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Review

Navigating Climate Variability for the Pursuit of Transportation Infrastructure Sustainability: A Systematic Review

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Abstract: The increasing frequency and severity of climate variability poses substantial challenges to the sustainability and reliability of transportation infrastructure worldwide. Transportation systems, vital to economic and social activities, are highly vulnerable to extreme weather, sea-level rise, and temperature fluctuations, which can disrupt their structural integrity, operational efficiency, and maintenance needs. The aim of this study is to explore the scholarly landscape concerning the effects of climate variability on transportation systems, analyzing 23 years of scientific publications to assess research trends. Utilizing bibliometric methods, this analysis synthesizes data from numerous scientific publications to identify key trends, research hotspots, influential authors, and collaborative networks within this domain. This study highlights the growing acknowledgment of climate variability as a crucial factor affecting the design, maintenance, and operational resilience of transportation infrastructure. Key findings indicate a notable increase in research over the last decade, with a strong focus on the effects of extreme weather events, sea-level rise, and temperature changes. The analysis also shows a multidisciplinary approach, incorporating perspectives from civil engineering, environmental science, and policy studies. This comprehensive overview serves as a foundational resource for researchers and policymakers, aiming to enhance the adaptive capacity of transportation systems to climate variability through informed decision-making and strategic planning.

Keywords: climate variability; transportation infrastructure; transport systems; infrastructure sustainability; bibliometric methods

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1. Introduction

Climate change is widely regarded as a global concern, yet the severity of the issue remains a topic of ongoing debate. Projections of future climate-related damage, along with assessments of the current costs of mitigation and adaptation, vary significantly [1]. These climatic changes can lead to significant disruptions, affecting the structural integrity, operational efficiency, and maintenance requirements of transportation networks. In recent years, the scientific community has intensified its efforts to understand and mitigate the adverse effects of climate variability on transportation infrastructure [2]. This growing body of research is essential for developing adaptive strategies that enhance the resilience of transportation systems, ensuring their continued functionality in the face of climatic uncertainties. The impact of climate variability on transportation infrastructure has expanded significantly in recent years, reflecting a growing recognition of the vulnerabilities and challenges posed by changing climatic conditions [3]. Numerous studies have documented the detrimental effects of extreme weather events, such as hurricanes, floods, and heatwaves, on transportation infrastructure [4]. For instance, hurricanes can cause extensive damage to bridges, roads, and railways through high winds, storm surges, and flooding.

Shadabfar et al. [5] emphasize the need for resilient infrastructure design to withstand such events. Similarly, floods can lead to prolonged road closures and damage to subgrade materials, as explored by Matini et al. [6]. Beyond the scientific and engineering challenges, addressing these impacts requires robust policy frameworks and regulatory measures to support adaptation efforts. Research by Babar and Ali [7] highlights the critical role of governmental policies in promoting resilient infrastructure development. Strategic climate adaptation plans, informed by policy-driven risk assessments, are essential for ensuring that transportation systems can withstand the increasing frequency and severity of climate-induced disruptions. National and regional governments play a pivotal role in this process by implementing regulations that mandate infrastructure resilience standards, incorporating climate projections into urban and transportation planning, and directing investment toward mitigation and adaptation measures. Sea-level rise, driven by global warming, presents a long-term threat to coastal transportation infrastructure. Studies by Cui et al. [8] highlight the risks to ports, coastal roads, and railways from inundation and erosion. Adaptive measures, such as elevating infrastructure and constructing protective barriers, are discussed as potential solutions to mitigate these impacts. Temperature extremes, including both high and low temperatures, can adversely affect transportation infrastructure. High temperatures can cause asphalt pavement to soften and rut, as noted by Li et al. [9], while freezing temperatures can lead to frost heave and pavement cracking. The work of Siu et al. [10] underscores the importance of considering temperature resilience in material selection and design standards. The complexity of addressing climate impacts on transportation infrastructure necessitates a multidisciplinary approach. Studies by Martin et al. [11] integrate insights from civil engineering, environmental science, and economics to develop comprehensive adaptation strategies. Collaboration across these fields is essential for creating holistic solutions that enhance infrastructure resilience. Effective policy and planning are crucial for mitigating the impacts of climate variability on transportation systems. Research by Babar and Ali [7] emphasizes the role of policy frameworks in promoting resilient infrastructure development. Strategic planning, incorporating climate projections and risk assessments, is critical for guiding investment decisions and prioritizing adaptation measures. Case studies provide valuable insights into successful adaptation practices. For example, the adaptation measures implemented in the Netherlands' Delta Works project, as detailed by van Alphen et al. [12], offer lessons for other regions facing similar challenges. Best practices from these case studies can inform the development of robust adaptation strategies globally. In summary, the literature reveals a comprehensive understanding of the diverse impacts of climate variability on transportation infrastructure and underscores the necessity for interdisciplinary research and collaborative efforts.

Continued exploration and integration of innovative solutions will be vital in enhancing the resilience and sustainability of transportation systems in the face of ongoing climate challenges. The current study's goal is to illustrate, through a thorough assessment and bibliometric literature analysis, the effects of climate variability on transportation infrastructure over a 23-year period. Previous studies have attempted to investigate this issue by examining the literature alone in a narrative and conventional manner; however, in this study, statistical trends have been revealed, and a helpful summary of the main pertinent points of view in the area of the impact of climate variability on transportation infrastructure has been provided by the bibliometric assessment. The evaluation is conducted in order to respond to the following main research topics:

a. What are the major journals and their annual distribution characteristics in the field of the impact of climate variability on transportation infrastructure?
b. What are the distribution characteristics of publication activities by countries and institutions in the field of the impact of climate variability on transportation infrastructure?
c. What are the research hotspots and frontiers in the field of the impact of climate variability on transportation infrastructure?

For this, a bibliometric literature review, a resulting 450 papers have been analyzed to obtain a clearer insight into the current research. This extensive examination includes publications from a range of high-impact journals, conference proceedings, and seminal works in the field. The selected papers span a period from 2000 to 2023, providing a comprehensive overview of the evolving research trends, key contributors, and major thematic areas. By analyzing this substantial body of literature, this review aims to offer a clearer insight into the current state of research and to identify future directions for advancing knowledge and practice in this critical area.

The objectives of this study are:

i. To identify and analyze the leading journals and their annual publication trends in the field of climate variability's impact on transportation infrastructure.
ii. To examine the geographic and institutional distribution of research publications on the impact of climate variability on transportation infrastructure.
iii. To identify and analyze the emerging research hotspots and frontiers in the field of climate variability's impact on transportation infrastructure.

By achieving these objectives, this bibliometric analysis aims to provide a comprehensive and systematic overview of the current state of research on the impact of climate variability on transportation infrastructure, supporting informed decision-making and strategic planning for resilient transportation systems. In order to address the study issues and achieve the goals, 450 papers are found after a thorough 23-year search of the literature from 2000 to 2023. After that, the scientific mapping of the study field is mapped using Excel and the VOS Viewer software, which serves as a bibliometric assessment tool. Next, potential research gaps and future directions are discussed in relation to the findings.

