comparisons of TSLC policies across regions are also gaining popularity, for example, the development, differences, and challenges of low-carbon transport policies in the ASEAN-4 countries have received attention [134].

In addition, carbon pricing mechanisms, which are the primary focus of TSLC policies, are widely viewed as effective low-carbon policies, as they shift internal and external environmental costs. Carbon pricing encourages consumers to adopt low-emission transportation options, which are essential for phasing out traditional vehicles and achieving low-carbon transportation goals [135].

5.1.4. Public Reaction and Participation

Public participation has become increasingly recognized as a crucial final step in the implementation of TSLC policies. Recent studies highlight the bidirectional relationship between low-carbon policies and public participation. The success of low-carbon technologies and policies is highly dependent on the public's level of acceptance [136]. Consequently, leading studies have focused on quantifying public awareness of low-carbon transportation [137] and exploring the selection of low-carbon transportation modes in specific contexts [138].

Some recent research considers the degree of public acceptance and participation as a key metric for evaluating low-carbon policies and actions. Recent studies have explored the role of public political agencies in shaping low-carbon transportation policies [139] and highlighted the significance of public understanding in low-carbon decision-making from a technological implementation perspective [140]. Public participation in green transportation is seen as a key component in the decarbonization of the transport sector [141]. Therefore, integrating public awareness, recognition, and participation into the development of low-carbon technologies and policies, along with employing a multi-level governance approach that combines national policy frameworks with local implementation and public involvement, is regarded as a critical factor in achieving the transportation sector's goals under the PA.

5.2. Potential Impacts of TSLC Policies and Practices

5.2.1. The Impact on the Circulation of Transport Commodities

First, from the perspectives of both producers and consumers, low-carbon incentive policies like the PA have played a significant role in advancing and implementing low-carbon transportation technologies such as EVs. Government-provided purchase subsidies, tax incentives, and specialized funding for the production and research of new energy vehicles [142] have effectively lowered the costs for both consumers and manufacturers. These measures reduce the price gap between traditional fuel vehicles and new energy vehicles. Policy-driven support has alleviated financial pressures on the supply side, increasing the motivation for green product research and development; on the demand side, decreased purchase costs have enhanced the appeal and demand for low-carbon products. This has not only increased the market share of new energy vehicles but also accelerated the green transition across the entire transportation sector.

5.2.2. The Impact on the Energy System

In terms of energy system development, government policy has promoted the use of new and renewable energy sources in transportation, reducing the sector's dependence on fossil fuels and significantly lowering greenhouse gas emissions. Specifically, electric vehicles can connect to the traditional power grid and recharge via renewable sources such as solar and wind energy, advancing the low-carbon transition. Additionally, ongoing research into hydrogen fuel cell technology in electric vehicles represents a transformative shift in the transportation energy system. Hydrogen energy is viewed as a vital pathway for achieving low- or even zero-carbon emissions in the future, particularly for heavy-duty transport modes such as trucks and ships. Policy support is expected to further expand the technological breakthroughs and applications of these renewable energy sources.

5.2.3. The Impact on the Transportation System

From a systemic perspective, low-carbon policies have improved infrastructure development, especially in charging networks and intelligent transportation systems. The availability and convenience of charging facilities are critical challenges for EV adoption. Through policy guidance, governments have accelerated the construction of charging station networks, thereby increasing EV adoption rates [143]. As infrastructure and related technologies advance, the adoption of new-generation transportation products, such as electric vehicles, new energy vehicles, and autonomous vehicles, has accelerated under governmental support. Moreover, low-carbon policies extend beyond private vehicles, encompassing the low-carbon transformation and upgrades of public transportation systems and adaptive traffic signals. As each segment advances in its low-carbon transition, an intelligent, low-carbon transportation network is gradually being realized. Furthermore, low-carbon policies also encourage citizens to choose low-carbon public transportation through fare subsidies and enhanced service convenience.

5.2.4. The Impact on Socio-Economic Development

The adoption of low-carbon transportation policies has had a profound impact on transportation, energy systems, and socio-economic development. From an economic growth perspective, the application of low-carbon transportation technologies, such as electric vehicles, renewable energy, and low-carbon infrastructure for transportation systems, has driven the development of related industries and created new drivers of economic growth [45]. At the same time, policies such as the PA have guided the public toward gradually accepting green travel modes, thereby increasing the social acceptance of low-carbon transportation systems. During this process, the social cognition shaped by policy

guidance and economic growth interact bidirectionally, effectively driving the transition to a low-carbon economy and making green industries key drivers of economic growth.

