Analysis of Emerging Trends in Sustainable Transportation: Designing a Framework for the Transformation of Urban Transportation Policy and Planning Models

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Abstract

Sustainable transportation, as one of the fundamental pillars of sustainable development, plays a significant role in reducing environmental impacts and improving quality of life. The present study was conducted with the aim of identifying scientific trends, detecting research gaps, and revealing emerging directions in sustainable transportation studies. This research adopts a bibliometric approach. The data were retrieved from the Scopus database through a systematic search covering the period from 2000 to 2024. In the initial stage, 1,522 records were identified. After removing 87 duplicate documents, 1,435 records remained for the preliminary screening stage. Subsequently, based on the review of titles and abstracts, 1,018 irrelevant documents were excluded. Following a full-text assessment of the remaining 418 records, a total of 269 articles were selected for the final analysis. The analyses included co-word, co-authorship, and co-citation analyses, and conceptual maps as well as scientific clusters were generated using VOSviewer and SciMAT software. The findings indicate that the literature on sustainable transportation is concentrated in several major conceptual clusters. The most prominent themes include sustainable urban transportation planning, reduction of transportation-related emissions, and the development of clean technologies, particularly electric vehicles. In terms of scientific output, the United States and China were identified as the leading contributors in this field. At the institutional level, Arizona State University, Colorado State University, and Sharif University of Technology emerged as the most prominent research institutions in sustainable transportation studies. The results also highlight the growing attention to emerging topics such as electric vehicles and shared mobility systems. However, areas such as rural transportation sustainability and social equity in transportation have received comparatively limited attention, indicating the presence of notable research gaps in this field.

Keywords: Climate Sustainability; Shared Mobility; Sustainable Development; Sustainable Transportation; VOS Viewer Visualization Tool; Zero-Carbon Infrastructure

1.Introduction

The unprecedented and rapid growth of cities worldwide has fundamentally transformed lifestyles, particularly in the domain of transportation. United Nations estimates indicate that the urbanization rate will increase from its current level of 56% to 65% by 2050 (Chen et al., 2025). This accelerated population growth places considerable pressure on transportation systems, leading to increased energy consumption, exacerbated traffic congestion, and heightened greenhouse gas emissions (Jiang et al., 2022; Sun et al., 2024). Since the early 2000s, scientific research on sustainable transportation has expanded dramatically. In the initial stages, the focus was primarily on reducing carbon footprints and developing advanced technologies (Erdem et al., 2024; Mihanović, 2024). In recent years, attention has shifted toward a more comprehensive approach encompassing "digital mobility solutions," "urban planning," and "behavioral changes" (Lai et al., 2023; Sohi et al., 2025).

Over the past five years, innovations such as "electric vehicles," "autonomous vehicles," and "Mobility as a Service (MaaS)" have significantly reshaped transportation systems and urban management. However, the effective implementation of these technologies depends on "coordinated policy-making," "adequate infrastructure," "behavioral adaptation," and "sustainable investment" (Zheng et al., 2013). Despite these advances, a comprehensive and integrated understanding of the sustainable transportation literature is still lacking. Existing reviews often focus on limited topics, short time frames, or specific regions, thus failing to provide a holistic picture (Araghi et al., 2023; Asha'ari et al., 2024).

The primary objective of this study is to analyze emerging trends in sustainable transportation and identify research gaps that have received less attention. The present study employs advanced scientometric visualization tools, including VOS viewer, to analyze the evolution of key concepts and emerging pathways in this field. Accordingly, this study seeks to answer the following questions: What emerging trends are identified in the field of sustainable transportation, and how have these trends influenced transportation policies and infrastructure? What gaps exist in the use of sustainability indicators (economic, social, and environmental) in sustainable transportation, and how can these gaps be addressed using new interdisciplinary frameworks? How can different dimensions of sustainable transportation (social, technological, and environmental) be analyzed using interdisciplinary approaches and emerging technologies, and how can such analyses help align research with policy objectives? What emerging developments are identified in new concepts, and how do these developments affect scientific collaboration structures and future research? Furthermore, this study aims to identify existing challenges and opportunities in sustainable transportation policies and infrastructure in order to provide a more accurate and comprehensive understanding of the current state and future research needs of this field.

Although sustainable transportation has become a central focus of research and policy-making over the past two decades, significant gaps remain in the literature. One such gap is the inconsistency and dispersion in the use of economic, social, and environmental sustainability indicators. Moreover, there is a clear need for integrative and diverse frameworks to measure and validly compare results. Additionally, the lack of interdisciplinary research that simultaneously analyzes different dimensions of sustainable transportation and integrates novel technologies with social considerations constitutes another challenge in this field. The present study attempts to address these gaps and, through a multidimensional approach, draw a comprehensive picture of the future pathways of this field.

The main innovation of this research lies in its use of scientometric and visualization tools to analyze scientific trends in sustainable transportation. In particular, this study focuses on designing an analytical framework based on "social sustainability," "urban governance and planning," and "clean technologies," which can reduce existing theoretical-practical gaps. Another innovation of this research is the identification of emerging developments in areas such as "shared mobility," "smart cities," and "equity in accessibility," which can help policymakers align sustainable mobility objectives with research.

2.Theoretical Foundations

2.1.Sustainable Transportation

The concept of sustainable transportation gradually entered the planning literature in the late twentieth century and has since undergone significant evolution. It was first introduced by the European Commission in 1992 in its Green Paper on the environmental impacts of transport. In subsequent decades, transportation sustainability gained a prominent place in global agendas, for instance being included in Sustainable Development Goal 11 (Sustainable Cities and Communities), which emphasizes the role of transport in promoting public health, social justice, and urban-rural linkages. From the early 2000s, research focused primarily on technological and environmental solutions, such as improving fuel efficiency, developing alternative fuels and clean vehicles, or implementing intelligent transport systems (Chen et al., 2025). With population growth and economic development, the transport sector has expanded, but its negative consequences including increased greenhouse gas emissions, air pollution, high energy consumption, traffic congestion, and road accidents – have raised broad concerns. Consequently, aligned with global sustainable development goals, the concept of "sustainable transportation" has emerged, emphasizing a balance between society's transport needs and limiting environmental, social, and economic harms (Heidari et al., 2023).

These early approaches mainly stressed technical and environmental aspects and brought significant achievements in reducing pollutants and improving system efficiency. However, it soon became apparent that transport sustainability is not merely a technical issue but also involves human and equity dimensions. From the mid-2010s onward, a new paradigm in urban transport planning took shape that, in addition to clean technology, emphasizes social equity and quality of life. According to some experts, the transition from mere urban growth to the stage of sustainable mobility crisis requires a fundamental rethinking of urban planning approaches, which has led to the emergence of the "sustainable mobility" paradigm. This new paradigm seeks to replace car-centricity and simple response to growing travel demand with demand management, high-quality public transport development, compact city design, and prioritization of pedestrians and cyclists (Griffiths et al., 2021). In recent years, the smart city concept has also emerged, employing digital technologies to optimize transport systems and enhance citizen participation. Thus, the evolution of the transport sustainability concept between 2000 and 2024 can be seen as a shift from a pure focus on clean technologies and the environment toward a more comprehensive approach that includes social justice and the smart city.

2.2.Transport Sustainability: Balancing Economic, Social, and Environmental Dimensions

The concept of sustainability classically emphasizes three main pillars: environmental protection, economic development, and social justice. In the transport sector, sustainability is achieved when a balance among these three pillars is established. From an environmental perspective, a sustainable transport system must minimize air pollution and greenhouse gas emissions, reduce the consumption of non-renewable energy resources, and play a lesser role in ecosystem degradation. From an economic viewpoint, sustainable transport requires cost efficiency and effectiveness, so that transport networks can provide adequate accessibility and support economic growth using reasonable financial resources. On the social dimension, transport sustainability means equitable access for all people to safe and affordable mobility services. Achieving transport justice implies that no group or region is systematically deprived of adequate transport services, and the benefits and costs of the system are fairly distributed among people (Amorim et al., 2025).

In analyzing the evolution of transport systems, socio-technical transition theories have been used to examine how these systems gradually change under the influence of innovations, policies, and social behavior. In planning, the concept of the "sustainable mobility paradigm," introduced in the 2000s, serves as a conceptual framework challenging traditional car-centric principles and moving towards flexibility and multimodality in planning. Furthermore, life cycle assessment models have been used to evaluate the environmental impacts of transport options, and travel demand models have been employed to predict the effects of policies on passenger behavior. Overall, recent studies indicate that one must go beyond merely technical solutions and incorporate social and strategic considerations into transport decisions. For example, some researchers believe that many past transport interventions (such as promoting electric vehicles or developing pedestrian paths) were implemented without analyzing the values and underlying motivations of stakeholders, which has led to limited results. In recent years, two interdisciplinary analytical approaches have received more attention: spatial justice in transport and multi-level governance (Burger, 2025).

The theoretical frameworks reviewed in this section including the evolutionary concept of sustainable transportation, the three dimensions of sustainability, the sustainable mobility paradigm, and equity-oriented approaches form the basis for the bibliometric analysis of this article in three ways:

1. **Determining search keywords** (e.g., sustainable mobility, social equity in transport, smart city);
2. **Categorizing thematic clusters** of the extracted articles based on their emphasis on technical, economic, or social dimensions;
3. **Interpreting temporal trends** of research from 2000 to 2024 to identify existing gaps (e.g., the lack of balanced integrative studies across the three sustainability pillars).

Thus, the theoretical foundations serve not as a separate review but as a roadmap for the bibliometric analysis.

3.Literature Review

A systematic review of previous research in the field of sustainable smart transportation can be categorized into four streams: (1) macro-level scientometric reviews focusing on gaps in integrating the three sustainability pillars; (2) reviews centered on the social dimension; (3)

reviews of green logistics and infrastructure; and (4) regional reviews emphasizing underrepresented contexts.

The first indication of this situation can be seen in the scientometric review by Tetteh et al., who systematically analyzed 39 studies from 2005 to 2023 and showed that the three pillars of sustainability (economic, social, environmental) have been used in a fragmented and inconsistent manner, making it urgent to develop integrative frameworks and diversify methods for valid measurement and comparison of results. In addition to identifying influential authors and sources, they proposed a "triple-bottom-line" framework to guide future research (Tetteh et al., 2024). Subsequently, Szpilko et al., using data from Scopus and Web of Science, documented the rapid growth of the "sustainability-smartness" literature between 2010 and 2022. The United States, Italy, and China lead in knowledge production, and thematic clusters such as "pollution," "health," "infrastructure," "technology," "Internet of Things," "urban logistics," "urban solutions," and "energy" shape the field. However, they emphasize a persistent theoretical-practical gap: the genuine integration of renewable energy sources into urban systems and the linking of technological interventions with governance and planning requirements have not yet reached operational maturity (Szpilko et al., 2023).

On the other hand, the social dimension of transport sustainability has been analysed less than needed. A comprehensive review by Bao et al. of 2,703 documents (1993–2021) shows that despite a remarkable increase in publications from 50 in 1993–2000 to 1,877 in 2015–2021, a coherent structural analysis of this dimension remains rare. Dominant themes such as "multi-objective optimization" and "social sustainability index" are well established, but emerging topics like "shared transportation," "smart cities," and "COVID-19 consequences" highlight new research questions and the need for more precise metrics (Bao et al., 2023). Simultaneously, in the domain of green/sustainable logistics, Ren et al., mapping 306 publications (1999–2019), organized five knowledge clusters (social-environmental-economic, planning and management, application, technology, and operations research) and 50 sub-domains. Nevertheless, this scientific categorization also reveals that knowledge transfer to practice faces policy and technological bottlenecks that cannot be resolved without real linkages among policy, technology, and implementation (Ren et al., 2020). A large-scale review by Roman of 1,238 records (2000–2022) presents a similar picture: five dominant axes – "urban mobility," "pollutants and fuels," "supply chain models," "performance metrics," and "policy" – are identified, but methodological limitations arising from reliance on a single database and search criteria indicate that even the existing body of literature requires reconfiguration and methodological enrichment to produce impactful, problem-oriented research (Roman, 2022).