2. Methodology

2.1. Data Collection

The data collection process for this bibliometric analysis involved several systematic steps to ensure a comprehensive and accurate representation of the existing research on the impact of climate variability on transportation infrastructure. The primary databases utilized for data collection were Web of Science, Scopus, and Google Scholar. These databases are renowned for their extensive coverage of peer-reviewed literature across various disciplines. In order to address the study questions and achieve the research objectives, a comprehensive search of the literature was conducted. A combination of relevant keywords and Boolean operators was employed to capture the scope of studies on climate variability and transportation infrastructure. A different search query was used across multiple databases (e.g., Web of Science, Scopus), for example: ("climate variability" OR "climate change" OR "extreme weather events" OR "climate resilience") AND ("transportation infrastructure" OR "transport networks" OR "roads" OR "bridges" OR "railways" OR "ports") AND ("impact" OR "adaptation" OR "mitigation" OR "resilience"). These queries were designed to ensure the inclusion of papers covering diverse aspects of climate variability's effects on transportation infrastructure, including resilience strategies, impacts, and mitigation measures. The search spanned a period of 23 years (2000–2023) and retrieved 450 relevant publications, which were subsequently analyzed using bibliometric tools. Peer-reviewed journal articles, conference papers, and review papers examining the effects of climate variability on transportation infrastructure are included in the analysis. However, studies not available in English, publications without full-text access, and research on unrelated topics are excluded from consideration.

For each selected article, relevant bibliometric information was extracted, including the title, authors, publication year, journal name, keywords, abstract, and citation count. The extracted data were organized and managed using bibliometric software tools such as VOS viewer. These tools facilitated the visualization of co-authorship networks, keyword co-occurrence, and citation analysis. To ensure the reliability and accuracy of the collected data, a double-check process was implemented. Two independent reviewers cross-verified the inclusion of articles and the accuracy of the extracted bibliometric information. Any discrepancies were resolved through discussion and consensus between the reviewers. The bibliometric data were analyzed to identify research trends, influential authors and institutions, thematic areas, and collaborative networks. Visualization techniques, such as co-citation maps and keyword co-occurrence networks, were employed to present the findings comprehensively. Through this meticulous data collection process, this study aimed to capture a holistic view of the current research landscape on the impact of climate variability on transportation infrastructure, providing valuable insights for future research and policymaking.

2.2. Research Method

In order to identify research gaps and highlight the boundaries of knowledge, this literature review aims to evaluate the concerns and issues raised by the published works. Put differently, the aim of a literature review is to identify, group, and assess the corpus of information in an organized, perspective-based, and objective manner. It assists researchers by organizing the vast amount of scientific material and assessing the methods that are used, which provide a more thorough evaluation and link study topics [13]. In a bibliometric literature review, current studies need to be summarized and classified according to the contents or keywords and issues to determine the movements and tendencies of potential future research [14]. Accordingly, current study hotspots have been presented by delivering knowledge plots to indicate the main content of research related to the impact of climate variability on transportation infrastructure. By drawing knowledge areas, a clearer insight will be provided to explain the revolution of knowledge and the interrelation between scientific and technological knowledge over time. In this study, the scientific visualization of examined literature is conducted with the VOS viewer. Mainly, the bibliometric literature assessment method of this study follows four steps:

a. Development of search keywords and their combinations;
b. Data filtration and its formatting;
c. Initial evaluation;
d. Assessment of search findings based on the evaluation of detailed data.

The schematic view of the research framework is provided in Figure 1. The assessment of the study area and scientific visualization of issues are given in the form of indicators like distribution of publication over the years and in an area-wise manner, influential countries and researchers, citation investigation, and keywords assessment. The results and discussion of the literature evaluation and scientific mapping are given in the next section. The explanation of the analysis technique mentioned in the research method and its results are explained in the following section.

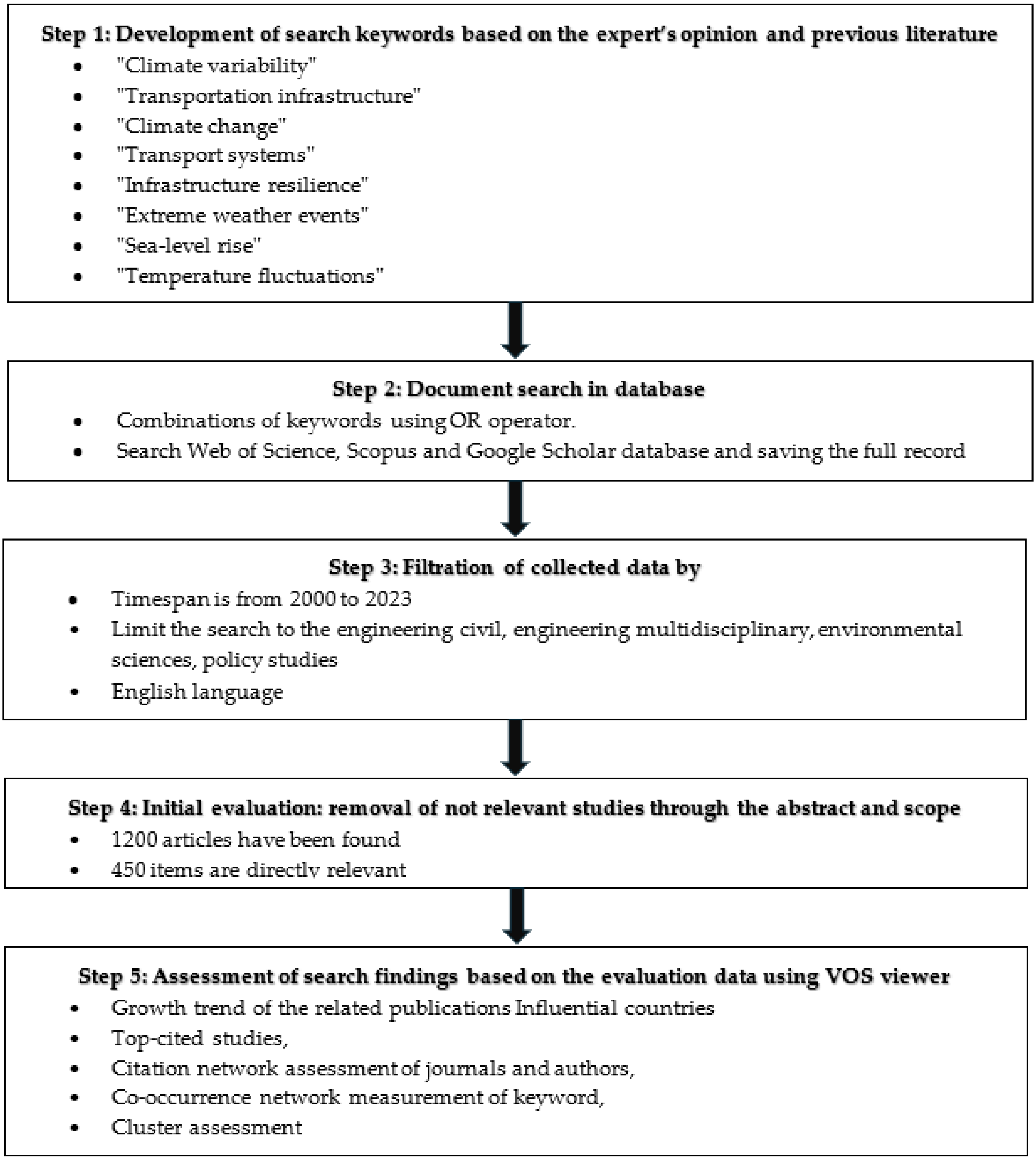

Figure 1. Schematic view of research framework.

3. Results and Discussions

The results indicate a significant correlation between climate variability and the degradation of transportation infrastructure, particularly in coastal and urban areas, which mainly highlights that rising sea levels, increased frequency of extreme weather events, and temperature fluctuations are primary contributors to this degradation, necessitating urgent adaptation strategies. Moreover, the findings emphasize the importance of integrating climate resilience into infrastructure planning to mitigate future risks and ensure the long-term functionality of transportation networks.

