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Bibliometric analysis of decarbonization and technology diffusion in heavy-duty road freight transport : Trends, challenges and policy implications.

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Abstract

The decarbonization of heavy-duty road transport has become an important research topic due to the sector's high energy consumption and greenhouse gas emissions. This study provides a bibliometric analysis of the scientific literature on heavy-duty road transport decarbonization, with particular attention to alternative propulsion technologies, technology adoption, and market development. A Scopus-based search was conducted, followed by a screening process based on the PRISMA guidelines. The final dataset comprises 99 articles published between 2003 and 2026. Bibliometric analysis was performed using Bibliometrix and Biblioshiny to examine scientific production, citation impact, leading sources, countries, institutional affiliations, and keyword co-occurrence. The results show a marked increase in scientific production, particularly after 2020. The United States is the most represented country, followed by Germany and China, while Transportation Research Part D : Transport and Environment is the most productive source. Keyword analysis identifies three major thematic areas: hydrogen and fuel-cell technologies; electric vehicles and technology adoption; and emissions, alternative fuels, and decarbonization. Overall, the findings highlight the interdisciplinary and rapidly evolving nature of the field and reveal a significant geographical research gap concerning emerging economies, particularly African countries.

Keywords: Alternative fuels; Technology adoption; Electric trucks; Fuel-cell electric trucks; Greenhouse gas emissions.

1 Introduction

Climate change has become one of the major global challenges of the twenty-first century, requiring substantial reductions in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), and a progressive decarbonization of human activities (Shi et al., 2024). The transport sector is a major contributor to global GHG emissions and therefore represents a critical area for the energy transition. Beyond its contribution to climate change, the continued reliance on fossil-fuel-based transport also contributes to local air pollution, which has important implications for public health (Bethoux, 2020). Population growth, urbanization, increasing freight demand, and continued dependence on conventional fuels are consequently intensifying the need for cleaner and more sustainable transport systems.

Within the transport sector, road freight transport deserves particular attention because of its strong dependence on heavy-duty vehicles (HDVs), which are predominantly powered by diesel. Heavy-duty road freight is estimated to account for approximately 25–30% of global transport-related GHG emissions (Manar et al., 2026). Moreover, the International Energy Agency (IEA) projects continued growth in CO_2 emissions from heavy-duty vehicles, with emissions expected to increase by 14.8% by 2030 under relevant baseline conditions (Pardhi et al., 2022). Although freight transport emissions may receive less public attention than those generated by passenger cars, the decarbonization of heavy-duty road transport is therefore essential for achieving global climate objectives (Çabukoglu et al., 2019).

The decarbonization of heavy-duty road freight is increasingly associated with the development and diffusion of alternative fuels and propulsion technologies (AFPs) capable of reducing dependence on conventional diesel. Several technological pathways have emerged, including hybrid diesel-electric vehicles, battery electric vehicles (BEVs), hydrogen fuel-cell electric vehicles (FCEVs), and other low-carbon or renewable-fuel solutions (Iyer et al., 2023). Electricity- and hydrogen-based propulsion systems have consequently attracted increasing scientific, industrial, and policy attention as potential alternatives to fossil-fuel-powered heavy-duty vehicles (Wanniarachchi et al., 2023). However, the environmental performance of these technologies cannot be assessed solely on the basis of vehicle operation. Depending on the energy pathway considered, emissions may be shifted from the vehicle-use phase to the production, conversion, transportation, and distribution stages of the energy system (Wanniarachchi et al., 2023). The contribution of AFPs to freight decarbonization therefore depends on both their technological characteristics and the wider energy system in which they are deployed.

Battery electrification is widely considered one of the principal pathways for decarbonizing road transport. Nevertheless, its application to heavy-duty and long-haul freight remains subject to important technical and operational constraints. In particular, the large and heavy battery packs required to provide sufficient driving range, together with relatively long charging times, may create challenges for long-distance freight operations (Shi et al., 2024). These constraints have contributed to growing interest in hydrogen-based propulsion, particularly FCEVs, as a potentially suitable solution for specific heavy-duty and long-haul applications. FCEVs can offer potentially significant CO_2 reductions in long-distance transport and may provide operational characteristics related to driving range, refueling time, power output, and powertrain efficiency that are compatible with certain heavy-duty freight requirements (Pardhi et al., 2022). Consequently, hydrogen has increasingly been investigated alongside battery electrification as part of a portfolio of technological options for the decarbonization of heavy-duty road freight.

Nevertheless, the environmental benefits of hydrogen depend strongly on its production pathway. Hydrogen produced through electrolysis can achieve substantially better life-cycle environmental performance when the electricity used originates from renewable sources, whereas electricity generated from non-renewable sources can considerably reduce its environmental advantage (Wanniarachchi et al., 2023). This distinction has contributed to the growing importance of green hydrogen, particularly within broader strategies aimed at replacing fossil fuels and reducing carbon emissions in hard-to-abate sectors. Fossil-fuel-dependent sectors are increasingly expected to transition toward green or low-carbon hydrogen and its derivatives, which may be used both as energy carriers and as industrial feedstocks (Jayawardhana et al., 2025).