At the infrastructure level, Badassa et al., through scientometric and visualization analysis of the 2000-2019 literature, clarified the evolution of themes and influential actors. However, while pointing to thematic improvements, they state that a clear roadmap for "the next step" both in defining priority areas and in implementation mechanisms – remains vague (Badassa et al., 2020). Extending the scope to under-researched contexts makes the gaps even more transparent. Agyei et al., in their study of Africa, using the PRISMA protocol and scientometric tools, identified five dominant themes and four knowledge gaps – from inattention to the "social dimension" and "community participation" to the lack of meaningful ICT integration in transport systems, the need to promote "non-motorized transport," especially "walking," and the examination of the relationship between transport and "disaster risk" – while also noting that the region suffers from a shortage of comprehensive reviews and requires a guided research agenda (Agyei et al., 2024).

In conclusion, it can be summarized that the "heterogeneity of metrics" and the lack of "valid integrative frameworks" for the three sustainability pillars limit measurability and comparability (Tetteh et al., 2024; Roman, 2022). At the intersection of "sustainability and smartness," the literature has grown, but actual implementation particularly in the "integration of clean energy" and "institutionalization of governance/planning components" has lagged (Szpilko et al., 2023). The social dimension, both theoretically and in under-represented geographical contexts, remains under-analyzed (Bao et al., 2023; Agyei et al., 2024). In "green transport" and "transport infrastructure," despite the mapping of knowledge structure, the transition from cognition to practice is hampered by policy/technological obstacles and ambiguity about future pathways (Badassa et al., 2020; Ren et al., 2020).

A critical review of previous studies reveals a common methodological shortcoming: most scientometric reviews have been content with identifying thematic clusters or keyword co-occurrences, neglecting the discovery of structural relationships among themes and the prioritization of indicators based on network linkage strength. In this regard, the "Thematic Network Analysis" method can fill this gap because, unlike purely descriptive or correlation-based methods, it can extract networks of basic, organizing, and global themes, reveal hierarchical relationships among indicators, and provide a systematic path for integrating social, technological, and governance dimensions into a single framework – something that previous reviews, due to their reliance on keyword co-occurrence or mere citation analysis, have been unable to achieve.

By employing "Thematic Network Analysis" as the primary integration method, the present study targets three key limitations of previous research: (1) it addresses the heterogeneity of metrics and the lack of an integrative framework (Tetteh et al., 2024; Roman, 2022) by providing a network of themes with weighted and prioritized relationships; (2) it fills the theoretical-practical gap in linking governance and technology (Szpilko et al., 2023) by identifying connecting nodes between "policy" and "technological infrastructure" themes; and (3) it remedies the neglect of the social dimension (Bao et al., 2023; Agyei et al., 2024) by incorporating themes related to community participation and transport justice into the network, rather than marginalizing them.

Accordingly, the present study targets the following central gap: "designing and validating an integrative framework of indicators and themes" that simultaneously covers the "social dimension," "governance/planning mechanisms," and the "integration of clean energy and ICT," reduces the "theoretical-practical gap," and possesses cross-context implement ability, especially in emerging economies – a framework grounded in "up-to-date scientometric evidence," "thematic network analysis," and "empirical studies," clarifying the path toward "operationalization" (definition of indicators, data, and actionable policy tools). In this way, the framework solidifies the research orientation and specifies the course of action.

In the literature review, the absence of an integrated framework for combining social, governance, and clean technology dimensions in sustainable transportation is clearly evident. Furthermore, despite the rapid growth of research in smart mobility and sustainability, significant gaps remain in the practical implementation of these concepts. By identifying these gaps and designing a framework based on scientometric evidence, the present study endeavors to provide an operational path for aligning research and policy-making in this field. The conceptual framework of the research is shown in Figure 1.

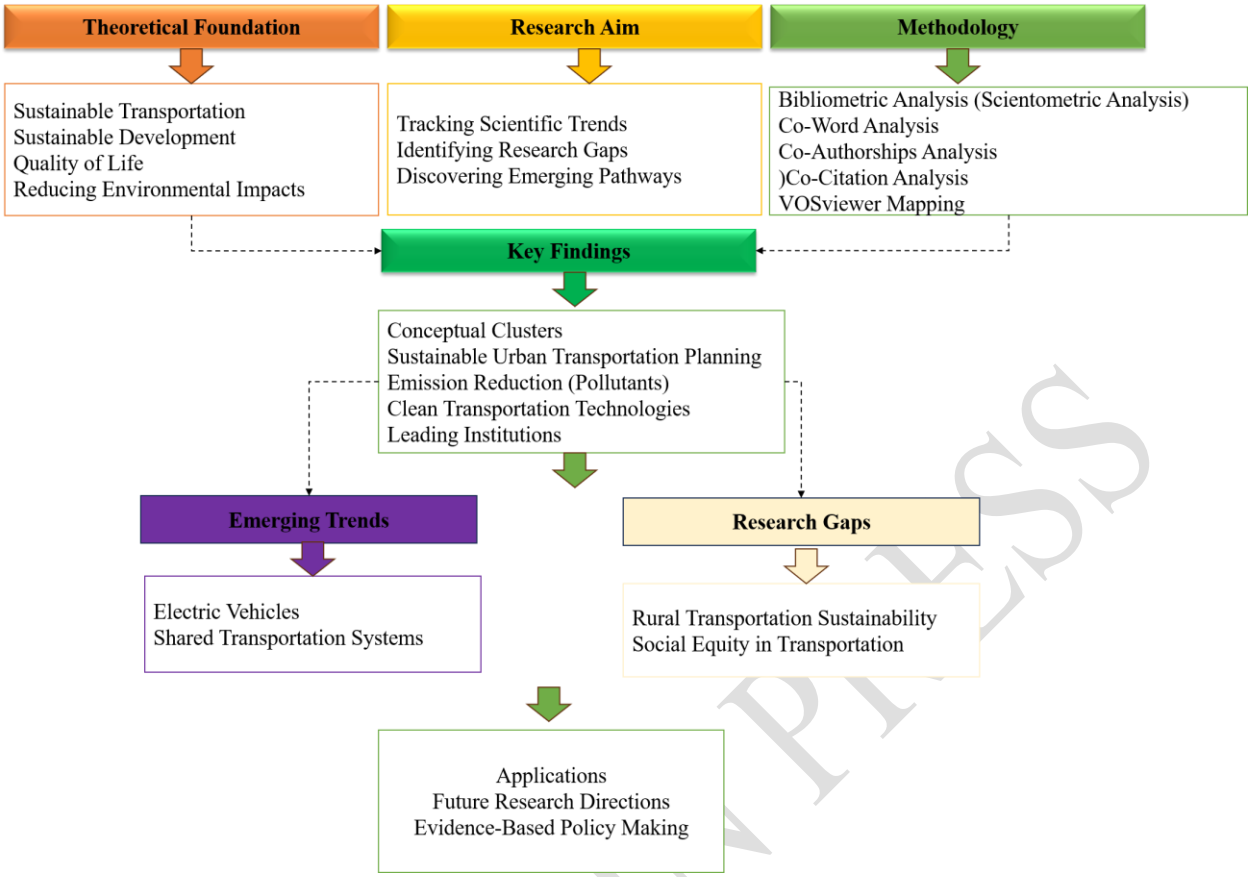

Figure 1: Trends and Framework of Scientometric Research in Sustainable Urban Transportation:

From Theoretical Foundations to Policy Applications

4.Materials and Methods

This study employs a scientometric approach to systematically analyze the intellectual structure, scientific collaboration patterns, and thematic evolution of research in the field of sustainable transportation. Scientometric analysis was selected due to its capacity to process large volumes of scientific publications and uncover hidden structural relationships in the production of scientific knowledge.

4.1.Data Source and Search Strategy

Bibliographic data for this study were exclusively extracted from the Scopus database. Scopus was chosen for its extensive interdisciplinary coverage, standardized bibliographic metadata structure, and compatibility with scientometric analysis tools. This database provides structured information including titles, abstracts, keywords, authors, institutional affiliations, countries, and citation references, all of which are essential for scientific network analyses.

The search was conducted in the TITLE-ABS-KEY field to ensure conceptual relevance of the documents to the research topic. The search strategy was defined as follows:

TITLE-ABS-KEY ("sustainable transportation" OR "transportation sustainability")

The time frame of the study covers the years 2000 to 2024. This period was selected because research related to sustainable transportation has received more structured attention in the scientific literature since the early 2000s, concurrent with the expansion of sustainable development discourse, climate change mitigation policies, and low-carbon transportation strategies. Restricting the study to this time frame allows for the examination of the formation and growth phases of this research field.

Only documents published in English and indexed in relevant subject areas such as Engineering, Environmental Sciences, Transportation, and Social Sciences were considered.

The document types included in the study were:

- Research articles
- Review articles
- Conference papers
- Book chapters

These document types were selected because they possess formal scientific structure, complete bibliographic metadata, and citable scientific content, making them suitable for network and citation analyses. In contrast, editorials, notes, short communications, and documents lacking sufficient bibliographic information were excluded to maintain the coherence and reliability of the analysis.

The execution of the search strategy initially retrieved 1,522 records.

4.2.Data Screening and Refinement Process

The identification, screening, and eligibility assessment of documents were conducted in accordance with the PRISMA 2020 framework to ensure methodological transparency and replicability of the research. The PRISMA flow diagram is presented in Figure 2.

In the first stage, duplicate records were identified and removed, resulting in the elimination of 87 documents, leaving 1,435 records for the screening stage.

In the second stage, the titles and abstracts of the documents were examined to assess their thematic relevance. Documents were excluded if they:

- Focused on sustainability without the transportation dimension;
- Addressed transportation technologies without a sustainability framework;
- Fell outside the conceptual scope of sustainable transportation.

In this stage, 1,018 records were removed.

In the third stage, the full text of the remaining 418 documents was reviewed (where accessible). Documents were excluded for the following reasons:

- Insufficient bibliographic metadata for network analyses;
- Non-conformity of document type with pre-established criteria;
- Weak conceptual alignment with the field of sustainable transportation.

After full-text assessment, an additional 148 documents were removed, and finally 269 papers were selected for the final scientometric analysis.

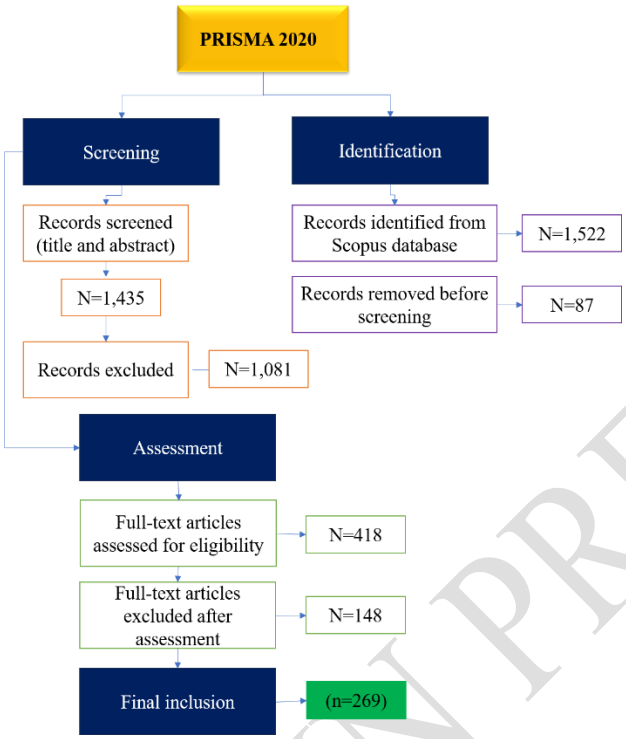

Figure 2: PRISMA 2020 flow diagram of the identification, screening, and selection process for documents in the scientometric study of sustainable transportation.