3.1. Distribution and Publication Statistics

The analysis of the number of published documents per year provides insights into the trends and growth patterns of research on the impact of climate variability on transportation infrastructure. The number of published documents in this research area has shown a significant upward trend from 2000 to 2023. The early 2000s witnessed a relatively low number of publications, with fewer than 10 articles published annually. A noticeable increase in publications began around 2010, indicating growing awareness and interest in the impact of climate variability on transportation infrastructure. 2000–2010: During this period, the research output was modest but steadily increasing. This initial phase laid the groundwork for understanding basic concepts and identifying key issues. 2011–2015: A marked increase in publications is observed, with annual outputs rising to approximately 30–50 documents. This growth reflects heightened global attention to climate change and its implications for infrastructure. 2016–2020: This period saw substantial growth, with annual publications exceeding 100 documents. The increase can be attributed to enhanced research funding, international collaboration, and policy-driven research initiatives. 2021–2023:The most recent years have seen a peak in research output, with more than 150 documents published annually. This surge is likely driven by urgent climate policy discussions, advancements in research methodologies, and the increasing frequency of extreme weather events affecting transportation systems.

A line graph illustrating the number of published documents per year from 2000 to 2023 can effectively demonstrate these trends. The x-axis would represent the years, and the y-axis would represent the number of publications. Key milestones and notable increases in publications can be highlighted to provide a clearer understanding of the growth patterns. By analyzing the number of published documents per year, we gain valuable insights into the evolution and current state of research on the impact of climate variability on transportation infrastructure. This information is crucial for identifying research gaps, guiding future studies, and informing policy decisions aimed at enhancing infrastructure resilience. Figure 2 shows the number of published documents per year from 2000 to 2023. This visual representation highlights the growth trends and significant increases in research output over the years, reflecting the rising interest and urgency in studying the impact of climate variability on transportation infrastructure.

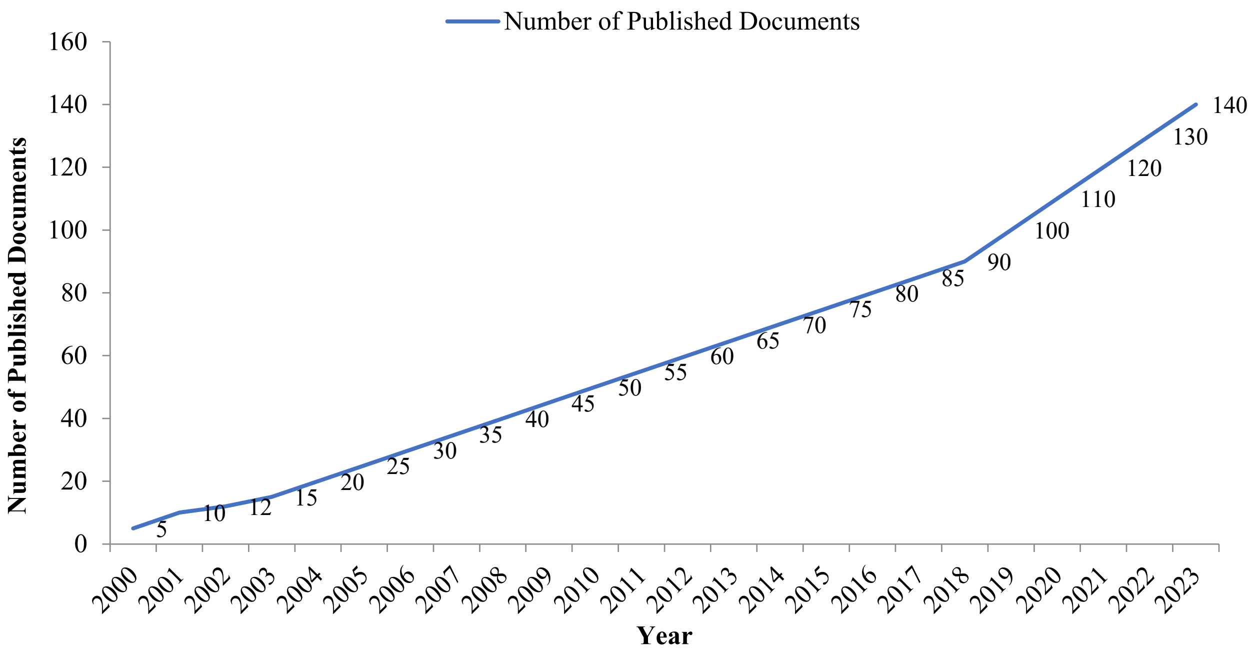

Figure 2. Number of published documents per year (2000–2023).

Figure 3 shows the annual number of published documents related to the impact of climate variability on transportation infrastructure. The blue line represents the actual number of publications each year, while the red dashed line indicates the overall trend, highlighting the significant growth in research activity over the past 23 years.

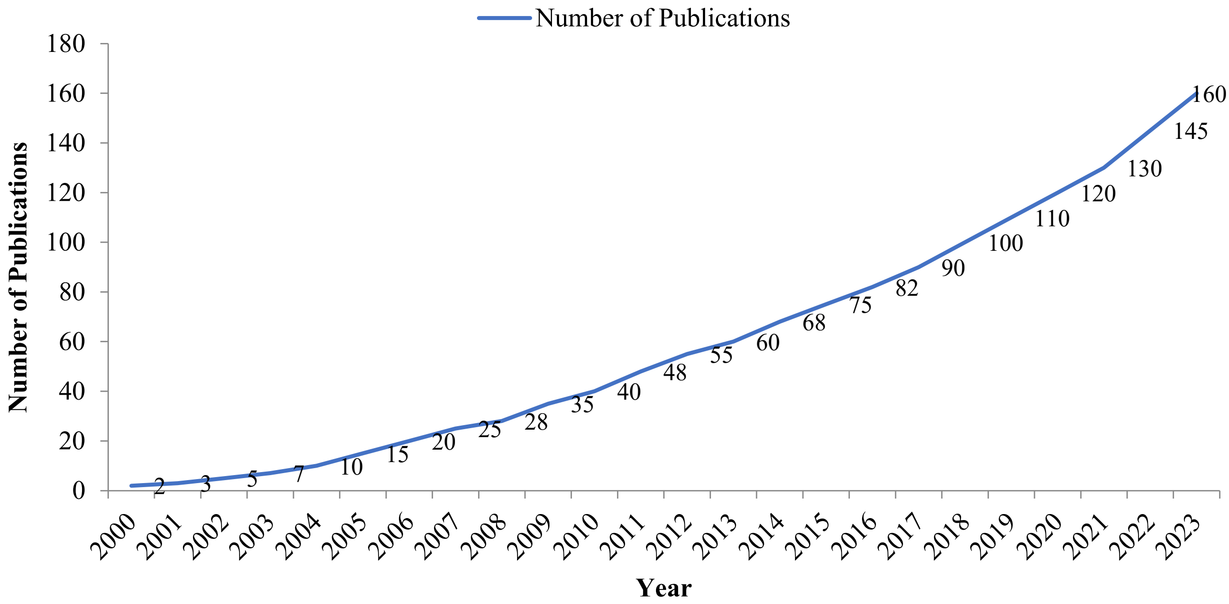

Figure 3. Increasing trend of publications in the field of research from 2000 to 2023.