The growing interest in AFPs is also closely connected to the evolution of international and regional climate and energy policies. Several countries and regions have adopted long-term net-zero targets and sought to accelerate renewable energy deployment and the decarbonization of high-emitting sectors, including transport (Rout et al., 2022). In Europe, climate ambitions have been accompanied by initiatives such as the European Green Deal and REPowerEU, which have positioned clean hydrogen as an important component of the broader energy transition (Jayawardhana et al., 2025 ; Steinbacher et al., 2026). These policy developments have stimulated research, investment, technological experimentation, and infrastructure development around alternative fuels and propulsion technologies for road transport.

The transition toward AFPs in heavy-duty road freight is therefore not solely a technological issue. It involves interconnected environmental, energy, economic, infrastructural, operational, and policy dimensions. The relative attractiveness and diffusion potential of technologies such as diesel, BEVs, FCEVs, and other alternative-fuel solutions depend on factors including vehicle costs, energy prices, infrastructure availability, driving range, refueling or charging time, payload requirements, energy-system characteristics, technological maturity, and public policy support. The diffusion of AFPs should therefore be understood as a multidimensional process involving technological development, market conditions, infrastructure, policy interventions, and stakeholder responses.

Despite the rapid expansion of research on alternative fuels, vehicle electrification, hydrogen mobility, and freight decarbonization, the scientific literature remains fragmented across technological pathways, methodological approaches, geographical contexts, and research perspectives. Existing studies have examined the environmental performance, economic feasibility, technological characteristics, infrastructure requirements, policy instruments, and adoption prospects of individual AFPs. However, the overall structure and evolution of scientific research concerning the diffusion of AFPs in heavy-duty road freight transport remain insufficiently characterized. In particular, it is important to understand which technological pathways have received the greatest research attention, how the intellectual structure of the field has evolved, which thematic areas are interconnected, and which emerging topics are shaping the research agenda.

This study conducts a bibliometric analysis of the scientific literature on the diffusion of alternative fuels and propulsion technologies in heavy-duty road freight transport. The study seeks to characterize the development and structure of this research field, identify its principal technological and thematic dimensions, examine relationships among major research themes, and highlight emerging research directions.

To achieve these objectives, the study addresses the following research questions :

RQ1. How has scientific research on the diffusion of AFPs in heavy-duty road freight transport evolved over time ?

RQ2. Which countries, institutions, authors, journals, and publications have made the most significant contributions to research on AFP diffusion in heavy-duty road freight transport ?

RQ3. What are the main technological and thematic areas emerging from the literature on AFP diffusion in heavy-duty road freight transport, and how are they interconnected?

RQ4. How has scientific research attention evolved across the main AFPs, particularly battery-electric, hydrogen fuel-cell, hybrid, and other low-carbon technologies ?

RQ5. What emerging research themes, technological trends, and knowledge gaps can be identified in the literature, and what directions do they suggest for future research on the decarbonization of heavy-duty road freight transport ?

By answering these questions, this study contributes to the literature in two main ways. First, it provides a systematic overview of the evolution and intellectual structure of research on AFP diffusion in heavy-duty road freight transport. Second, it identifies emerging technological and thematic directions that may help researchers, policymakers, and other stakeholders better understand the evolving knowledge base surrounding the transition toward low-carbon heavy-duty freight transport.

The remainder of this paper is organized as follows. Section 2 presents the literature review, focusing on the decarbonization of heavy-duty road freight transport and AFPs. Section 3 describes the methodology adopted for the bibliometric analysis, including the database, search strategy, data collection and screening procedure. Section 4 presents the main results of the bibliometric analysis, including publication trends, influential contributors, geographical and institutional patterns, keyword analysis, thematic structures, and emerging research areas. Section 5 discusses the main findings in relation to the existing literature and highlights their implications for understanding the diffusion of AFPs in heavy-duty road freight transport. Finally, Section 6 concludes the study, presents its main contributions and limitations, and outlines perspectives for future research.

2 Literature review

2.1 GHG emissions from heavy-duty road freight transport

Climate change has emerged as one of the most pressing challenges of the twenty-first century, calling for significant reductions in GHG emissions across all economic sectors (IPCC, 2013). In response to this global challenge, countries have progressively strengthened international and national commitments to mitigate CO_2 and other GHG emissions (United Nations, 1998; European Commission, 2015).

Within this context, the transport sector has become a major source of energy-related emissions. Road freight transport is particularly important because of its strong dependence on fossil fuels, its high energy consumption and its continuous expansion in response to increasing demand for the movement of goods.