4.3.Data Extraction and Preparation

The extracted bibliographic information included:

- Article title
- Author names
- Year of publication
- Authors' institutional affiliations
- Country
- Author keywords and indexed keywords
- Citation references

Records were exported in formats compatible with scientometric analysis software. Prior to analysis, a data cleaning process was performed to enhance accuracy. This process included:

4.4.Removal of incomplete records

- Standardization of similar author and organization names in case of inconsistencies
- Development of a thesaurus file to merge synonymous terms or different spellings of keywords

This preprocessing step helped reduce dispersion in keyword co-occurrence networks and improved clustering validity.

4.5.Scientometric Analysis Techniques

Scientometric analysis was conducted using VOS viewer and SciMAT software to enable simultaneous examination of the conceptual and citation structures of the field.

4.6.Keyword Co-occurrence Analysis

To identify the main research topics and conceptual clusters, keyword co-occurrence analysis was performed using VOS viewer. A minimum keyword occurrence threshold of five was set to eliminate low-frequency terms and obtain a clearer conceptual structure. To assess the stability of the results, sensitivity analysis was also performed with thresholds of three and seven.

The overlay visualization feature was used to examine temporal trends. Keywords with a more recent average publication year were considered indicators of emerging topics.

4.7.Co-authorship Analysis

Co-authorship networks were analyzed at three levels:

- Authors
- Organizations
- Countries

For each level, a minimum threshold of three documents was applied to ensure that the resulting networks were analytically meaningful and visually interpretable. This analysis helped identify scientific collaboration patterns and influential actors in the field.

4.8.Co-citation and Bibliographic Coupling Analysis

To investigate the intellectual foundations and thematic relationships among documents, both co-citation and bibliographic coupling analyses were conducted.

- Co-citation analysis was used to identify foundational works and the intellectual structure of the field.
- Bibliographic coupling analysis was employed to examine thematic proximity among more recent research.

These network methods, due to their direct reliance on scientific citation relationships, are more suitable for analyzing knowledge structure than simple correlation-based methods.

4.9.Strategic Diagram and Thematic Evolution

To analyze the dynamics of research topics, SciMAT software was used to generate a strategic diagram. This diagram enables the classification of topics into four groups:

- Motor themes
- Basic themes
- Emerging or declining themes

- Peripheral themes

This analysis contributes to understanding the maturity and significance of each thematic cluster in the sustainable transportation literature.

To increase the validity of the results, cluster stability was examined by varying analysis parameters, and a sample of documents from each cluster was reviewed to assess thematic convergence.

Distribution of Document Types

The distribution of document types is shown in Figure 3. The results indicate that research articles constitute the majority of documents, reflecting the predominance of original knowledge production in this field. Furthermore, the presence of review articles, conference papers, and book chapters indicates the interdisciplinary and dynamic nature of research related to sustainable transportation.

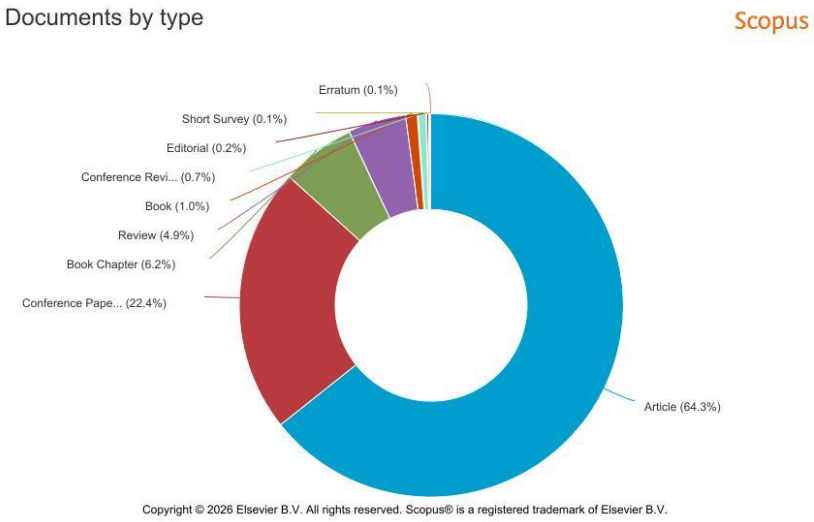

Figure 3: Distribution of document types in the sustainable transportation literature (2000–2024).

4.9.Methodological Limitations

This study relies solely on data extracted from the Scopus database. Although this database offers broad coverage and structured metadata, some scientific works indexed in other databases may not be included in this analysis. This limitation has been taken into consideration when interpreting the results of the study.

5.Findings

This section presents the research findings and the analysis of the research data. Initially, the research outputs generated by the software (VOS viewer) are examined, followed by a detailed analysis of each corresponding map. Subsequently, in order to interpret the findings and identify emerging thematic areas and research gaps, further analytical procedures are undertaken.

5.1.Analysis of the Historical Trend of Quantitative Growth in Scientific Publications

The line chart, directly extracted from the Scopus database, offers a clear illustration of the growth trajectory of scientific production in the field of sustainable transport from 2000 to 2024. This progression can be delineated into four distinct phases. From 2000 to 2014, scientific output remains sparse and fragmented – a pattern characteristic of the 'pre-paradigmatic stage' of nascent fields, wherein researchers explore foundational concepts independently, without a shared theoretical framework. A pivotal turning point occurs around 2015, coinciding with the adoption of the United Nations Sustainable Development Goals (SDGs) and the intensification of policy mandates for low-carbon transport. This simultaneity suggests that the evolution of the field is not endogenous but rather exogenous, representing a response to institutional and policy pressures. The surge in the number of articles from 20 documents in 2018 to over 40 documents in 2024 signifies the field's transition towards 'quantitative maturity'. However, the relative decline observed in 2024 (partly attributable to indexing delays) raises an evolutionary question: has the field reached a saturation plateau, or is it on the verge of a qualitative leap (e.g., towards mixed-method and interdisciplinary approaches)? Answering this question necessitates a qualitative analysis of the conceptual structure, not merely a trend enumeration. In summary, the pattern of increasing, albeit recently fluctuating, growth indicates that the sustainable transport field has moved from an 'idea generation' phase into a phase of 'paradigmatic reconfiguration'.

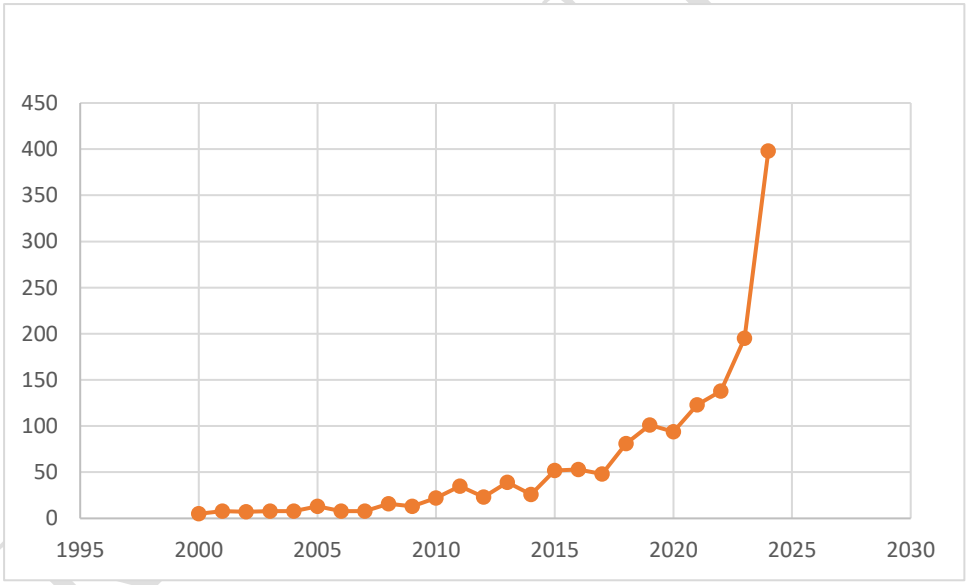

Figure 4. Number of articles indexed in Scopus on sustainable transport from 2000 to 2024, illustrating the historical evolution and the increasing scholarly interest in this domain.

5.2.Network of Leading Authors in Sustainable Transport Research (2000–2024)

At this stage, the co-authorship patterns among researchers in the field of sustainable transport from 2000 to 2024 were analysed. According to the network map illustrated in Figure 5, the author co-authorship network reveals that the research community is divided into two relatively separate clusters (red and green). This bicluster structure indicates a divergent evolution within the field: two independent intellectual currents have emerged with minimal overlap. From the perspective of scientific evolution, such divergence typically occurs during the intermediate stages of a field's maturation, when distinct methodological or problem-oriented approaches become established. The presence of only one bridging link (Zachary D. Asher) suggests that the field has not yet reached a stage of systemic integration, and that the cognitive and methodological costs of collaboration between these two currents remain high. For future evolution, research policies should purposefully create "more bridges" between these clusters, rather than merely increasing scientific output within each cluster. Otherwise, there exists a risk of falling into an echo chamber trap, accompanied by a decline in interdisciplinary innovation.

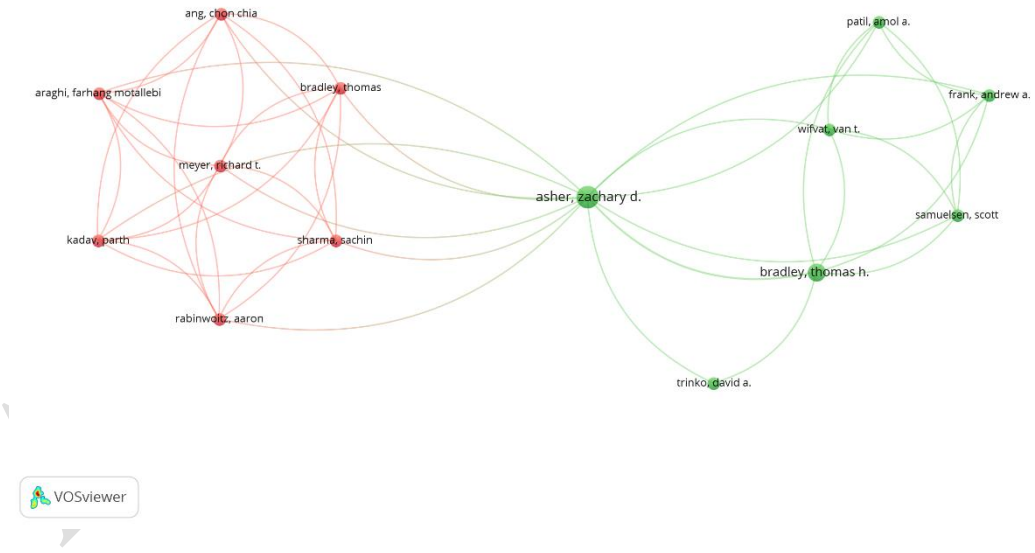

Figure 5. Co-authorship relationships among key researchers in the field of sustainable transport based on Scopus data (2000–2024). Clusters represent groups of authors with close collaborative ties.