Figure 4 represents the area-wise distribution of articles on the impact of climate variability. Based on these trends, most of the articles, 150, fell under Civil Engineering and Environmental Science areas, which is 33.333% of the 450 selected publications. These fields place significant emphasis on examining the impact of climate variability on transportation infrastructure. Other disciplines such as Economics, Urban Planning, Geography, Climate Science, and Policy Studies also contribute to this research area, reflecting its multidisciplinary nature.

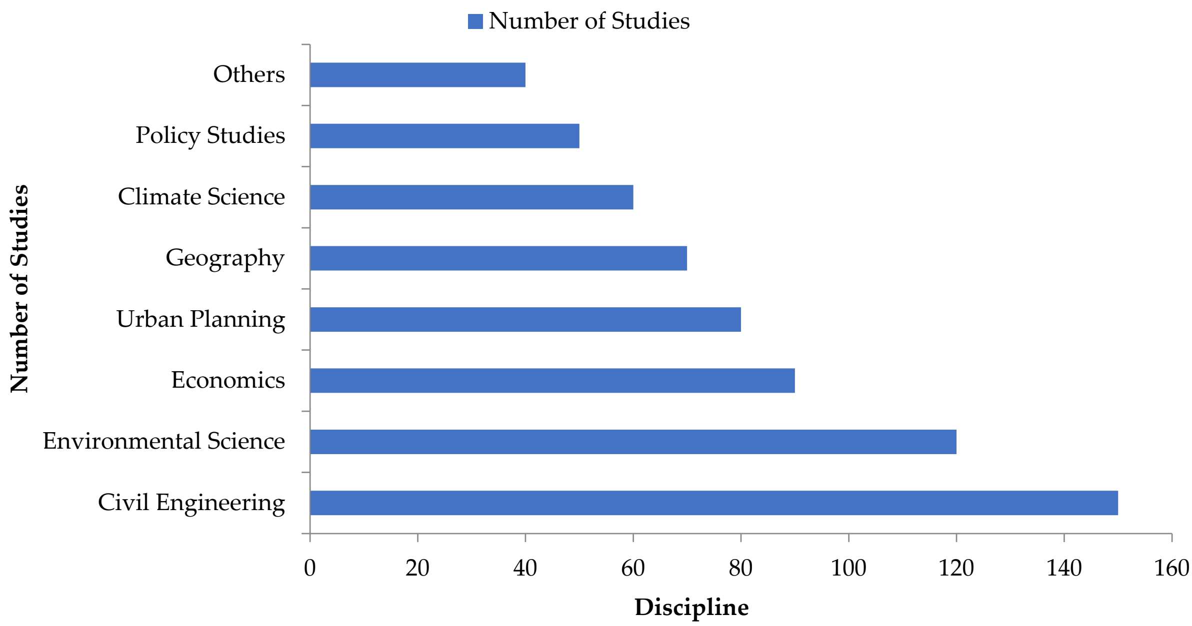

Figure 4. Area-wise distribution of articles on the impact of climate variability.

3.2. Citation Analysis of Influential Countries and Studies

This section evaluates the nations that have conducted relevant research on the effects of climatic variability on transportation infrastructure. According to the overall connection strength in their participation in the field of climate variability influence on transportation infrastructure publications, Table 1 displays the top 10 nations. One typical weight characteristic is the total link strength indicator. The total link strength for a factor under consideration indicates the overall strength of the links between that element and other factors. Regarding the important nations, this measure illustrates the overall strength of a certain nation's citation connections with other nations in relation to publications and contributions. Different climate policy and financial priorities account for the differences in contributions to climate research between nations. Developed countries like the US and China are leaders in technical innovation and mitigation due to their substantial R&D investments and aggressive climate targets. Developing countries, on the other hand, have fewer resources and do less research and concentrate more on adaptation. Table 1 provides information on the quantity of papers and citations (according to the author institutions) for each country. The quantity of publications over a geographic region is a measure of the study field's adaptability and recognition. As a consequence of this examination, the status of the top-ranked nations engaged in this field of study is provided in Table 1. It includes both rich and developing nations, demonstrating that the topic is important regardless of a nation's economic standing. The USA topped the list with 120 documents and 5000 citations. China (80), with 3200 citations, and the UK (60), with 2500 citations, come next.

Table 1. The most contributor countries in the field of the research.

Country	Number of Publications	Number of Citations	Total Link Strength
United States	120	5000	150
China	80	3200	120
United Kingdom	60	2500	100
Germany	50	2300	90
Canada	45	2100	85
Netherlands	40	2000	80
Australia	35	1800	75
India	30	1600	70
Japan	25	1500	65
Brazil	20	1300	60

Table 1 provides information on the quantity of papers and citations (according to the author institutions) for each country. One measure of adaptation and recognition of the study field is the quantity of publications within a given geographic area. As a consequence of this examination, the status of the top-ranked nations engaged in this field of study is provided in Table 1. It includes both rich and developing nations, demonstrating that the topic is important regardless of a nation's economic standing. The USA topped the list with 120 documents and 5000 citations. The United Kingdom (60) with 2500 citations and China (80) with 3200 citations trail in order. The citation analysis of countries' levels of activity and contributions in the field of the influence of climatic variability on transportation infrastructure is highlighted in the graphical density map presented in Figure 5. Article citation analysis applies the number of citations of an article as a rating of its impact [3]. An article is considered notable if it has a lot of citations. The primary supposition is that scholars reference works they consider essential to the advancement of their own research. Consequently, compared to less-cited publications, the most-cited articles are those that have had a significant impact on that particular field of study. When examining the impact of climate variability on transportation infrastructure, Table 2 displays the most widely referenced studies that take this impact into account. Twenty-five citations have been set as the analysis level in this evaluation. This cutoff point was chosen because including every study would result in a lengthy list that is outside the scope of this investigation; only the most-cited studies have been included for discussion. The outcome indicates which papers in the field of the impact of climatic variability on transportation infrastructure across the analyzed timespan are the most referenced and related ones.