HDVs represent a particularly challenging segment of road transport decarbonization. Although heavy trucks constitute a relatively small proportion of the overall truck fleet, they account for a disproportionately large share of vehicle activity because they are extensively used for long-distance freight operations. Their high annual mileage, high payload requirements and relatively high fuel consumption contribute substantially to road transport emissions.

The decarbonization of HDVs is therefore more complex than the decarbonization of passenger cars. Heavy trucks generally operate over long distances, carry substantial loads and require high availability and operational flexibility. These characteristics impose specific requirements in terms of driving range, refuelling or charging time, payload capacity, vehicle reliability and infrastructure availability. Consequently, technological solutions that are effective for passenger vehicles cannot necessarily be transferred directly to heavy-duty freight transport.

Conventional diesel technologies have achieved substantial efficiency improvements over recent decades. However, the potential for further reductions through incremental improvements to conventional diesel powertrains is considered relatively limited compared with the reductions required to achieve ambitious climate targets (Eiband & Hohaus, 2018). This has increased interest in AFPs capable of substantially reducing, or potentially eliminating, direct emissions from heavy-duty road transport.

2.2 AFPs for heavy-duty vehicles

The literature identifies a broad range of technological options for reducing the carbon intensity of heavy-duty road freight transport. These include alternative fuels, electrified powertrains and combinations of conventional and emerging technologies. Among the main alternatives are compressed natural gas (CNG), liquefied natural gas (LNG), biofuels, biomethane, synthetic fuels, BEVs, FCEVs, hybrid vehicles and electric road systems (ERS).

Natural gas-based technologies have historically been considered potential transition solutions because of their compatibility with existing internal combustion engine technologies and their potential to reduce certain local pollutants compared with conventional diesel. However, their long-term contribution to deep decarbonization remains debated because their environmental performance depends on fuel production pathways, methane leakage and the extent to which they can deliver substantial lifecycle GHG reductions. Similarly, biofuels and biomethane can contribute to emissions reduction when sustainable feedstocks and low-carbon production pathways are available, although their scalability is constrained by resource availability and competing uses of biomass.

Electrification has progressively emerged as one of the most important pathways for the decarbonization of road freight. BEV offer the potential for zero tailpipe emissions and high drivetrain efficiency. Nevertheless, their applicability to heavy-duty operations depends strongly on vehicle mass, battery capacity, driving range, charging time, electricity prices and the carbon intensity of electricity generation. Recent studies emphasize that the economic and technical competitiveness of BEVs varies considerably according to vehicle category, operating conditions and geographical context (Parviziomran & Bergqvist, 2025).

Fuel-cell vehicles (FCVs) represent another important pathway, particularly for long-distance and high-utilization applications. Hydrogen fuel cells can provide electric propulsion while avoiding direct CO_2 emissions at the vehicle level. Their potential advantages include relatively high operational range and shorter refuelling times compared with conventional battery charging. However, their deployment is constrained by the cost of fuel-cell systems, hydrogen production and distribution, vehicle costs and the availability of hydrogen refuelling infrastructure. The environmental benefits of hydrogen also depend critically on its production pathway, with renewable or low-carbon hydrogen being necessary to achieve substantial lifecycle emissions reductions.

Other technologies have also attracted attention. ERS, for example, aim to supply electricity dynamically to vehicles through overhead catenaries, conductive rails or other systems, potentially reducing the need for large onboard batteries. Hybrid powertrains can combine different propulsion technologies and may provide transitional benefits. More recently, emerging concepts such as mobile carbon capture (MCC) have been investigated as potential approaches to reducing emissions from internal combustion engine vehicles (Saafi et al., 2024). The coexistence of these alternatives illustrates that the decarbonization of heavy-duty transport is not necessarily associated with a single technological pathway.

2.3 Economic and operational competitiveness of alternative technologies

The diffusion of AFPs depends strongly on their economic competitiveness relative to conventional diesel vehicles. A substantial body of research has therefore examined the Total Cost of Ownership (TCO) of different heavy-duty powertrains. TCO analyses generally consider vehicle acquisition costs, energy or fuel costs, maintenance, operating expenses and other costs associated with vehicle use. The importance of TCO arises from the fact that alternative technologies frequently involve higher upfront investment costs, which may potentially be compensated by lower energy and maintenance costs during vehicle operation.

Research indicates that the economic competitiveness of alternative powertrains varies considerably according to vehicle category and operating conditions. Danielis et al. (2025), for example, show that battery electric technologies can become economically competitive for some light- and medium-duty applications, whereas heavy-duty applications remain more challenging. Regional differences are also significant because vehicle prices, energy prices, electricity mixes, taxation systems, incentives and infrastructure costs differ substantially across countries and regions.

However, economic competitiveness cannot be reduced to monetary operating costs alone. Heavy-duty freight vehicles are productive assets, and their profitability depends on their ability to perform transport missions efficiently. Consequently, operational characteristics such as driving range, payload capacity, refuelling or charging time, vehicle availability and reliability can significantly influence the attractiveness of alternative technologies. A vehicle with low energy costs may nevertheless be unattractive to a freight operator if charging or refuelling results in significant downtime or if the vehicle cannot complete the required routes without operational constraints.