However, the practice of TSLC systems faces socio-economic challenges. First, policy implementation requires additional government expenditure to support the protection of relevant industries and subsidies for goods, which puts pressure on regions with lower fiscal capacities. Ensuring the equitable implementation of these policies has become an urgent issue to resolve. Secondly, the development of low-carbon transportation has disrupted the traditional fossil fuel vehicle industry, potentially leading to job losses and the growing pains of industrial transformation. Therefore, in policy implementation, it is essential to focus on facilitating the smooth transition of related industries to alleviate socio-economic pressures.

5.3. Knowledge Mapping of the Low-Carbon Pathways in Transportation

Based on the discussion above, we summarize the pathways for the low-carbon transition of the transport sector from three perspectives: the supply side, the demand side, and the industrial chain (Figure 9). (i) Supply-side transition. The core of the supply-side low-carbon transition lies in promoting the green transformation of high-carbon-emission vehicles through low-carbon technological innovation and applications. This is mainly reflected in the widespread adoption of EVs and the research and application of hydrogen fuel technologies. Furthermore, optimizing the energy structure and developing infrastructure play a critical role in supporting this transition. (ii) Demand-side transition. The demand-side transition focuses on promoting the widespread adoption of low-carbon transportation behaviors through policy guidance and social behavioral changes. At the individual level, travel subsidies, vehicle purchase incentives, and other policy measures have promoted the decarbonization of personal transportation consumption. At the societal level, optimizing traffic management, improving travel patterns, and regulating traffic flow have further reduced unnecessary emissions. (iii) Industrial chain coordination. Coordination and collaboration within the industrial chain are essential for a successful low-carbon transition. Within the transport industry, building a green supply chain that spans raw material procurement, production, sales, and after-sales services is key. Additionally, from a cross-industry perspective, technology sharing and resource integration have accelerated the decarbonization process of the transport system. The collaborative efforts both within and beyond the industry provide critical momentum for the low-carbon transition of the transport system.

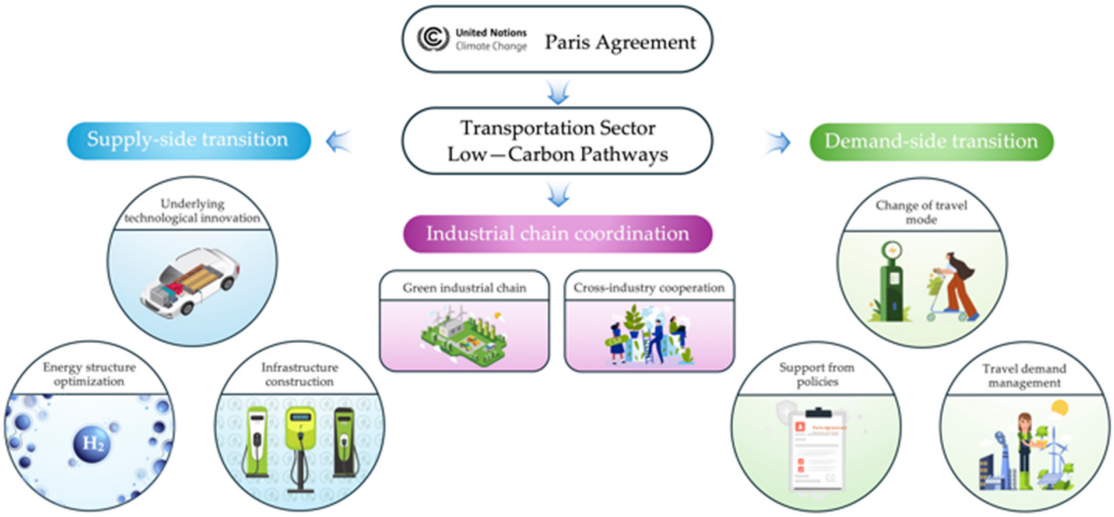

Figure 9. Knowledge map of TSLC pathways.