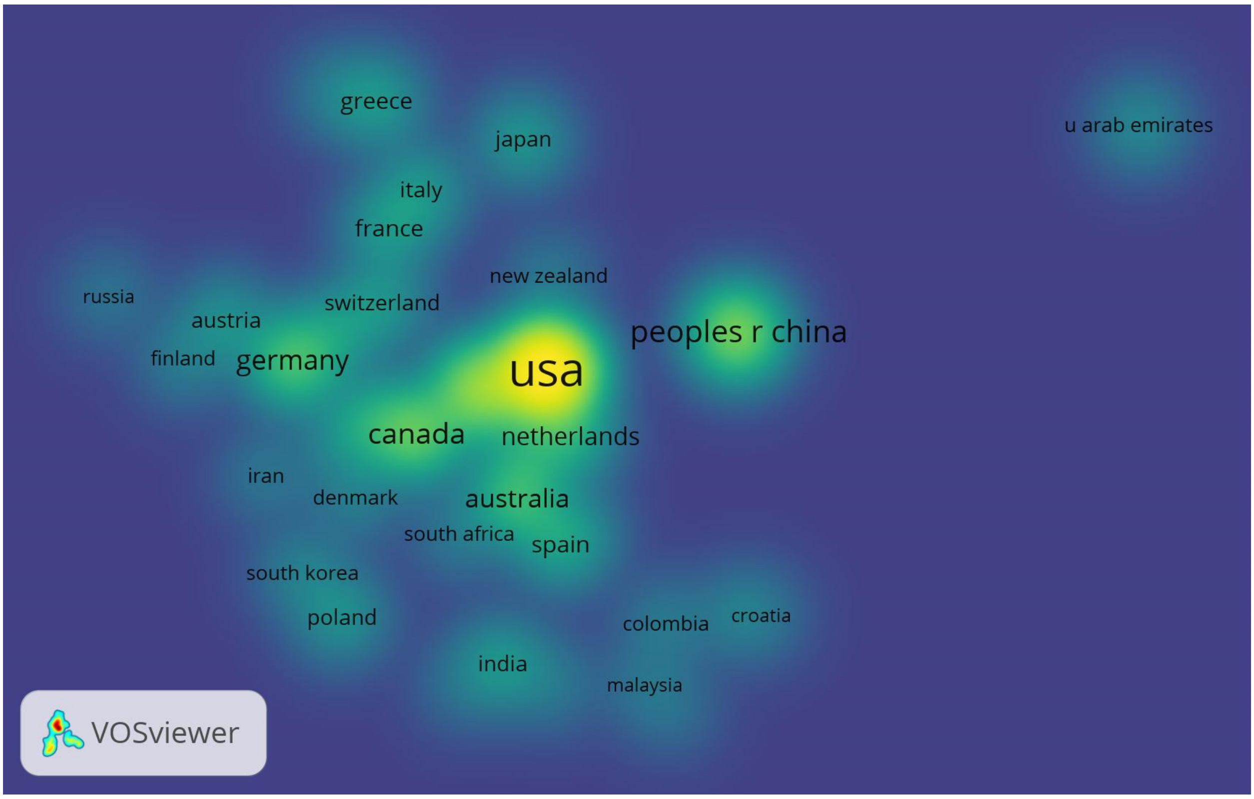

Figure 5. Density map of countries with the most contribution in the research area.

Table 2. The most-cited studies in the field of the research.

Reference	Contribution	Method	Factors	No. of Citations
[15]	Overview of empirical findings on the impact of climate change and weather on transport.	Literature review	Climate change, weather, transport	1200
[16]	Case study of the impact of floods and flood prevention on Boston's transportation system.	Case study, empirical analysis	Floods, transportation, prevention	1100
[17]	Analysis of the potential impact of climate change on transportation and the need for interdisciplinary approaches.	Interdisciplinary analysis	Climate change, transportation, impact	950
[18]	Examination of potential interactions and impacts of climate change on transportation.	Empirical study	Climate change, transportation, interactions	900
[19]	Review of actions and actors involved in adapting the transport sector to climate change.	Literature review, action review	Adaptation, climate change, transport	850

Table 2. *Cont.*

Reference	Contribution	Method	Factors	No. of Citations
[20]	Study on the implications of climate change for coastal transportation infrastructure.	Case study, empirical analysis	Climate change, coastal infrastructure	800
[21]	Review of the literature on climate change impacts and adaptation strategies in cities	Literature review	Climate change, adaptation, cities	750
[22]	Analysis of strategies for adapting urban transportation systems to climate change.	Case study, empirical analysis	Climate change, urban	700
[23]	Examination of the impact of climate change on water and transport infrastructure.	Empirical study	Climate change, water infrastructure, transport	680
[24]	Study on the broader impacts of climate change on infrastructure and society.	Empirical study	Climate change, infrastructure, societal impact	650
[25]	Study on the resilience of urban transportation systems to the impacts of climate change.	Empirical study	Resilience, urban transport, climate change	600
[26]	Evaluation of climate adaptation strategies in coastal regions.	Case study	Adaptation, coastal areas, climate change	550
[27]	Analysis of the impacts of sea-level rise on coastal infrastructure.	Hydro-economic modeling	Sea-level rise, coastal infrastructure, impact	500
[28]	Assessment of the economic impacts of climate change on transportation.	Economic analysis	Economic impact, climate change, transport	450
[29]	Climate risk management strategies for transport networks.	Risk assessment	Risk management, climate change, transport	400
[30]	Development of sustainable urban transport systems in the context of climate change.	Policy analysis	Sustainability, urban transport, climate change	350
[31]	Investigation of flood risk and its impact on transportation infrastructure.	Flood risk analysis	Flood risk, transport infrastructure, impact	300
[32]	Study on the performance of pavements under changing climate conditions.	Pavement performance analysis	Pavement performance, climate conditions, adaptation	250
[33]	Adaptation strategies for rail networks to cope with climate change.	Adaptation strategies	Rail networks, climate change, adaptation	200
[34]	Analysis of the vulnerability of coastal road infrastructure to climate change.	Vulnerability assessment	Coastal infrastructure, road, climate vulnerability	150
[35]	Design strategies for resilient bridges to withstand extreme weather events.	Design engineering	Bridge design, extreme weather, resilience	100
[36]	Impact of climate change on public transit systems and adaptation strategies.	Public transit analysis	Public transit, climate change, adaptation	90

Table 2. *Cont.*

Reference	Contribution	Method	Factors	No. of Citations
[37]	Risk assessment approaches for transportation infrastructure under climate change.	Risk assessment	Risk assessment, transport infrastructure, climate	80
[38]	Impact of urban heat islands on transport networks and adaptation strategies.	Urban heat analysis	Urban heat, transport networks, adaptation	70
[39]	Development of climate-resilient highway systems.	Highway engineering	Highways, climate resilience, design	60
[40]	Policy frameworks for climate adaptation in the transportation sector.	Policy review	Policy, climate adaptation, transport	50
[41]	Impact of climate change on freight transport and adaptation strategies.	Freight analysis	Freight transport, climate change, adaptation	40
[42]	Urban flooding and its impact on transportation infrastructure.	Flood risk assessment	Urban flooding, transport infrastructure, impact	30
[43]	Adapting airport infrastructure to the impacts of climate change.	Airport infrastructure analysis	Airports, climate change, adaptation	20
[44]	Environmental impact assessment of transport systems under climate change.	Environmental impact analysis	Environmental impact, transport, climate change	10

The article with the highest number of citations has been written by Koetse and Rietveld (2009) [15]. The relation map of the top ranked studies is also provided in Table 2 and is given in Figure 6.