Recent literature has consequently moved beyond conventional TCO comparisons by incorporating less easily monetized factors. Charging time, loss of payload due to battery weight, vehicle utilization and operational flexibility can affect the economic value of different technologies (Boroujerdi et al., 2025). These considerations are particularly important in long-haul freight transport, where vehicle utilization rates are high and time represents an important component of operating costs.

2.4 Infrastructure as a determinant of technological diffusion

The deployment of alternative HDVs is closely interconnected with the development of energy infrastructure. Battery electric trucks require appropriate charging networks, while hydrogen-powered trucks require hydrogen production, distribution and refuelling infrastructure. The availability, geographical coverage and capacity of these infrastructures can therefore influence the feasibility of alternative powertrains.

A central issue identified in the literature is the mutual dependence between vehicle adoption and infrastructure deployment. Freight operators may be reluctant to purchase alternative vehicles when charging or hydrogen refuelling infrastructure is insufficient. At the same time, infrastructure providers may have limited incentives to invest in networks when the number of alternative vehicles remains low. This interaction can generate a self-reinforcing barrier during the early stages of technological diffusion.

Infrastructure requirements are particularly demanding for heavy-duty freight because charging and refuelling facilities must accommodate high-energy consumption, high vehicle utilization and strategically important freight corridors. Yang et al. (2025) emphasize the substantial investment requirements associated with the deployment of charging infrastructure for electric heavy-duty vehicles. Similar challenges arise for hydrogen, where the development of refuelling stations must be coordinated with hydrogen production, storage and distribution systems.

2.5 Public policy and technological diffusion

Public policy represents a major determinant of the transition toward low-carbon heavy-duty road transport. Road freight generates significant environmental externalities that are not fully reflected in conventional market prices, particularly through GHG emissions and local air pollution. Environmental policies can therefore influence the relative attractiveness and competitiveness of different fuels and propulsion technologies.

Carbon pricing is one of the principal policy instruments discussed in the literature. By increasing the effective cost of fossil fuel use, carbon pricing can improve the relative competitiveness of low-carbon technologies and encourage the transition away from conventional diesel. Other policy instruments include purchase subsidies, tax incentives, fuel taxation, infrastructure support, emissions standards, zero-emission vehicle mandates, and restrictions on conventional diesel vehicles. The effectiveness of these instruments depends not only on their individual design and duration but also on their interaction with energy and transport markets.

Policy support can be particularly important during the early stages of technological development, when alternative vehicles and their associated infrastructure remain more expensive than established diesel technologies. Public intervention can reduce investment barriers, mitigate the risks associated with emerging technologies, and stimulate sufficient market demand for vehicle manufacturers, infrastructure providers, and energy suppliers. Such support can therefore contribute to overcoming the initial barriers that often characterize the diffusion of new technologies. However, the effectiveness of policy instruments varies according to the technological pathway, market conditions, institutional framework, and geographical context.

The importance of coordinated public and private investment is particularly evident in the case of hydrogen-powered freight transport. The development of hydrogen refuelling infrastructure requires substantial investment and coordination among governments, energy suppliers, infrastructure providers, and vehicle manufacturers. Wanniarachchi et al. (2023) argue that investments by governments and private institutions in hydrogen refuelling infrastructure can contribute to the development of hydrogen-fuelled freight vehicles and their potential to reduce GHG emissions in road transportation. This highlights the interdependence between technological adoption and infrastructure development: policy support for vehicles alone may be insufficient if the corresponding energy infrastructure is not available.

Similarly, the adoption of BEVs and fuel-cell electric trucks (FCETs) depends on the simultaneous evolution of technology, regulation, and economic incentives. Anderhofstadt and Spinler (2020) emphasize that technological innovation, together with new regulations and appropriate incentives, is necessary to facilitate the adoption of BEVs and FCETs. These findings suggest that public policy does not simply influence the relative cost of alternative technologies, it can also shape the market conditions, infrastructure availability, and institutional environment required for their diffusion.

2.6 Technology adoption and market diffusion in heavy-duty road freight

The literature increasingly considers the transition toward low-carbon heavy-duty transport as a process of technological diffusion rather than simply a technical substitution between powertrains. Rogers (2003) defines diffusion as the process through which an innovation is communicated and progressively adopted within a social system. From this perspective, the adoption of alternative heavy-duty technologies depends on their perceived relative advantages, compatibility with existing transport practices, complexity, trialability and observability.

These dimensions are particularly relevant to freight transport because vehicle investment decisions are strongly connected to operational requirements and commercial profitability. Freight operators may be reluctant to adopt technologies that are perceived as technologically immature, operationally risky or incompatible with their existing routes. Conversely, technologies that demonstrate reliable performance, competitive operating costs and adequate infrastructure may progressively gain market acceptance.