6. Conclusions

6.1. Main Results

We conducted a bibliometric analysis of 746 TSLC (transportation sector low-carbon) research articles from the WoS (Web of Science) Core Collection published since the PA came into effect. First, a visualization analysis of the basic information from these publications reveals that research output in this field has steadily grown, with significant increases in two periods: 2016–2020 and 2021–2024. China, the United States, and the United Kingdom lead in research production, with Tsinghua University being the most prolific institution. The journals *Sustainability*, the *Journal of Cleaner Production*, and *Transportation Research Part D-Transport and Environment* publish the highest volume of TSLC articles, while *Energy Policy*, *Applied Energy*, and the *Journal of Cleaner Production* are the most cited journals in the field. D'amore F. is the most active researcher. Next, we conducted an in-depth literature analysis using CiteSpace, categorizing significant studies into three modules—low-carbon policies and targets, emission reduction technologies and methods, and sustainable energy and transport—resulting in 13 clusters. The most frequently appearing keywords are CO_2 emissions, emissions, and energy. Research topics are grouped into ten clusters, with the largest clusters focusing on passenger transportation, adaptive traffic light, and emission reduction, representing key research directions in the field.

This study offers a detailed overview of the development, research hotspots, and future trends in TSLC studies, mapping the trajectory of low-carbon research in the transportation sector since the PA and filling a gap in bibliometric analysis in this area. Through a systematic review, this study identifies three critical research developments: renewable energy and technology applications, the evolution of intelligent transport systems (ITS), and policy support and public participation. It also provides an in-depth analysis of the potential impacts of low-carbon policies on transportation development, emphasizing the need for future progress in integrating renewable energy, further enhancing EV infrastructure, and optimizing ITSs. Future research should focus on the ongoing development of sustainable transportation technologies, the impact of carbon pricing policies, and the role of public participation in achieving large-scale low-carbon transitions. These efforts are essential for ensuring that the transportation sector can effectively contribute to global climate targets.

6.2. Recommendations on Future TSLC Policies

Undoubtedly, TSLC policies have been and will continue to play a key role in addressing climate issues. Based on the comprehensive review above, we offer the following recommendations for future TSLC policies. First, future TSLC policies should continue to strongly support the deep integration of electrification and renewable energy sources. This means that future policies should not only focus on advancing EV charging infrastructure, technological innovations in fuel cells, and the integration of renewable energy but also ensure the low-carbon transformation of traditional high-energy-consuming transportation industries. Future policies need to lead TSLC technological innovation while ensuring the smooth resolution of related socio-economic issues. Second, future TSLC policies should place greater emphasis on the development of low-carbon incentives and the low-carbon market in transportation. Building on research on carbon pricing, emission trading, tax incentives, and subsidy policies, future policies should target the individual level of green travel consumers, leveraging policy incentives to effectively reduce transportation-related carbon emissions. Finally, future policies may need to consider guiding and encouraging the process of transportation industry cooperation and international collaboration. In light of increasingly severe climate change, isolated policies will struggle to address extreme events. Promoting the deep integration of the TSLC industry chain and uniting global

efforts for transportation emission reduction is the only viable path for the development of TSLC systems.

6.3. Limitations and Future Research

Despite the comprehensive analysis of TSLC research trends and hotspots, there are some limitations. First, the data source is limited to the WoS Core Collection, which may exclude relevant studies from other databases or non-English publications. Second, the bibliometric analysis focuses mainly on quantitative metrics, such as publication volume and citation counts, which may not fully capture the qualitative impact of individual studies. Third, the temporal scope of the analysis is limited to the decade following the PA, which may overlook other policies beyond the PA.

Future research should address these limitations by expanding data sources to include multidisciplinary databases and non-English research. In addition, qualitative methods, such as expert interviews or case studies, could complement the bibliometric analysis to provide deeper insights into the impact of key studies. There is also a need to further explore regional disparities in TSLC research and implementation, particularly in developing countries. Finally, future studies should examine the long-term effects of carbon pricing policies, the integration of renewable energy in transport, and the role of public behavior in achieving large-scale low-carbon transitions. These efforts will contribute to a more holistic understanding of TSLC development and its alignment with global climate goals.

Author Contributions: X.Z.: conceptualization, resources, methodology, data analysis, writing, reviewing, and editing. J.H.: conceptualization, resources, methodology, data analysis, writing, original draft preparation, and reviewing. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Social Science Foundation of Liaoning Province (No. L23CGL008).

Acknowledgments: The authors thank the Social Science Foundation of Liaoning Province for the financial support which allowed them to fully focus on this research.

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

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