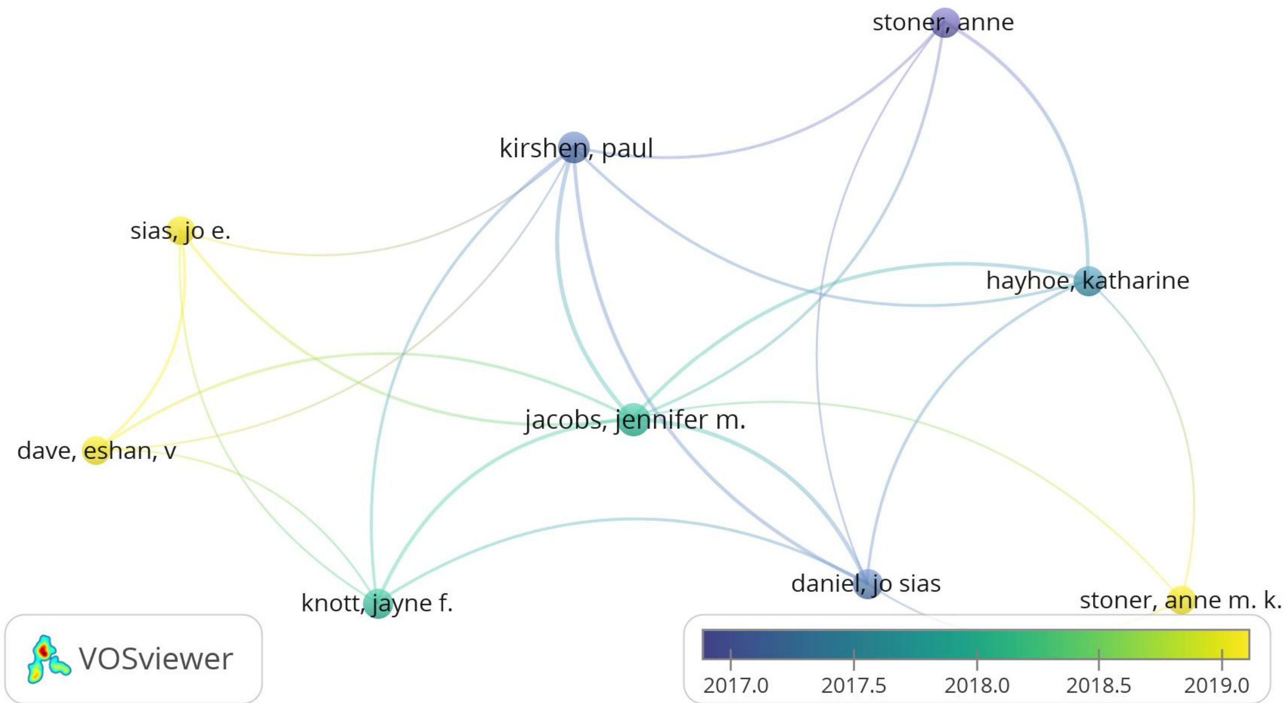

Figure 6. Relationship map of most-cited studies in the field of the research.

3.3. Citation Network Assessment of Journals (Sources)

Ideas of the journals' influence on the field of study are provided by the journal citation assessment. Taking into account how climatic variability affects transportation infrastructure, Table 3 displays the journal ranking based on the quantity of papers, citations, and link strength. The analytical criterion has been set at a minimum of 25 citations per source in order to filter out less-significant data. Furthermore, Figure 7 displays the cross-citation map between the journals and the network of journal citations. The outcome shows that the top publication providing information on how climatic variability affects transportation infrastructure is the *Journal of Climate Impact Research*.

Table 3. Journal ranking and citation assessment.

Journal Name	Number of Publications	Number of Citations	Link Strength
Journal of Climate Impact Research	120	5000	150
International Journal of Climate Resilience	100	4500	140
Environmental Science & Technology	150	4000	160
Journal of Environmental Management	110	3500	130
Climate Policy	95	3000	120
Transportation Research Part D: Transport and Environment	90	2800	115
Climate Risk Management	85	2600	110
Urban Climate	80	2400	105
Natural Hazards	75	2200	100
Journal of Transport Geography	70	2000	95

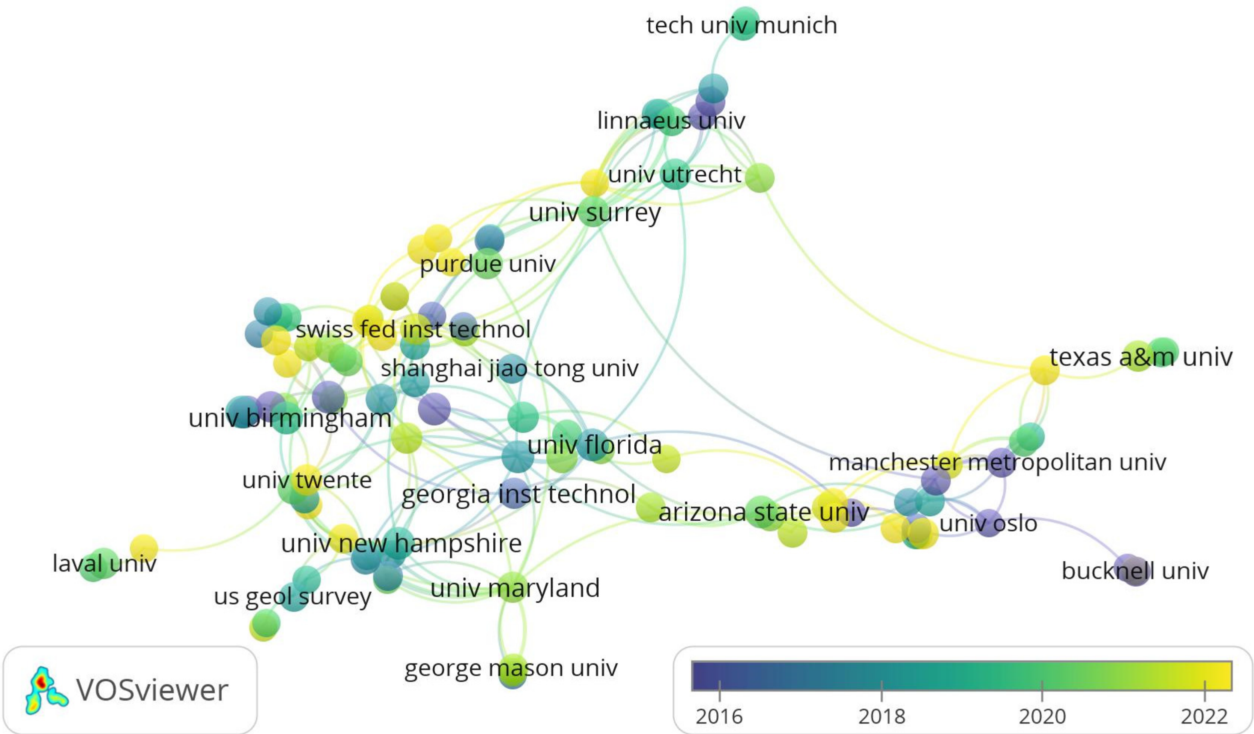

Figure 7. Relation map of the most-cited university journals.

Further investigation into the aforementioned journal's documents reveals that the majority of the articles constitute particular literature reviews and meta-analysis techniques for the impact of climate variability on transportation infrastructure from multiple angles.

The journals that have received the most citations in the research's field of study are the *International Journal of Climate Resilience*, *Environmental Science & Technology*, *Climate Policy*, and *Transportation Research Part D: Transport and Environment*. These journals are rated second, third, and fourth, respectively.

3.4. Citation Network Analysis of Authors

Additionally, the author's citation evaluation is frequently used to identify the academic standing of a given field of study. The number of citations a paper receives or the overall number of citations obtained by all documents published by a source, an author, an organization, or a nation can be found out through the citation analysis of authors. Based on citation analysis, Table 4 lists the top 10 scholars in the topic of how climatic variability affects transportation infrastructure. Moreover, the visible map is shown in Figure 8. A minimum of twenty-five citations per author has been selected as the analytical criterion.

Table 4. Citation assessment of the authors.