The diffusion process may therefore involve different stages, beginning with experimentation and demonstration projects, followed by limited commercial deployment and potentially broader market penetration. The speed of this process can vary substantially between technologies. Battery electric trucks (BETs) may benefit from the rapid development of battery technology and charging infrastructure, whereas FCETs may depend more heavily on the simultaneous development of hydrogen production, distribution, and refuelling systems.

The literature also suggests that several technological pathways may coexist rather than one technology necessarily replacing all others. The appropriate solution can depend on distance travelled, payload requirements, vehicle utilization, energy prices, infrastructure availability and local policy conditions. Consequently, technological diffusion in heavy-duty freight should be understood as a process of competition and coexistence among multiple technological options.

3 Research Methodology

3.1 Literature search and selection process

This study adopts a bibliometric research design to systematically examine the development, structure, and evolution of scientific research on decarbonization, AFPs, and technology diffusion in heavy-duty road freight transport. The study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent and reproducible process for the identification, screening, eligibility assessment, and final selection of scientific publications. The bibliographic search was conducted using the Scopus database, which was selected because of its broad multidisciplinary coverage of research in transportation, energy, environmental sciences, engineering, economics, and sustainability.

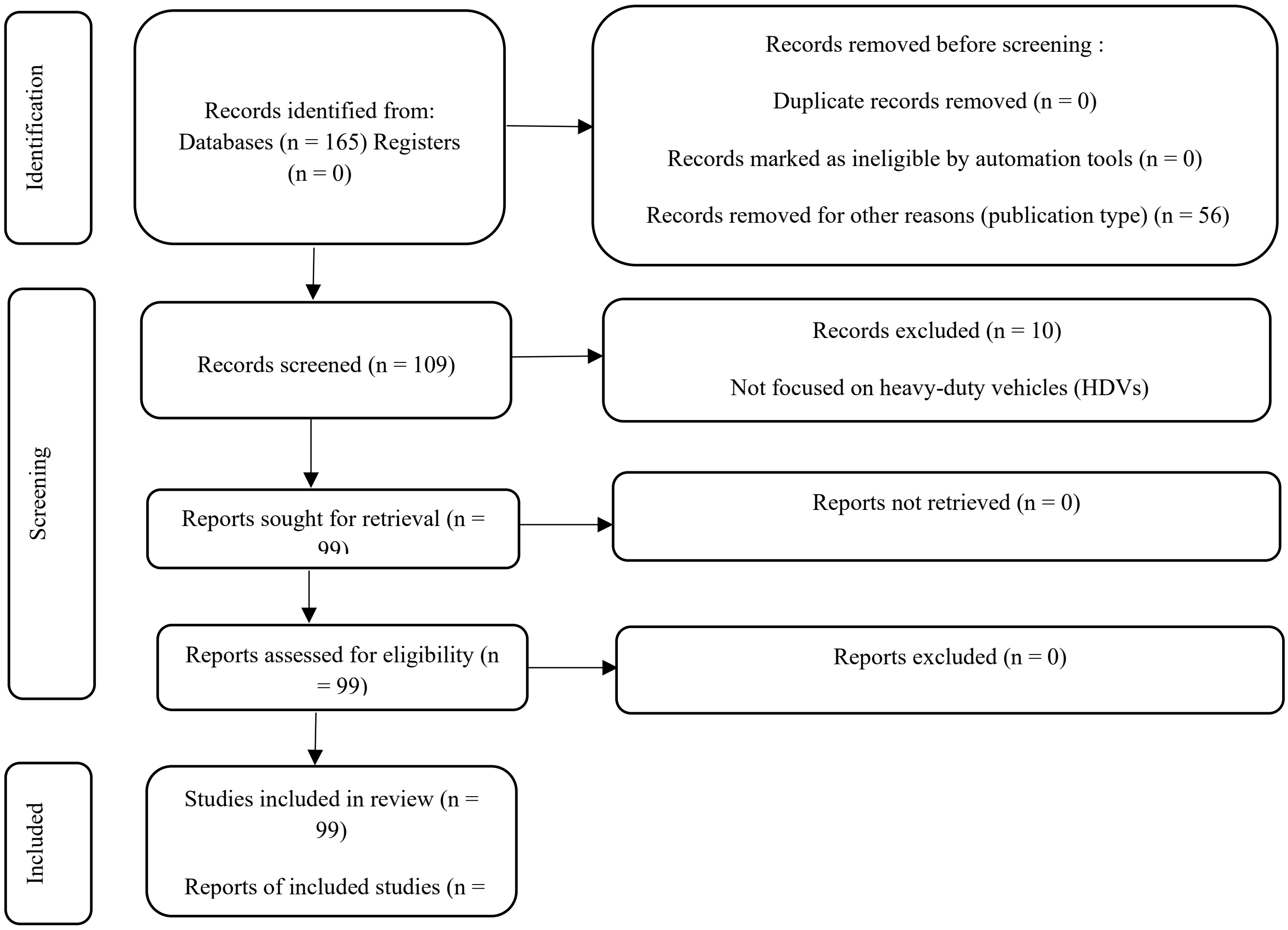
The search strategy combined three blocks of terms related to (i) HDVs and road freight transport, (ii) AFPs, including decarbonization-related technologies, and (iii) market diffusion, technology adoption, and market penetration. The search was performed using the TITLE-ABS-KEY field, covering article titles, abstracts, and keywords. The Scopus search returned publications spanning the period from 2003 to 2026. This publication-year range reflects the results retrieved from the Scopus database, with the relatively small number of publications in the earlier years indicating the recent emergence and development of this research field.