5.3.Co-authorship Network in Sustainable Transport Research (2000–2024)

In this section, a network of collaborations among universities and research centres in the field of sustainable transport was analysed. For this purpose, articles published between 2000 and 2024 were utilized. What was observed in this network is that nearly all of these institutions are, in some manner, collaborating and interconnected with one another. The institutional co-authorship network, in contrast to the author network, exhibits an integrated and cohesive structure. This pattern suggests that, at the macro-organizational level, the field of sustainable transport has reached a stage of *institutional maturity*, wherein organizational boundaries no longer impede collaboration. The presence of institutions with diverse specializations (urban planning, economics, agriculture, tourism, remote sensing) within a unified network indicates that the evolution of the field is no longer proceeding based on a single parent discipline (e.g., civil engineering), but has rather transformed into an *established interdisciplinary configuration*. However, the concentration of collaborations within a few central nodes (e.g., urban planning departments) signifies a *core–periphery structure*; while this structure is initially efficient in the evolution of fields, in the long term it may lead to *path dependency* and a decline in innovative diversity. Therefore, the next stage of evolution necessitates strengthening the role of peripheral institutions and creating new nodes. Such collaborations can contribute to the development of comprehensive models and solutions for addressing the challenges of this field. Figure 6 illustrates the co-authorship network of academic institutions involved in sustainable transport research between 2000 and 2024, based on Scopus data and generated using VOS viewer. This visualization highlights the patterns and intensity of collaboration among institutions in this domain.

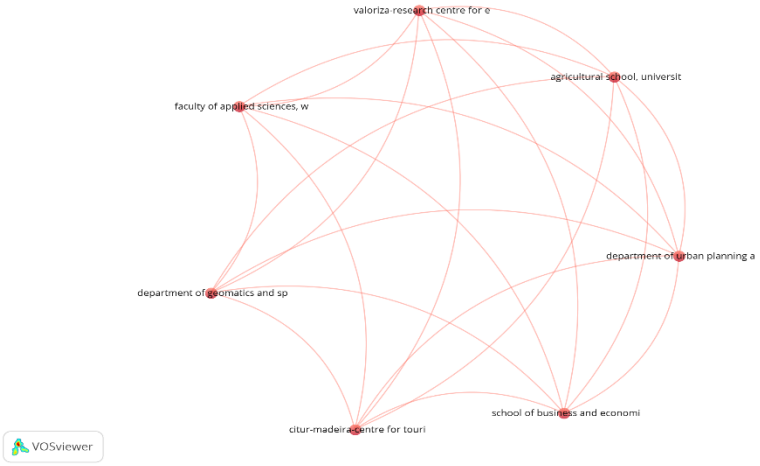

Figure 6. Co-authorship relationships among academic institutions active in sustainable transport research based on Scopus data (2000–2024): the network of inter-institutional collaborations and patterns of institutional interaction.

As illustrated in Figure 7, the institutional collaboration chart reveals the role that universities and research centres have played in the production of knowledge within the field of sustainable transport from 2000 to 2024. In this ranking, Arizona State University ranks first with seven publications. Colorado State University and Sharif University of Technology are tied for second place, each with six publications. The presence of Sharif University among the top institutions underscores the significant role those Iranian researchers have played in this domain. Furthermore, this analysis also identified other active institutions, including the Georgia Institute of Technology, the University of the Southeast, and Purdue University. Another noteworthy observation from this review is the contribution of non-academic institutions, such as the United States Environmental Protection Agency (US EPA). This serves as a reminder that collaboration between academic centres and policy-making bodies is of paramount importance. Overall, the data indicate that universities located in the United States have accounted for a large share of scientific activity in this field. However, alongside this concentration, a gradual expansion of international participation, particularly from Asian countries, is observable. This trend suggests that cross-border scientific collaborations and the establishment of inter-organizational networks are becoming increasingly significant in the field of sustainable transport.

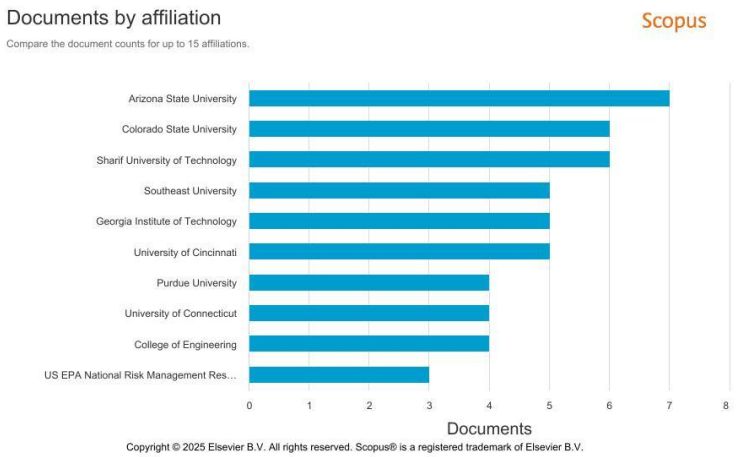

Figure 7. Number of Scopus-indexed articles on sustainable transport by organizational affiliation. Arizona State University ranks first, followed by Colorado State University and Sharif University of Technology. The chart illustrates the prominent role of U.S. institutions and the increasing international participation, particularly from Asia.

5.4.Institutional Co-authorship by Time Period (Overlay Visualization)

The diagram presented in Figure 8, generated using the overlay visualization technique, illustrates the temporal evolution of scientific collaborations among research institutions in the field of sustainable transport from 2000 to 2024. In this type of visualization, the colour of each circle (representing a scientific institution) indicates the average publication year of co-authored documents attributed to that institution. The temporal display of institutional co-authorship offers a depiction of the *temporal layers of evolution*: purple institutions (the initial core, approximately 2010–2015) are predominantly American and European research institutions; yellow institutions (recent entrants, 2019–2023) include institutions from Asia, Southern Europe, and more applied-oriented organizations. This colour shift from purple to yellow signifies a *gradual succession of actors in the field* and a *globalization of the geography of knowledge production* – a process that typically occurs during the maturation of established fields. Institutions that are both part of the older central core and exhibit a yellow colour (e.g., urban planning departments) exemplify persistent actors that have successfully adapted to evolving research questions; in contrast, institutions that appear only in purple have likely drifted away from the mainstream of research. From the perspective of field evolution, this

pattern indicates that sustainable transport research has moved from a stage of *leadership by a few pioneering institutions* to a stage of *broad-based competitiveness and multipolarity*. The policy implication is an opportunity for developing countries (including Iran) to enter the mainstream by collaborating with the new yellow-coloured institutions.

This pattern demonstrates that such institutions have played a more active role in recent research waves, and stronger inter-institutional collaborations have been formed during this period. A noteworthy point is that institutions such as the Department of Urban Planning and the School of Business and Economics, while maintaining their central position in the network, have also exhibited significant research activity in recent years. This suggests that these institutions have functioned as bridging links, connected smaller research groups and facilitated interdisciplinary collaboration. Furthermore, the uniform distribution of colours across the entire network indicates that the globalisation process of scientific collaboration has occurred gradually and pervasively, and has not been confined to a few specific institutions. The disciplinary diversity of participating institutions across fields such as applied sciences, geomatics, urban planning, agriculture, tourism, and economics further underscores that research in sustainable transport inherently necessitates interdisciplinary and integrated approaches. In summary, the findings indicate that, although the roots of institutional collaboration trace back to the mid-2010s, a notable increase in collaborative activities has been observed between 2019 and 2023. This trajectory provides a valuable opportunity for researchers and policymakers to identify emerging key actors and institutions, define novel collaborations, and design more targeted agendas for future multi-institutional partnerships.

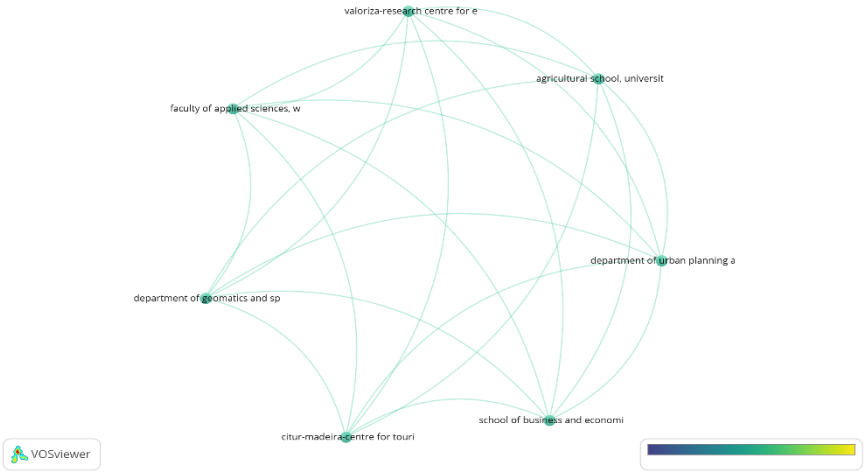

Figure 8. Temporal visualization of institutional co-authorship in sustainable transport research. Node colours indicate the average publication year per institution, ranging from purple (early contributors) to yellow (recent entrants), reflecting the evolving dynamics of inter-organizational collaborations.

5.5.International Co-authorship Network at the Country Level in Sustainable Transport Research (2000–2024)

Figure 9 illustrates the international scientific collaboration network among countries that have been active in sustainable transport research between 2000 and 2024. This diagram reflects a significant increase in scientific collaborations among universities, research institutions, and planning centres at the international level. The aforementioned network was constructed using the network visualization technique in VOS viewer software, based on co-authorship analysis at the country level. The overlay visualization of institutional co-authorship, derived from Scopus data, indicates that institutions such as the VALORIZA Research Centre, the Faculty of Applied Sciences, agricultural universities, the Department of Urban and Spatial Planning, the Madeira Tourism Research Centre (CITUR Madeira), and a range of business and economics schools have played a pivotal role in shaping the knowledge structure of this field.

Following this, an analytical overview of five seminal studies exemplifying extensive collaborations among these institutions is presented:

In a study by Castanho et al. (2020), the sustainability of the transport system in the Canary Islands was analysed. This research resulted from a multi-institutional collaboration involving WSB University of Applied Sciences in Poland, the University of the Azores, the VALORIZA Research Centre, and CITUR Madeira. The findings underscore the undeniable necessity of designing region-oriented sustainable transport models tailored to the geographical and structural characteristics of island territories.

Continuing this line of inquiry, Castanho et al. (2021) examined transport patterns in the Azores Archipelago. This article, developed through collaboration among VALORIZA, CITUR Madeira, WSB University, and researchers from Spain and Serbia, has garnered considerable attention in academic circles. In this study, the authors emphasise that the lack of institutional synergy in island transport systems constitutes a fundamental barrier to sustainable development.Another study by Vulevic et al. (2020) investigated accessibility dynamics and cross-border collaborations between Portugal and Spain. This research involved institutions such as the CIP Transport Institute of Serbia, the VALORIZA Research Centre, WSB University, and schools of agriculture and urban planning. This collaboration reflects a regional effort in Southern Europe to enhance infrastructural cohesion. The study's findings on spatial inequalities in transport accessibility have been widely received by the scientific community.

In a further study, Naranjo Gómez et al. (2022), published in the journal *European Planning Studies*, examined transport logistics and infrastructure sustainability in the Iberian Peninsula. This research resulted from interdisciplinary collaboration among researchers from the University of Extremadura, the VALORIZA Research Centre, and the CIP Institute. The findings underscore the importance of integrating engineering, urban planning, and regional policy in sustainable transport research.Finally, an article by Castanho et al. (2024) was also reviewed. This research, conducted in collaboration with researchers from universities including the University of the Azores and the University of Las Palmas de Gran Canaria (Spain), investigates the role of inter-island transport in improving spatial and territorial cohesion in the Azores Archipelago. The results of this article indicate that, despite supportive

policies, the lack of alignment between transport plans and the actual needs of residents represents a serious obstacle to the spatial integration of island regions.