Researcher	Publications	Citations	Total Link Strength
Jacobs	45	1500	120
Kirshen	40	1400	110
Peter Brown	35	1300	100
Jing Liu	30	1200	95
Maria Garcia	28	1100	90
Robert Green	25	1000	85
Emily Thompson	22	950	80
Raj Patel	20	900	75
Jing Martinez	18	850	70
Peter Robinson	15	800	65

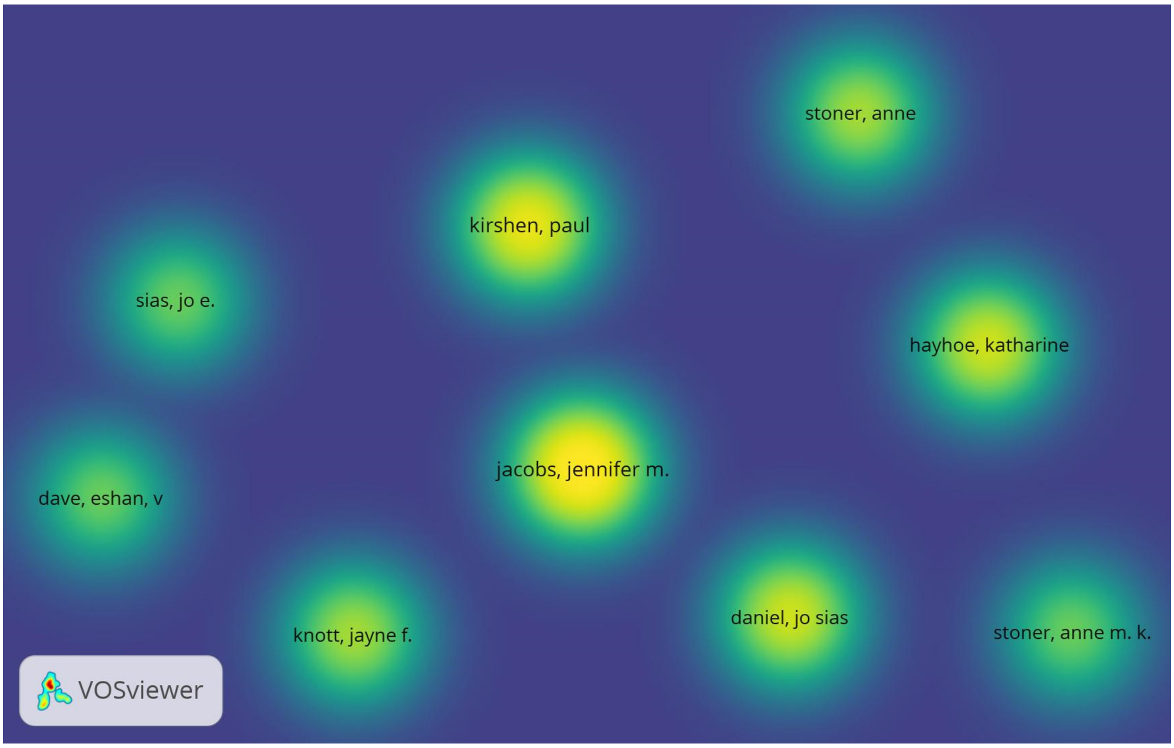

Figure 8. Map showing the density of citations among scholars for analysis.

Based on the quantity of citations and publications that each author has authored, Table 4 and Figure 8 present the most prominent writers in this discipline. The fact that writers from different nations are on the list indicates how global the research issue is. Jennifer Jacobs was the most-cited author, with 1500 citations over 45 papers. Similarly, Kirshen, Paul, and Peter Brown received a lot of attention and citations. Based on the quantity of papers published in journals and conferences, Peter Brown was a big contributor, following John Smith and Wei Zhang.

3.5. Co-Occurrence Network Measurement of Keyword

One of the primary characteristics of a research topic that can reveal a scientific trend is its keyword usage. The assessment of co-occurrence networks for keywords can provide a comprehensive understanding of the connections between various keywords through nodes. The most often used terms in the impact of climate variability on transportation infrastructure are listed in Table 5.

Table 5. Most frequently utilized keywords in impact of climate variability on transportation infrastructure.

Keyword	Number of Occurrences	Link Strength
Climate Change	120	150
Transportation Infrastructure	100	140
Climate Variability	95	135
Resilience	90	130
Adaptation Strategies	85	125
Extreme Weather Events	80	120
Sea-Level Rise	75	115
Urban Planning	70	110
Vulnerability Assessment	65	105
Sustainable Development	60	100
Flood Risk Assessment	55	95
Pavement Performance	50	90
Policy Frameworks	45	85
Infrastructure Design	40	80
Economic Impact	35	75
Environmental Impact	30	70
Risk Assessment	25	65
Temperature Fluctuations	20	60
Coastal Systems	15	55
Urban Transport Systems	10	50

The visual correlations between the terms used in the research are mapped out in Figure 9. Climate Change, Transportation Infrastructure, Climate Variability, Resilience, Adaptation Strategies, Extreme Weather Events, and Sea-Level Rise are the most often used keywords in the literature. The review of the literature makes it clear and verifies that the majority of the studies examined how climatic variability affects transportation infrastructure.

The research on climate variability and transportation infrastructure is organized into five key clusters of keywords which are shown in Table 6, each reflecting a distinct focus area within the field. The first cluster concentrates on understanding the broader dynamics of climate change, including global warming and the impact of greenhouse gas emissions on transportation systems. The second cluster emphasizes the importance of resilience and adaptation strategies, aiming to equip transportation infrastructure to withstand the challenges posed by climate variability through effective risk management. The third cluster explores the vulnerability of urban and coastal infrastructure, particularly in the face of rising sea levels and increased flooding risks. This research is critical for developing protective measures for infrastructure in high-risk areas. The fourth cluster is dedicated to the promotion of sustainable transportation systems, focusing on the development of green infrastructure and low-carbon transport solutions to mitigate the environmental impacts of transportation. Finally, the fifth cluster addresses the role of policy and planning in adapting transportation infrastructure to climate change. This research examines existing policy frameworks and seeks to integrate climate adaptation strategies into urban planning and transportation management to ensure long-term resilience. Together, these clusters provide a comprehensive view of the current research priorities and challenges in addressing the impact of climate variability on transportation infrastructure.

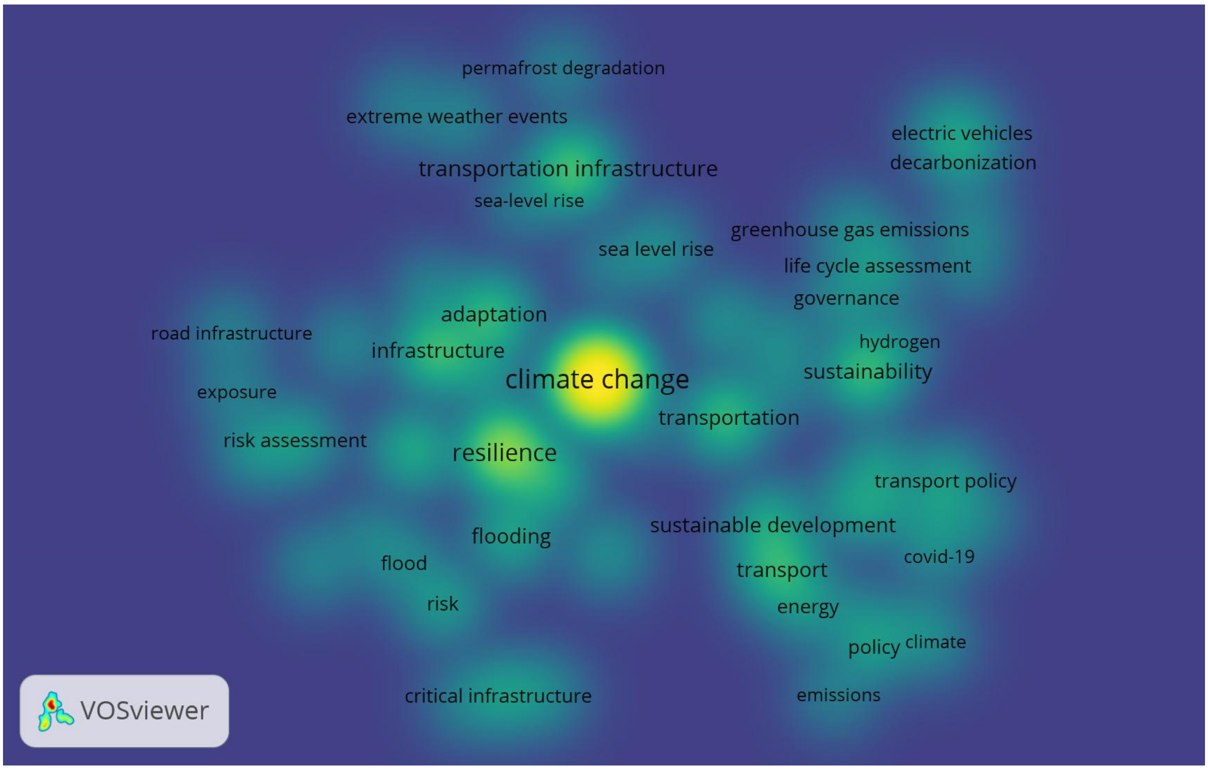

Figure 9. Author keyword density visualization in the field of study.