The Scopus search query was formulated as follows:

TITLE-ABS-KEY ((truck* OR "heavy-duty vehicle*" OR "heavy goods vehicle*" OR "heavy commercial vehicle*" OR "freight truck*" OR "long-haul truck*" OR "road freight vehicle*") AND ("alternative fuel*" OR "alternative powertrain*" OR "alternative propulsion*" OR "clean fuel*" OR "low-carbon fuel*" OR "renewable fuel*" OR electrification OR "electric truck*" OR "battery electric vehicle*" OR "fuel cell vehicle*" OR hydrogen OR "hydrogen fuel cell*" OR biofuel* OR biomethane OR "natural gas" OR LNG OR CNG OR "electric road system*" OR "road electrification" OR decarbonization OR decarbonisation) AND ("market diffusion" OR "market penetration" OR "technology diffusion" OR "technology adoption" OR "technology uptake" OR "market adoption" OR "adoption rate*" OR "diffusion rate*" OR "market share" OR "technology transition"))

The initial search identified 165 records. After applying the publication-type criterion and retaining only peer-reviewed journal articles, 109 records remained for further screening. No duplicate records were identified. The remaining records were screened based on their titles, abstracts, and available content to assess their relevance to the research scope. Studies were excluded when they did not focus on HDVs, particularly in the context of road freight transport, or when they were not relevant to the diffusion, adoption, market penetration, or transition of AFPs. Following this screening process, 10 records were excluded because they did not focus on HDVs, resulting in a final sample of 99 articles included in the bibliometric analysis.

Fig.1 . PRISMA flow diagram of the literature identification, screening, and selection process.



Source : Authors' elaboration.

The table below summarizes the PRISMA process for the identification, screening, eligibility assessment, and selection of studies.

Table 1. PRISMA-based screening and selection process

PRISMA Stage	Description	Number of Records
Identification	Records identified from Scopus	165
Screening	Peer-reviewed articles retained	109
Duplicate removal	Duplicate records identified and removed	0
Screening	Records screened based on title, abstract, and content	109
Exclusion	Records excluded because they did not focus on HDVs	10
Inclusion	Articles meeting the eligibility criteria	99
Final sample	Articles included in the bibliometric analysis	99

Source : Authors' elaboration.

3.2 Bibliometric Analysis

The bibliometric analysis was conducted using the Bibliometrix package in R and its web-based interface, Biblioshiny. The analysis was performed on the final dataset of 99 articles retained after the screening process. These tools were used to examine the main characteristics and intellectual structure of the literature, including annual scientific production, source and country productivity, citation patterns, keyword occurrence, keyword co-occurrence, and thematic structure.

Keyword co-occurrence analysis was performed to identify the main research concepts and their relationships within the selected literature. The analysis was based on Keywords Plus extracted from the bibliographic records. It examined how frequently different keywords appeared together across the selected publications. The resulting network was used to identify relationships among keywords and to group closely related terms into clusters. These clusters were then examined to identify the principal research themes and conceptual connections within the literature on decarbonization and technology diffusion in heavy-duty road freight transport. The bibliometric analysis was complemented by descriptive analyses of publication trends, sources, countries, and citation patterns. Together, these analyses provide an overview of the evolution of the research field and its conceptual structure, while the keyword co-occurrence and thematic analyses provide insights into the relationships and development of the principal research themes.

4 Results

4.1 Descriptive analysis of the dataset

The final dataset consists of 99 articles published between 2003 and 2026 across 54 scientific sources. The annual scientific production increased at an average rate of 13.11%, reflecting a growing interest in the research field. On average, the selected documents are 4.37 years old and have received 32.69 citations per document. The dataset includes 4625 cited references, 412 Author's Keywords, and 1022 Keywords Plus. International co-authorship represents 18.18% of the publications, highlighting a moderate level of international research collaboration.