Overall, this body of studies demonstrates that progress in the field of sustainable transport is highly dependent on robust scientific collaborations among universities, research centres, and policy-making institutions at both national and international levels. Furthermore, co-authorship in the production of scientific articles not only enhances the academic and citation impact of research outputs but also contributes significantly to the development of comprehensive, applied, and policy-oriented solutions for achieving sustainable transport in urban, border, and island regions.

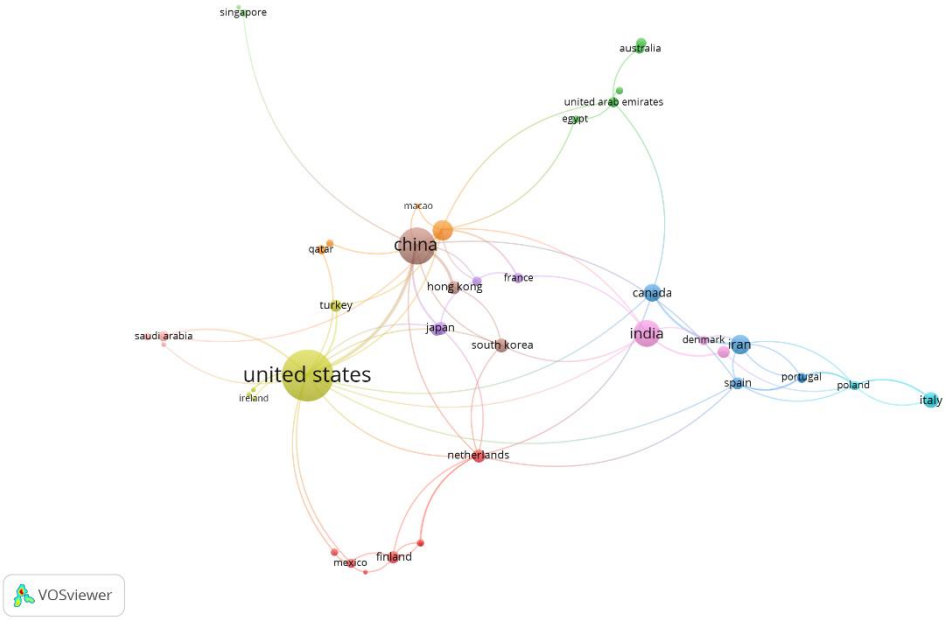

Figure 9. *International co-authorship network. Nodes represent countries, with node size proportional to scientific output and edge thickness indicating collaboration intensity. The United States and China serve as major hubs, while countries such as India, Iran, and Spain act as bridging links between regional clusters, reflecting research dynamics at both global and regional scales.*

Figure 10 presents the geographical distribution of scientific output in the field of sustainable transport, based on data extracted from the Scopus database. This chart, which compares the number of scientific publications at the country level, indicates a concentration of research

activities within several key regions of the world. According to Figure 10, the United States ranks first with approximately 90 published articles, underscoring its pivotal and pioneering role in advancing knowledge in this domain. This dominance can be attributed to the country's robust research infrastructure and substantial investment in sustainable transport. In second place, the People's Republic of China accounts for over 40 scientific publications, reflecting the remarkable growth of China's international scientific participation over the past two decades. This position highlights China's strategic focus on the development of smart transport technologies and carbon reduction policies. Following China, India ranks third, with a considerable number of publications and an increasing presence in recent years, indicating that the country has secured an important position within the scientific literature of this field. In the intermediate ranks, countries such as the United Kingdom, Iran, Canada, and Italy are observed. The presence of Iran, which even surpasses some developed nations, demonstrates the growing interest of Iranian researchers in topics such as sustainable urban development, transport-related pollution, and environmental policymaking. In subsequent tiers, several East Asian countries, including South Korea, Hong Kong, and Japan, appear. Although their current share of scientific output is relatively modest, global trends suggest a gradual increase in the scientific contribution of these countries in the future. Overall, the structure of this chart indicates that, while knowledge production in sustainable transport has become global in nature, a distinct geographical concentration persists. In other words, it can be concluded that countries with advanced research infrastructure and coherent policy frameworks continue to play a decisive role in shaping the scientific landscape of this field.

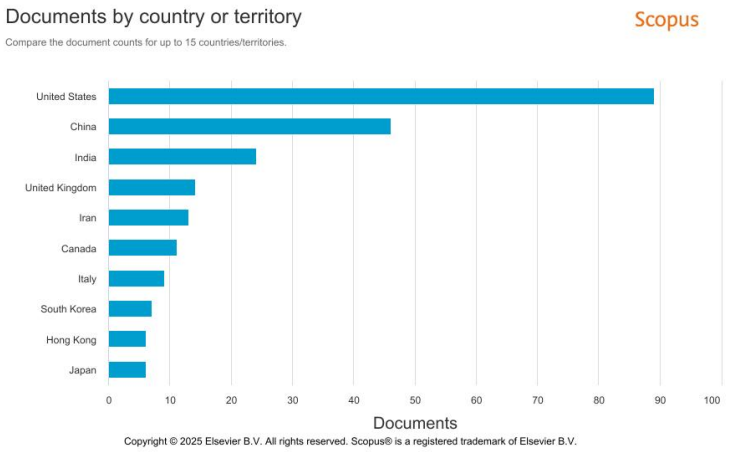

Figure 10. Number of Scopus-indexed articles on sustainable transport by country or region (2000–2024). The United States leads by a substantial margin, followed by China and India. The chart illustrates regional disparities in research production and the dominant role of countries with advanced research infrastructure and strategic investment in sustainable transport.

5.6.Keyword Co-occurrence Network in Sustainable Transport Research

Figure 11 presents the keyword co-occurrence network in the field of sustainable transport, constructed based on keyword co-occurrence analysis for the period 2000–2024 using VOSviewer software. This analysis organises the conceptual structure of the research into several distinct thematic clusters.

The keyword co-occurrence structure (Figure 11) reveals three evolutionary layers:

- Central core (red cluster – established themes): Includes "sustainable development," "urban transport," and "pollutant emissions." The presence of this core indicates that the field has developed a *mature central discourse* – a stage of evolution in which foundational concepts have reached theoretical saturation and no longer constitute the primary challenge.

- Intermediate clusters (green and blue – methodology and technology): Such as "data envelopment analysis," "fuzzy logic," "smart city." The emergence of these clusters signifies a *methodological turn* in the field's evolution: a shift from questions of "what?" and "how much?" to questions of "how to integrate?" and "how to manage intelligently?"

- Periphery (scattered keywords such as intermodal transport, supply chain logistics): This dispersion indicates *evolutionary gaps* – areas that possess the potential to become new cores but have not yet reached maturity. From the perspective of field evolution, the closer a keyword is to the periphery, the higher the probability of either *thematic death* or a *future leap to the core*. Distinguishing between these two possibilities requires temporal analysis (presented in Figure 12).

The co-occurrence network demonstrates that the sustainable transport field has passed the stage of "forming a shared vocabulary" and is now in a phase of specialisation and bifurcation into subdomains. The primary evolutionary challenge ahead is the reintegration of these subdomains into a unified framework – precisely what the present study undertakes through a "network-based thematic analysis."

The research by Anderson (2008), although conducted within the context of food systems, has significant implications for transport infrastructure due to its focus on social policies and distributive justice. By adopting a rights-based approach, this study emphasises broader governance processes that can be applied to transport policymaking. The study by Wey and Huang (2018) highlights the lack of integrated planning and the misalignment among different transport modes in developing countries. In the co-occurrence map, keywords such as "intermodal transport" and "air carriers" are situated in peripheral sections, indicating neglected potentials and research gaps in this area.

On the other hand, Zheng et al. (2013) provide a practical framework for developing performance indicators in sustainable transport policies. Drawing on case studies from American cities, this study underscores the necessity of connecting empirical data with long-term sustainability goals and promoting evidence-based decision-making. More recent comparative studies (2024) have examined changes in public transport systems from the perspectives of urban planning and operational performance during economic and climate crises. The findings indicate an increasing scientific focus on the resilience and adaptability of urban transport systems.

In summary, the keyword co-occurrence map and the review of related research works indicate that sustainable transport is deeply rooted in environmental and urban discourses and is methodologically transitioning toward complex data-driven analyses, causal modelling, and policy-oriented design. However, the dispersion of peripheral concepts suggests the existence of significant gaps in the literature, thereby opening new pathways for future interdisciplinary research.

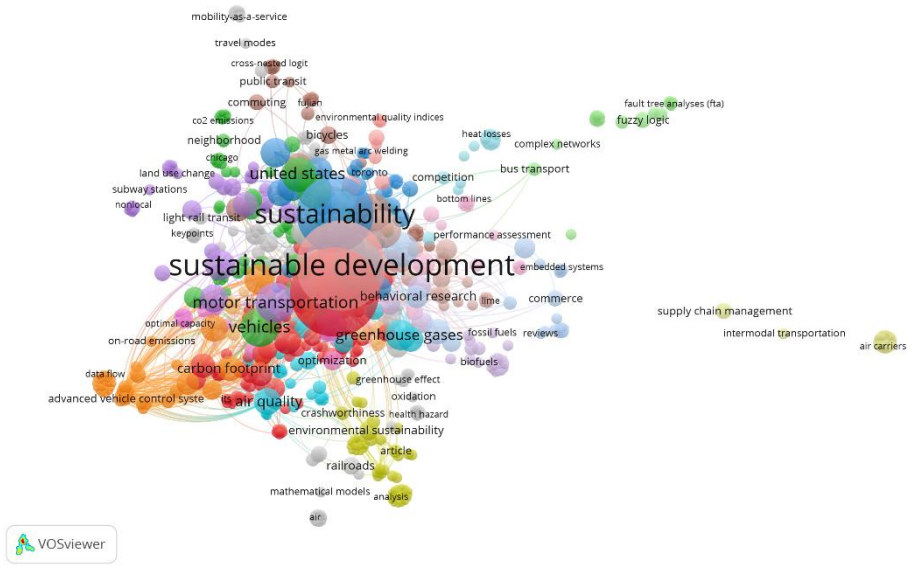

Figure 11. Keyword co-occurrence network in sustainable transport research (2000–2024). The map includes main thematic clusters around sustainability, environmental impacts, public transport, and technological innovation. Node size indicates keyword frequency, and cluster colours represent conceptual groupings. Peripheral terms denote specific or less-explored research areas.

5.7.Keyword Co-occurrence Network in Sustainable Transport Research

Figure 12 graphically illustrates the temporal and thematic evolution of scientific research in the field of sustainable transport through a conceptual co-occurrence map. This analysis was conducted using the overlay visualisation functionality in VOS viewer software. The temporal co-occurrence map (Figure 12) provides the most significant evidence for an integrated narrative of the field's evolution. The colour transition from blue (2010) to yellow (2024) can be interpreted in terms of three successive paradigms:

First paradigm (blue, 2010–2014): Technical efficiency and pollution control. Dominant keywords: CO_2 emissions, energy consumption, fuel optimization. At this stage, the central problem of the field was defined as "how to reduce transport pollution?" Approaches were predominantly engineering-oriented and univariate.

Second paradigm (green, 2015–2020): multi-criteria decision-making and hybrid methodologies. Emerging keywords: fuzzy logic, reliability analysis, multi-criteria indicators. This transition indicates that the field recognized that sustainability cannot be measured by a single indicator (e.g., CO_2); consequently, it turned to integrated tools. From the perspective of scientific evolution, this stage represents *methodological maturity*.