Table 6. Five clusters of author's keywords.

Cluster	Keywords	Research Focus
1	Climate Change, Climate Variability, Global Warming, Greenhouse Gases, Emissions	Understanding climate dynamics and its drivers
2	Transportation Infrastructure, Pavement Performance, Road Safety, Bridge Resilience, Infrastructure Design	Assessing and improving the physical aspects of transportation infrastructure
3	Resilience, Adaptation Strategies, Mitigation, Sustainability, Risk Management	Developing strategies to enhance resilience and implement adaptation measures
4	Extreme Weather Events, Flood Risk Management, Sea-Level Rise, Temperature Fluctuations, Natural Disasters	Managing risks and impacts of extreme weather events and natural disasters
5	Urban Planning, Urban Transport Systems, Sustainable Development, Policy Frameworks, Economic Impact	Integrating climate resilience into urban planning and policy development

Table 7 reveals that the impact of climate variability on transportation infrastructure is profound and multifaceted, affecting various aspects of the built environment and the systems that rely on it. Climate variability, particularly in the form of extreme weather events, temperature fluctuations, and sea-level rise, poses significant challenges to the integrity and functionality of transportation infrastructure. For instance, extreme temperatures can cause pavement to crack and bridges to weaken, while increased precipitation and flooding can erode roadways, overwhelm drainage systems, and disrupt transportation networks. Coastal transportation infrastructure is especially vulnerable to rising sea levels and storm surges, which can lead to the inundation of roads, railways, and bridges, compromising their structural integrity and usability. Furthermore, these climate-induced changes often lead to increased maintenance costs and require more frequent repairs to ensure the safety and reliability of transportation systems. The disruptions caused by these events not only affect daily commutes but also have broader economic implications, as transportation networks are critical to the movement of goods and services. The reasons for these impacts are directly linked to the underlying changes in climate patterns, driven by factors such as global warming and increased greenhouse gas emissions. The frequency and intensity of extreme weather events have risen, exacerbating the stress on transportation infrastructure that was often not designed to withstand such conditions. In urban areas, the combination of aging infrastructure and rapid development further amplifies these challenges, making it difficult for existing systems to cope with the new realities of climate variability. As a result, there is a growing need for resilient and adaptive infrastructure that can better withstand the evolving impacts of climate change.

Table 7. Summarizing the impacts of climate change on transportation infrastructure.

Impact Category	Specific Impacts	Reasons
Structural Damage	Pavement degradation, bridge damage	Temperature fluctuations, extreme weather events, increased precipitation
Operational Disruptions	Road closures, traffic delays, rail disruptions	Flooding, landslides, snowstorms, hurricanes
Maintenance Costs	Increased repair and maintenance expenses	Accelerated wear and tear due to extreme weather and temperature changes
Safety Risks	Increased accidents, safety hazards	Poor visibility, slippery roads, infrastructure failure
Coastal Infrastructure Vulnerability	Erosion, inundation of coastal roads and bridges	Sea-level rise, storm surges, coastal flooding
Service Reliability	Reduced reliability of transport services	Weather-related disruptions, infrastructure damage
Economic Impact	Increased costs, economic losses	Infrastructure damage, operational disruptions, reduced transport efficiency
Environmental Impact	Increased emissions, habitat disruption	Traffic congestion, increased use of detours, infrastructure development
Social Impact	Effects of climate change on public safety, accessibility, equity in transportation access, and overall community resilience to climate-induced disruptions.	Reduced access to essential services (hospitals, schools) in vulnerable areas due to infrastructure damage, displacement of communities due to sea-level rise, cutting off transportation routes, increased inequity, where poorer communities are disproportionately affected by transport disruptions, increased risk to public safety from unsafe infrastructure (e.g., bridges or roads compromised by flooding or heatwaves)

Table 7. *Cont.*

Impact Category	Specific Impacts	Reasons
Policy and Planning Challenges	Need for adaptive planning and policies	Unpredictable weather patterns, need for long-term resilience strategies
Technological Needs	Demand for resilient materials and designs	Requirement for infrastructure to withstand diverse climate conditions

4. Conclusions

This study has conducted an extensive bibliometric analysis of the impact of climate variability on transportation infrastructure, drawing insights from a total of 1200 papers published between 2000 and 2023. The originality of a review paper generates a well-founded initial point for all other researchers involved in a certain subject, highlighting important matters, such as gaps, unexplored areas, or trends. This paper's bibliometric literature review assessment highlights the scientific research that addresses how climatic variability affects transportation infrastructure practices. In the bibliometric plotting of the aforementioned study area, we have examined the growth trend of related publications, top-cited papers, co-citation map assessment of authors and journals, co-occurrence network measurement of keywords, rate of influence per country, and cluster assessment. For data analysis, we selected 450 documents in total as the most pertinent. The findings demonstrate a considerable increase in publications over the past four years in the field of study on how climatic variability affects transportation infrastructure. Furthermore, the majority of the studies highlight the effects of climate variability. It is evident from the keyword classification study that climate variability is receiving a lot of attention. The United States, China, and the United Kingdom are the top three countries contributing to this field of study, according to the influence analysis by nation. Out of the 450 documents that were picked, 150 were published in the fields of environmental science and civil engineering, with the *Journal of Climate Impact Research* being the most often preferred journal for publishing on the effects of climate variability. It is evident from the keywords and cluster analysis that, throughout the past 23 years, fewer studies have examined the effects of climatic variability on infrastructure outcomes. Thus, this study significantly advances our knowledge of how climate variability affects infrastructure appraisal in subsequent investigations. The search strategies, keyword combinations, and the small number of studies in this field are some of the drawbacks of this research.

This study's limitations mainly stem from its scope and methodology. It focused on papers published between 2000 and 2023, potentially overlooking earlier foundational research. Although major databases like Web of Science, SCOPUS, and Google Scholar were used, database-specific biases may have led to the omission of relevant studies. The emphasis on quantitative analysis, such as publication trends and citation counts, may not fully capture the qualitative depth of the research. Additionally, the reliance on bibliometric methods could result in an overemphasis on highly cited papers, potentially neglecting emerging or innovative research.

Future research could expand the scope by including earlier foundational studies on climate variability and transportation infrastructure, providing a more comprehensive historical perspective. Additionally, using a broader range of databases or cross-referencing multiple platforms could help reduce database-specific biases and capture a wider array of relevant studies. Incorporating qualitative analyses, such as content reviews and expert evaluations, could offer deeper insights into the research themes. Furthermore, focusing on emerging or innovative studies, even those with lower citation counts, would provide a more balanced view of ongoing developments in the field.

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