Table 2. Main characteristics of the bibliometric dataset

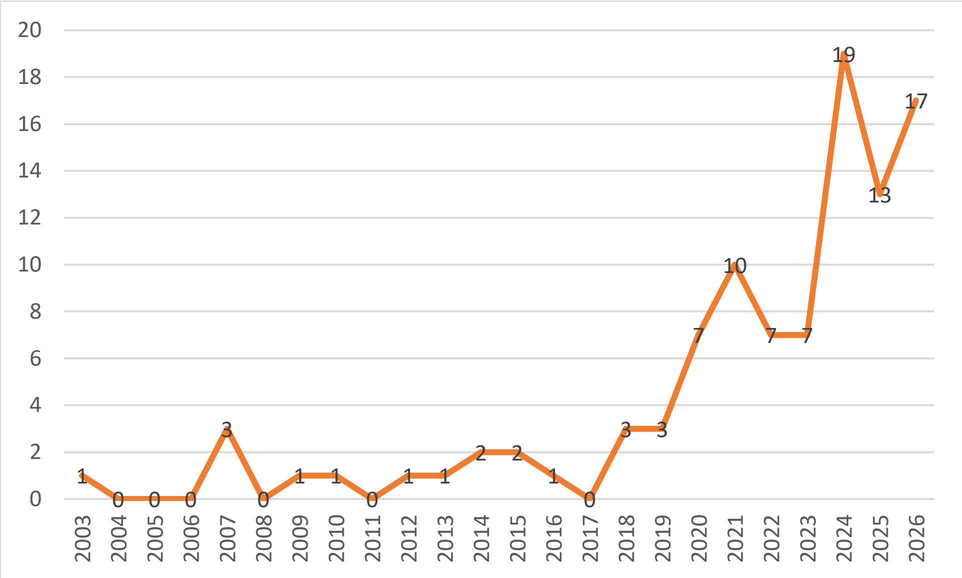
Description	Results
Annual Growth Rate %	13,11
Article	99
Author's Keywords (DE)	412
Authors	4
Average citations per doc	32,69
Co-Authors per Doc	4
Document Average Age	4,37
Documents	99
International co-authorships %	18,18
Keywords Plus (ID)	1022
References	4625
Single-authored docs	0
Sources	54
Timespan	2003 :2026

Source : Authors' elaboration based on Biblioshiny results.

4.2 Annual scientific production

The scientific production remained relatively limited during the period from 2003 to 2019, with only a small number of articles published each year. A noticeable increase occurred from 2020 onward, with the number of publications reaching 10 articles in 2021. The strongest growth was observed in 2024, with 19 publications, followed by 17 publications in 2026 and 13 in 2025. Overall, the distribution indicates a marked intensification of research activity on heavy-duty transport and decarbonization in recent years.

Fig.2 . Annual scientific production from 2003 to 2026



Source : Authors' elaboration based on Biblioshiny results.

4.3 Average citation impact by publication year

Table 3 presents the evolution of the citation impact of the publications according to their year of publication. The results show substantial variations in the average number of citations per article throughout the study period. The highest citation impact was observed for publications published in 2007, which received an average of 202 citations per article, despite the relatively small number of publications in that year. This exceptional level of citation impact suggests that the publications from this early period have had a strong and sustained influence on subsequent research in the field.

The second-highest average citation rate was recorded in 2021, with 103.6 citations per article, based on ten publications. High citation impacts were also observed for publications from 2015 (86.5 citations/article), 2014 (71.5 citations/article), and 2019 (64.67 citations/article). These years appear to correspond to particularly influential periods in the development of research on heavy-duty transport decarbonization and related technological pathways.

A different pattern can be observed for the most recent publications. The average number of citations per article decreased to 37.14 in 2022, 10.57 in 2023, 14.79 in 2024, 5 in 2025, and 1 in 2026. However, these lower values should not be interpreted as evidence of reduced scientific relevance. Rather, they are strongly influenced by the limited time available for recent publications to accumulate citations. The CitableYears indicator confirms this temporal effect, declining from 24 years for publications from 2003 to only one year for publications from 2026.

Table 3. Average citation impact by publication year

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2003	1	1	0,04	24
2007	202	3	10,1	20
2009	27	1	1,5	18
2010	7	1	0,41	17
2012	9	1	0,6	15
2013	10	1	0,71	14
2014	71,5	2	5,5	13
2015	86,5	2	7,21	12
2016	40	1	3,64	11
2018	27,33	3	3,04	9
2019	64,67	3	8,08	8
2020	30,14	7	4,31	7
2021	103,6	10	17,27	6
2022	37,14	7	7,43	5
2023	10,57	7	2,64	4
2024	14,79	19	4,93	3
2025	5	13	2,5	2
2026	1	17	1	1

Source : Authors' elaboration based on Biblioshiny results.

4.4 Most Productive Scientific Sources

Table 4 presents the most productive scientific sources in the selected literature. The results indicate that Transportation Research Part D: Transport and Environment is the leading publication source, with 14 articles, representing the largest contribution to the dataset. It is followed by the International Journal of Hydrogen Energy, with 10 articles, and Energy Policy, with 9 articles.