Third paradigm (yellow, 2021–2024 and projection to 2025): Intelligent, shared, and equity-oriented systems. Dominant keywords: Mobility-as-a-Service (MaaS), shared mobility, advanced air mobility, artificial intelligence, spatial justice. This colour shift from green to yellow signifies the most profound evolutionary change in the field: not only the tools, but *the very problem itself* has been redefined. The central question now is: "How can we design a transport system that is simultaneously low-carbon, equitable, intelligent, and accessible to all?" This transition is equivalent to a *paradigm shift* in the Kuhnian sense.

Evolutionary gaps revealed in the map: The weak presence of concepts such as "intermodal transport" and "supply chain logistics" in the yellow zones warns that these subdomains may fall behind the mainstream of evolution unless they are linked to intelligent concepts (e.g., IoT in logistics). The present study, in full alignment with the third paradigm, seeks precisely to integrate indicators of equity, governance, and clean technologies through a *network-based thematic analysis* – i.e., precisely what the yellow-coloured map indicates as the future trajectory.

In this regard, the research by Mahajan et al. (2021) enriches this conceptual axis by presenting an integrated framework for assessing urban transport sustainability that combines environmental, economic, and social dimensions through multi-criteria decision-making (MCDM) and data-driven methods. Alongside these established axes, particularly topics related to carbon reduction such as carbon footprint and CO_2 emissions, more recent studies, including those by Du et al. (2021) and Rezaei et al. (2023), have examined decarbonisation strategies in transport systems, emphasising the role of public policy, technological innovation, and energy efficiency improvements in the development of low-carbon transport.

The green areas of the map, corresponding to the 2015–2020 period, include methodological keywords such as fuzzy logic, reliability analysis, and multi-criteria indicators, representing a methodological turn in the field toward cross-sectoral and data-driven analyses. For instance, Heidari et al. (2020) developed a composite urban sustainability index using fuzzy numbers and logic, demonstrating the capacity of advanced assessment tools.

Conversely, the yellow zones of the map represent the most recent and rapidly growing research axes. Keywords such as Mobility-as-a-Service (MaaS), shared mobility, and advanced air mobility (AAM) imply the field's transition toward digital, networked, and intelligent transport models. In this context, Liu et al. (2023), through a comprehensive conceptual review of Advanced Air Mobility, examined issues including eVTOL design, regulatory considerations, and governance challenges. Likewise, Li et al. (2023), through an extensive analysis of policy complexities in shared mobility ecosystems, contributed to a deeper understanding of the managerial and institutional challenges in this sector. In a similar vein, other studies have proposed data-driven, real-time analytical frameworks for intelligent transport to monitor urban emission patterns, which hold particular significance for urban sustainability monitoring.

In the peripheral sections of the network, concepts such as intermodal transport, supply chain logistics, and regional sustainability exhibit weaker connections, indicating emerging or less-developed research orientations. In this context, Chen et al. (2025) examined transport sustainability in island regions, emphasising the necessity of locally tailored policies and adaptive infrastructure planning.

Overall, the temporal and thematic patterns displayed in the co-occurrence map, together with the review of recent literature, indicate that the field of sustainable transport is transitioning from early technical and environmental approaches toward data-driven policy-making, equitable spatial planning, shared systems, and integrated smart services. In this transition, the yellow clusters represent promising axes for future research, particularly at the intersection of sustainable transport with digital innovation and artificial intelligence.

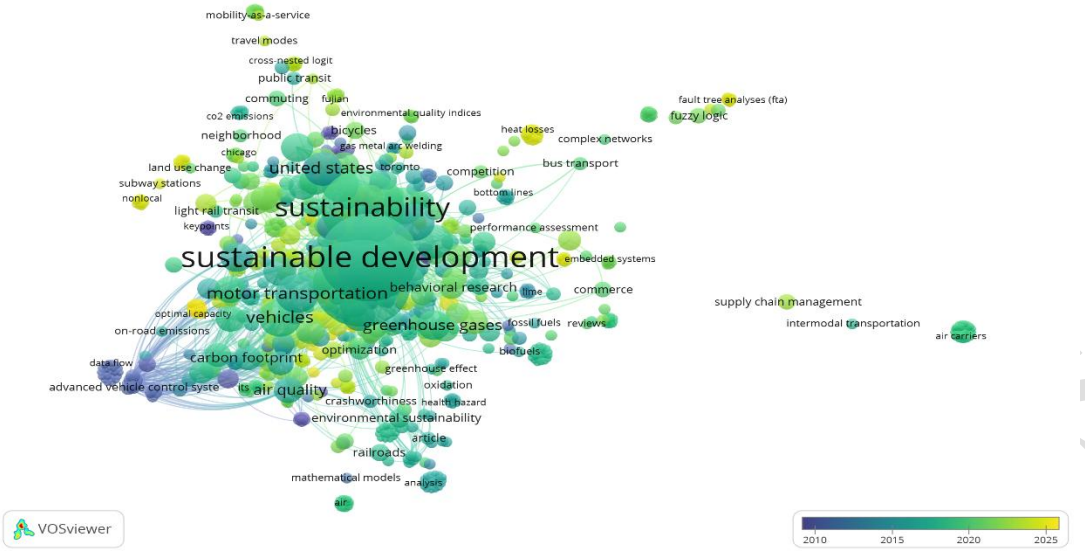

Figure 12. Overlay of keyword co-occurrence in sustainable transport research (2000–2024). Node colours represent the average publication year of each keyword, ranging from blue (early concepts, circa 2010) to yellow (emerging concepts, circa 2024). Node size indicates keyword frequency, and edge thickness reflects co-occurrence strength. The conceptual evolution shifts from an environmental and technical focus toward smart mobility, digital services, and spatial justice.

5.8.Citation Analysis of Documents Aimed at Identifying Knowledge Clusters and Emerging Research Pathways in Sustainable Transport

The map below presents the results of the citation analysis at the document level in the field of sustainable transport over the period 2000–2024. In this visualisation, each node represents a scientific work (article or research document), with node size proportional to the number of citations received. Edges (connections) represent citation relationships among articles, and node colour indicates a distinct conceptual cluster.

The citation network (Figure 13) reveals the hidden layer of the field's evolution – namely, the flow of influence and the succession of ideas. Three key findings can be interpreted from the perspective of scientific evolution:

a) Existence of a paradigmatic hard core (core set): The large nodes at the centre (e.g., Mihyeon & Amekudzi, 2005; Steg, 2005; Haghshenas, 2012) are articles that have defined the

foundational frameworks of the field. These works act as "living textbooks," with every new study compelled to cite them. From an evolutionary standpoint, this core indicates that the field has entered a stage of *normal science*, wherein a dominant paradigm exists and researchers engage in problem-solving within it.

b) Structural gap between the green/purple cluster (behavioural-environmental) and the red cluster (corporate policy): The red cluster (research on sustainable supply chains and corporate social responsibility), with very limited connections to the network centre, represents a classic example of *insular evolution*. This disconnect constitutes a serious evolutionary warning: if these two currents are not connected, the field will experience a *vertical knowledge gap* – i.e., behavioural findings will never translate into corporate policy, and vice versa. Bridging such clusters typically requires integrative research (e.g., collaborative case studies) and the use of approaches such as network-based thematic analysis.

c) Peripheral nodes (e.g., Grigoroudis, 2022; Zu, 2021; Antunes, 2023): These nodes, while recent in terms of publication date, exhibit weak connections to the core. They present two possible evolutionary interpretations: (i) pioneers of a new paradigm that have not yet gained acceptance but will become central in the future; (ii) uninfluential marginal works that never enter the mainstream. Distinguishing between these two possibilities requires deeper content analysis. Through its systematic review, the present study demonstrates that topics such as MCDA and artificial intelligence belong to the first category.

Overall, the results of this citation analysis highlight three key gaps:

- The disconnect between behavioural studies and macro-level policy research;
- The weak integration of Iranian research into the global scientific discourse;
- The lack of network connectivity for emerging concepts in recent years.

These findings can serve as a valuable foundation for defining future research trajectories, particularly in areas such as smart mobility, spatial equity, shared transport systems, and integrated behavioural-environmental analyses based on big data-driven methods.

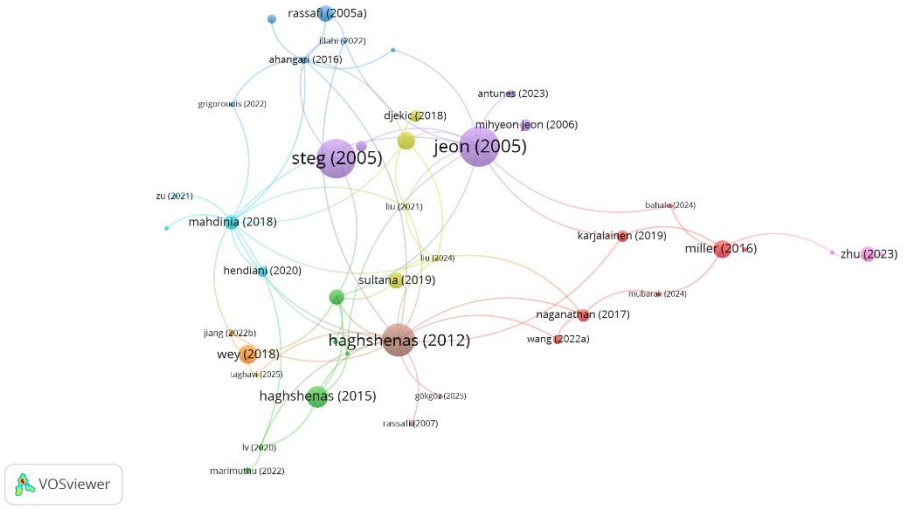

Figure 13. *Citation network of scientific documents in the field of sustainable transport (2000–2024). Each node represents a publication; node size indicates citation count, and colours denote conceptual clusters. The central axes include key thematic areas such as behavioural analysis, sustainability modelling, and environmental assessment. The red cluster, focused on corporate policy and supply chains, exhibits limited integration with mainstream research currents, indicating conceptual gaps and emerging pathways.*

In this study, the concepts of strategic diagrams were employed to analyse emerging trends and evolutionary dynamics within the field of sustainable transport. These diagrams effectively simulate the conceptual transformations in this domain across four principal categories:

1. Motor themes (active and prominent themes): These themes include shared mobility and smart cities, which are currently attracting the greatest attention in scientific research within this field.

2. Emerging themes: Themes that have grown rapidly in recent years, such as artificial intelligence in transport and health-oriented transport, are progressively becoming major research axes in this area.

3. Basic themes (sustainable themes): These themes pertain to issues that have remained stable over time, such as carbon reduction and environmental sustainability, which still constitute substantial portions of sustainable transport research.

4. Declining themes: Themes that are gradually diminishing and receiving less attention include passenger transport and walking. These concepts have experienced a decline in focus in recent studies.

These trends indicate that in recent years, new topics such as artificial intelligence and health-oriented mobility have grown significantly, whereas traditional topics like passenger transport have experienced waning attention. Such developments reflect a transition from classical paradigms towards more novel frameworks, emphasising advanced technologies, social sustainability, and health.

To compare and contextualise these findings with previous analyses, the emerging trends identified in the strategic diagrams were contrasted with co-authorship and co-word analyses. The results demonstrate that prominent authors in this field have largely moved towards emerging themes, while classical themes have attracted less attention from the scientific community. These shifts notably indicate changes in research methodologies and a growing focus on social and technological sustainability.

6.Discussion

6.1.Comprehensive Perspective and Innovation of the Study Compared to Previous Research

This study presents a comprehensive and complete view of research trends in sustainable transportation, a perspective often lacking in previous works. Numerous prior studies have neglected social sustainability in favor of focusing on specific aspects of sustainability, such as environmental or economic issues (Bao et al., 2023). In contrast, the present study fills this gap by simultaneously examining the economic, environmental, and social pillars of sustainability over a broader period (2000-2024). Furthermore, by combining bibliometric techniques with visualization tools – including co-occurrence, co-authorship, and citation

mapping through VOS viewer this study reveals broad patterns and hidden linkages in the data. This multidimensional approach adds greater depth and richness to the findings. Essentially, while previous studies each illuminated parts of the sustainable transportation research landscape, this study offers a more comprehensive and up-to-date perspective. The results provide a clear, documented, data-driven answer to the main research question: identifying dominant and emerging trends in sustainable transportation research.

6.2.Temporal Evolution and Paradigm Shift in Sustainable Transportation Research

Over the past 25 years, research in this field has experienced continuous evolution, moving from a focus on fundamental issues such as pollution control and macro transportation policy toward the integration of advanced technologies and social considerations (Hosseinian et al., 2024). For example, while earlier research mainly concentrated on planning methods, carbon emission reduction, and lower fossil fuel consumption, recent years have seen a remarkable growth in themes such as smart cities, electric and autonomous vehicles, and transportation system resilience. These changes indicate that the field has moved beyond a one-dimensional stage and now adopts a comprehensive, systematic, and interdisciplinary view of sustainability in transportation. The emerging pathways identified in this study include:

- Transition toward electrification and clean energy, from electric vehicles to hydrogen-based fuels.
- Integration of digital technologies and artificial intelligence in transport management, including advanced simulations and machine learning.
- Increasing focus on human-centered, equity-oriented, and health-oriented mobility, including active transport, walkability, and equitable urban access.
- Emergence of resilience-based approaches in response to global challenges such as pandemics and climate change.

Collectively, these developments provide a well-reasoned, multifaceted answer to the research question and show that, while building on the foundations of past research, the field is expanding toward new scientific and technological frontiers.

6.3.Analysis of Paradigmatic Shifts and Their Impact on Sustainable Transportation Research

As one of the key pillars of sustainable development, sustainable transportation has witnessed major transformations in concepts, approaches, and implementation policies over the past two decades. When the field first emerged, its primary focus was on environmental issues and mitigating the negative impacts of transport on the planet. Over time, however, social and economic dimensions have also been recognized as core pillars of transport sustainability, and these paradigmatic changes have driven research in this field toward a more comprehensive, interdisciplinary approach. The shift from a sole focus on environmental issues to more comprehensive approaches that encompass social, economic, and health dimensions has been a major paradigmatic change in sustainable transportation research over the last two decades. Initially, sustainable transport research was mainly concerned with environmental issues such as reducing carbon footprints and adopting green technologies.

Gradually, this one-dimensional view changed, and social dimensions such as equitable access to transport, improved public health, and economic resilience also moved to the center of attention. These changes indicate that sustainable transport is no longer merely an environmental issue but has become an interdisciplinary topic that simultaneously considers social and economic aspects. One important aspect of this paradigm shift is the emergence of new indicators for assessing transport sustainability that more comprehensively consider environmental, social, and economic impacts. This approach is particularly emphasized in recent studies on smart cities, shared mobility, and Mobility-as-a-Service (MaaS). Recent research (e.g., Grigoroudis et al., 2022) shows that these integrated models align social needs and environmental objectives more effectively than older approaches.

6.4.Impact of the COVID-19 Pandemic on Research Trends and Developments in Sustainable Transportation

The COVID-19 pandemic has had significant effects on mobility patterns and transport demand worldwide. Social distancing measures and travel restrictions led to a sharp decrease in work-related and long-distance travel, especially in urban areas. These changes pushed many activities toward telework and the use of digital technologies, reducing the need for conventional transport (Li et al., 2023). After the crisis, attention to transport system resilience and the necessity of deploying smart technologies and real-time traffic management increased. Researchers have paid more attention to using artificial intelligence, intelligent transport

systems, and real-time data analytics models as tools for crisis management and improving transport system performance under critical conditions (Sohi et al., 2025). These changes have led to the revision of policies and the development of new strategies in the design and implementation of transport systems.

6.5.Emerging Trends, Technological Challenges, and Inequality in Access

In the future, several emerging trends are likely to shape sustainable transportation research. Shared mobility, transport electrification, and the incorporation of smart city frameworks are among the most important innovative areas. The integration of artificial intelligence and big data in transport design and management will bring major changes, particularly in optimizing energy consumption and improving system efficiency. Research shows that the use of big data for real-time, smart decision-making in transport management is growing, especially in large cities (Liu et al., 2023). However, these technology-driven developments also create challenges, particularly regarding equitable access to technologies and infrastructure. While digitalizing transport systems offers many benefits, the lack of access to new technologies for certain groups can exacerbate inequalities. Future research should focus on these challenges and offer solutions for the fair distribution of the benefits of these developments.

6.6.Implementation Challenges in Sustainable Transportation Policy

Implementing sustainable transport policies faces numerous challenges. Problems such as budget constraints, political resistance, and lack of inter-institutional cooperation are among the main obstacles on the path to implementation. Research has shown that for successful implementation of these policies, effective coordination and cooperation among governments, the private sector, and scientific institutions must be strengthened (Sohi et al., 2025). Moreover, the deployment of essential infrastructure such as electric vehicle charging stations, intelligent traffic management systems, and public transport systems requires considerable time and resources. Researchers must continuously identify and address these barriers at different scales and provide operational solutions to facilitate this process.

6.7.Addressing Research Gaps: Previous Shortcomings and How This Study Resolves Them

One of the most important shortcomings was the lack of a comprehensive assessment of the entire body of studies in the field of sustainable transportation; previous research mainly focused on limited aspects or specific branches of this field. By adopting a broad, multidimensional approach, this study has filled this gap and simultaneously examined various dimensions of the field. For example, one problem raised in previous research was the lack of a precise understanding of the temporal evolution and function of scientific research in this field (Asha'ari et al., 2024). In this regard, the present study conducted a longitudinal analysis of publication trends from 2000 to 2024 to provide a clear picture of the temporal evolution of research.

Another gap was the lack of attention to new, interdisciplinary topics such as autonomous vehicle technologies and the link between transport and health – areas that were still in their early stages when earlier studies were conducted. By identifying and highlighting these emerging areas, including the impacts of the COVID-19 pandemic and the application of artificial intelligence in transport systems, this study has enriched the existing literature and charted future research directions.

Furthermore, by revealing geographic gaps (i.e., regions and countries with low participation in sustainable transportation research), this study indirectly addresses another important shortcoming in the literature. Previous research has largely been driven by developed countries and has consistently emphasized the need for greater participation from developing countries. Although scientometric studies cannot directly remedy these inequalities, by highlighting the scientific underrepresentation of these regions, they can underscore the importance of science policies in strengthening research capacity and knowledge production in those countries.

Overall, the identified gaps whether thematic, temporal, or geographic have either been directly covered in this study or have been highlighted in a way that paves the way for addressing them in the future.

6.8.Comparison with Previous Scientometric Studies: Similarities and Innovations

The findings of this study are consistent with the results of many recent scientometric studies in the field of sustainable transportation while also having distinct innovations.

In terms of keyword co-occurrence analysis, the thematic clusters identified in this study are highly similar to the findings of previous research. For instance, Asha'ari et al. (2024) identified high-frequency topics such as transport planning, policy-making, climate change, electric vehicles, and public transport which align with the main clusters of the present study, including policy-making, clean technologies, and environmental issues. Similarly, Bao et al. (2023) introduced terms such as shared mobility, smart city, and sustainable mobility as growing keywords in the field of social sustainability concepts that were also observed as emerging trends in the present analysis.

In terms of temporal coverage, this study shows that from 2020 onward, research attention to topics such as the COVID-19 pandemic and autonomous vehicles has increased significantly, while more classical topics have experienced a relative decline. This pattern is consistent with the findings of İnce (2025), who reported that terms such as public health and walkability entered the scientific literature around 2020-2021 and have since been considered emerging urban topics. That study also confirmed that "COVID-19" and "autonomous vehicles" are now among the most dynamic research axes in urban transport a finding fully consistent with the results of this study.

Regarding co-authorship networks and international scientific collaborations, both the present study and previous research emphasize the dominance of a small number of countries in sustainable transportation knowledge production. For example, Bao et al. (2023) identified the United States, China, and the United Kingdom as the main players in this field a finding that matches the results of Judi Janto et al. (2025) as well as the present analysis.

Citation analysis has also yielded similar results; both types of studies have identified a set of highly cited, influential sources that form the theoretical foundation of the field. For instance, the scientometric study by Badassa et al. (2020) showed that articles related to sustainability indicators and low-carbon transport policies received the highest number of citations. Similarly, the present analysis has revealed a comparable set of foundational works, including both classical studies on sustainable transport approaches and recent technological innovations.

Overall, the findings of this study are largely confirmed by scientometric studies published after 2020, while simultaneously adding value to the existing scientific body by highlighting new trends and underexplored areas such as novel technologies, smartization, and

crisis-induced topics. This overlap reinforces the validity and robustness of the present study's results and shows that its methodology and findings are aligned with mainstream scientific discourse while also helping to address previously neglected knowledge gaps.

6.9.Data-Driven Conceptual Framework and Its Validation

The conceptual model presented in this study is designed based on structural analysis and a novel synthesis of theories and findings from urban sciences, with the aim of illustrating how macro drivers and internal relationships affect urban transformation outcomes, grounded in a conceptual diagram.

Macro Drivers: At the highest level, the model introduces four main drivers demographic changes, climate change, globalization, and technological innovation as external factors influencing the urban system. These drivers, directly and indirectly, shape the path of urban governance and policy-making and affect indicators of environmental quality, social justice, and resilience.

Urban Governance and Planning: In the second layer, urban governance plays an intermediary role between external drivers and the pillars of urban transformation. In this part, the model shows that the quality of policy-making, decision-making, management practices, and citizen participation processes can modulate the intensity or direction of the macro drivers' effects and lead to the realization of the main transformation dimensions.

Four Pillars of Urban Transformation: The innovation of the research model lies in introducing and explaining four fundamental pillars of urban transformation:

- **Social and Spatial Justice:** This pillar emphasizes strengthening equal access, social cohesion, reducing spatial discrimination, and improving the quality of the living environment for citizens.
- **Economic Policy and Dynamics:** It focuses on improving economic productivity, employment, economic justice, and the financial sustainability of cities.
- **Technological Innovation and Smart City:** Includes the implementation of new technologies, use of data, digital infrastructures, and enhancement of urban efficiency and services.

- **Climate and Environmental Resilience:** This pillar aims to protect the environment, adapt to climate change, reduce vulnerability, and ensure urban sustainability in the face of natural hazards.

Each pillar is explained based on specialized sub-components and two-way relationships with other pillars, forming a network of horizontal and vertical interactions.

Intermediate and Final Outcomes

In the lower part of the model, the outcomes resulting from the interactions among drivers, governance, and the four transformation pillars are described.

Intermediate outcomes include:

- Enhanced urban resilience
- Improved social cohesion
- Economic dynamism and prosperity
- Increased security
- Improved health
- Better accessibility

The **final outcome** of the model is the improvement of quality of life and citizen satisfaction with the urban environment, considered the ultimate goal of urban planning.

Causal Relationships and Model Innovation

Causal relationships in the model:

The connections in the model are indicated by directional arrows, showing that macro drivers first affect governance, then, through governance and policy-making, influence the four pillars. Each pillar interacts bidirectionally with other dimensions and produces its own practical and social outcomes. The main motivation and innovation of the model lie in its theoretical synthesis of different dimensions of urban transformation into a coherent structure and its applicability in the decision-making process.

Innovation aspect of the research:

This model integrates, for the first time, the four transformation pillars with an interactive and causal approach and a direct link from theory to policy application. Its main advantage is the ability to simultaneously analyze various urban outcomes and create a pattern for evidence-based evaluation of urban policies. The conceptual model of the research serves not only as the theoretical framework of the study but also as an analytical guide for interpreting findings, formulating strategic recommendations, and conducting evidence-based policy-making in the field of urban planning. The model can be used for evaluating different scenarios, identifying strengths and weaknesses, and improving citizens' quality of life, and it is adaptable to other case studies.

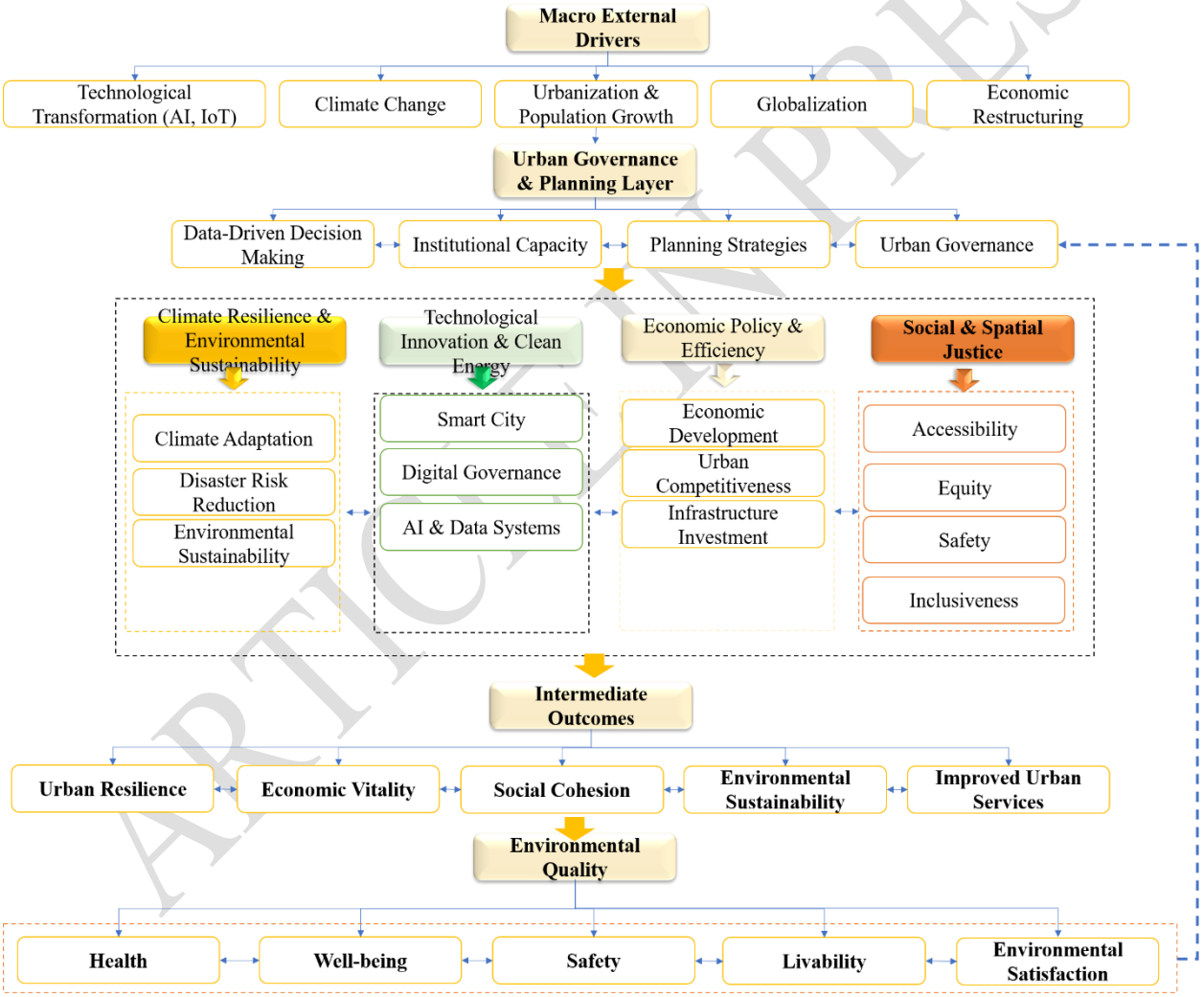

Figure 14: Data-Driven Conceptual Framework of the Research

7.Conclusion

This study employed a multi-layer scientometric approach to map the structural evolution and emerging research trends in transportation sustainability over the period 2000–2024. The analytical findings confirm that, from the mid-2010s onward, this field has emerged as a rapidly growing and conceptually mature scientific domain, driven by the convergence of global climate change mitigation policies and the imperatives of sustainable urban planning. The results indicate that, after an initial phase of gradual and fragmented growth, the field entered a stage of rapid expansion and conceptual maturity around the mid-2010s. This evolutionary trajectory aligns with international climate change policies, sustainable urban development, and the restructuring of transportation infrastructure.

Using three core analytical approaches co-word analysis, co-authorship analysis, and citation analysis – this study provides a comprehensive picture of the knowledge drivers and influential scientific collaborations that have shaped the field. The main conceptual clusters are:

I. Transport policy and urban planning
II. Technological innovation focused on clean vehicles and energy efficiency
III. Environmental and climate issues emphasizing decarbonization and climate resilience
IV. Social dimensions including equity, accessibility, and user satisfaction

These clusters delineate a pattern that reflects the interdisciplinary nature of sustainable transportation research, where environmental, technological, and human-centered considerations are simultaneously intertwined. The temporal analysis of keywords reveals that, since 2020, new concepts such as Smart City, Shared Mobility, AI in Transport, Mobility-as-a-Service (MaaS), and Health-Oriented Transport have emerged as prominent scientific trends. In contrast, more traditional concepts such as Passenger Transport and Walking have experienced a relative decline in research attention. This shift indicates a transition from classical environmental-technological paradigms toward data-driven, equity-oriented, and health-focused frameworks.

From a geographical perspective, the results confirm that developed countries continue to dominate knowledge production and international collaboration networks in this field. The United States, China, and several European nations play leading roles, while countries of the Global South – particularly low-income and developing regions remain underrepresented in the scientific literature. This geographic inequality in knowledge production and dissemination not only limits scientific inclusivity but also indirectly reduces the applicability of research findings across diverse socio-spatial contexts. Network analysis further shows that a small number of universities and research institutions play a pivotal role in shaping the scientific discourse of the field. Nevertheless, the growing presence of new institutions from Asian countries signals increasing diversity within the knowledge ecosystem. Citation analysis also confirms that influential scientific works have primarily focused on designing sustainable planning frameworks, implementing low-carbon transport policies, and fostering technological innovations. At the same time, areas such as real-time analytics, AI-driven models, health-transport integration, and equity assessment have been identified as emerging but underexplored themes with high potential for future research.

In addition to mapping past and present trends, this study has identified important gaps in the existing literature:

- Insufficient focus on the social and human dimensions of sustainable transport (health, gender, social participation)
- Limited geographic coverage, especially in low-income countries and rural areas

- Weak theoretical integration among behavioral, technological, and policy-oriented research
- A shortage of interdisciplinary studies that combine big data, machine learning, and health indicators in transport modeling

By adopting a multi-layer, 25-year scientometric approach and simultaneously addressing the three pillars of sustainability environmental, social, and economic this study offers innovative contributions that are rarely found in previous research. In response to the research questions, the findings show that from 2015 onward, the growth and dynamism of scientific collaborations in sustainable transportation have been significantly strengthened, although regional inequalities persist.

The findings highlight the need to redefine policy priorities along two main axes:

1. **Prioritizing equity and health dimensions:** Policymakers should facilitate the design of policies that integrally incorporate urban equity, accessibility, and public health considerations into transport planning through targeted investment in behavioral and social research.
2. **Investing in data infrastructure:** To effectively harness emerging trends (AI and MaaS), allocating resources for the development of real-time analytics infrastructure and data-driven models is indispensable.

Scientometric and co-word analyses have clearly mapped conceptual advances and emerging research pathways, offering strategic guidance for future research. The findings of this study provide a comprehensive, multidimensional framework for researchers, policymakers, and urban planners. By delineating thematic pillars, emerging trends, and structural shortcomings, this study offers an evidence-based framework that can help redefine future research priorities, develop smart and inclusive mobility systems, and design resilient, equity-oriented transport policies in the face of climate change. Ultimately, the field of sustainable transportation is entering a new phase of complexity and interdisciplinary convergence – a phase that demands a focus on conceptual coherence, democratization of knowledge, and interdisciplinary innovation.

Given the emerging trends and fundamental transformations examined in this study, existing scientific evidence can be effectively employed to design effective and operational policies at various levels of governance. The findings indicate a rapid expansion and conceptual maturation of the field in recent years, particularly in areas such as digital mobility, social justice, emerging technologies, and climate change. However, challenges remain, including geographic disparities, research gaps in social and human dimensions, and the need for greater integration among different sustainability indicators. Therefore, addressing these challenges and guiding future research calls for comprehensive and coherent approaches in sustainable transport policy-making.

Based on these findings, this study offers several data-driven policy recommendations derived from scientometric and co-word analyses that can help improve international collaborations, develop sustainable and AI-driven infrastructure, and enhance social justice in urban transport planning. The findings show that in recent years, the field of sustainable transportation has moved from a purely environmental approach toward a multidimensional, data-driven, and human-centered framework. Scientometric trend analysis indicates that concepts such as digitalization, artificial intelligence, social justice, public health, clean energy, and system resilience have become emerging research foci.

Accordingly, several key implications for future policy and planning can be drawn:

a) Strengthening data-driven approaches and leveraging AI technologies should be considered a core pillar of transport policy-making. Developing data infrastructure and using predictive algorithms can lead to optimized public transport, smart traffic management, and travel demand forecasting. In this framework, integrating MaaS into urban policies can enhance accessibility, service integration, and transport network efficiency.

b) The prominence of social justice and health concepts in recent knowledge clusters indicates that sustainable transport policies must go beyond carbon emission reduction and attend to social and distributional dimensions. Designing equitable transport systems, especially in underserved and rural areas, as well as developing active transport infrastructure such as walking and cycling, can improve quality of life and reduce spatial inequalities.

c) The growing convergence between clean energy research and transportation suggests that investment in electric infrastructure, alternative fuels, and low-carbon technologies should be prioritized in development programs. Expanding electric vehicle charging networks and supporting innovation in renewable energy not only helps reduce greenhouse gas emissions but also facilitates the transition toward sustainable and cost-effective mobility systems.

d) The results of scientific collaboration analysis reveal increasing international and interdisciplinary interactions in this field. This trend indicates that solving the complex challenges of sustainable transportation requires the synergy of engineering, social sciences, urban planning, and public policy. Strengthening joint research networks, particularly with the participation of developing countries, can facilitate knowledge transfer, localize solutions, and accelerate the achievement of sustainable development goals.

Finally, the growing prominence of the concept of resilience in recent years – especially after global crises – shows that the future of sustainable transportation depends on designing smart and flexible systems. Leveraging real-time analytics and smart technologies can enhance the responsiveness of transport networks to crises such as pandemics, natural disasters, and climate change, ensuring their stable performance under conditions of uncertainty. Overall, the results of this study indicate that the future of sustainable transportation will be shaped at the intersection of digitalization, social justice, energy transition, and system resilience – a nexus that requires an integrated, data-driven, and multi-level approach to policy-making and planning.

Authors' Contributions

First author (25%), Second author (25%), Third author (25%), Fourth author (25%).

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Conflict of Interest

The authors declare no conflict of interest.

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