Other important sources include the Journal of Cleaner Production and Transport Policy, with 4 articles each, followed by Transportation Research Part A: Policy and Practice, with 3 articles. Several journals, including Applied Energy, Energy, Environmental Science and Technology, Sustainability, Transportation Research Interdisciplinary Perspectives, and World Electric Vehicle Journal, each contributed two articles to the dataset.

Table 4. Most productive scientific sources

Sources	Articles
Transportation Research Part D: Transport And Environment	14
International Journal Of Hydrogen Energy	10
Energy Policy	9
Journal Of Cleaner Production	4
Transport Policy	4
Transportation Research Part A: Policy And Practice	3
Applied Energy	2
Energy	2
Environmental Science And Technology	2
Sustainability (Switzerland)	2
Transportation Research Interdisciplinary Perspectives	2
World Electric Vehicle Journal	2
Zwf Zeitschrift Fuer Wirtschaftlichen Fabrikbetrieb	2

Source : Authors' elaboration based on Biblioshiny results.

4.5 Affiliations of the Most Productive Institutions

The analysis of institutional affiliations shows that the University of California is the most represented institution in the dataset, with 22 articles, clearly ahead of the other affiliations. It is followed by Carnegie Mellon University, with 6 articles, while the Fraunhofer Institute for Systems and Innovation Research (ISI) and the University of Waterloo each contributed 5 articles. Other institutions, including Coventry University, Imperial College London, Purdue University, Southwest Jiaotong University, Tsinghua University, the University of Illinois, and the University of Science and Technology Beijing, each contributed three articles. The distribution indicates a strong representation of research institutions from the United States, Europe, Canada, and China, highlighting the international and multidisciplinary character of research on heavy-duty transport decarbonization.

Table 5. Affiliations of the Most Productive Institutions

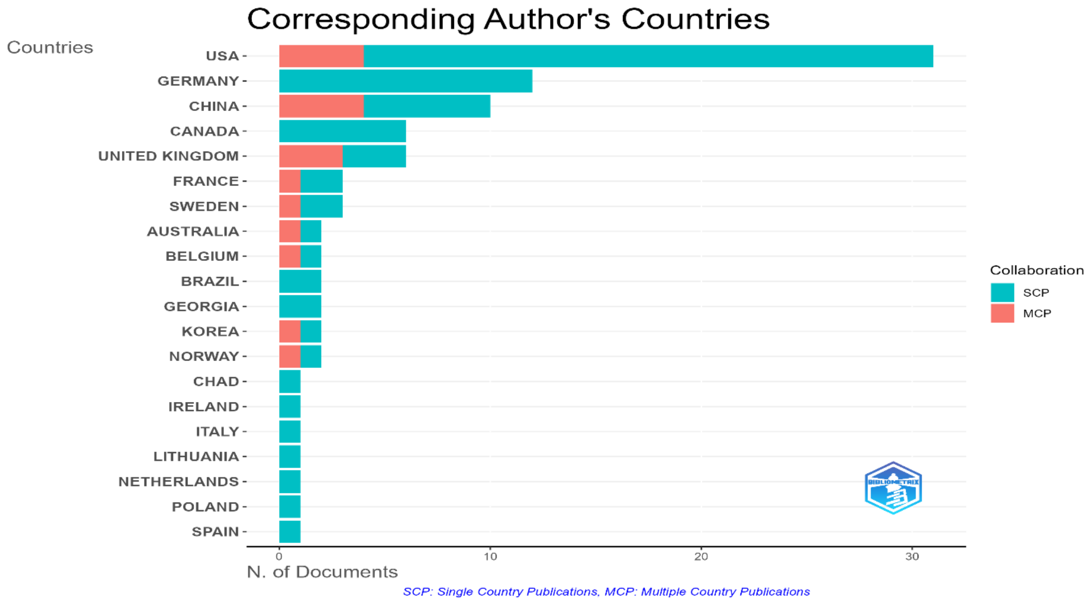
Affiliation	Articles
University Of California	22
Carnegie Mellon University	6
Fraunhofer Institute For Systems And Innovation Research Isi	5
University Of Waterloo	5
Coventry University	3
Imperial College London	3
Purdue University	3
Southwest Jiaotong University	3
Tsinghua University	3
University Of Illinois	3
University Of Science And Technology Beijing	3

Source : Authors' elaboration based on Biblioshiny results.

4.6 Corresponding Author's Countries

The United States is the leading country in terms of corresponding-author publications, with approximately 31 documents, followed by Germany and China with around 12 and 10 publications, respectively. Canada and the United Kingdom rank next, with about 8 publications each. The results also show a clear predominance of single-country publications (SCP) across most countries. However, the United States, United Kingdom, and several European countries demonstrate a notable level of international collaboration (MCP). Overall, the research field remains concentrated in a few major scientific centers, particularly in North America, Europe, and Asia.

Fig.3 . Corresponding Author's Countries



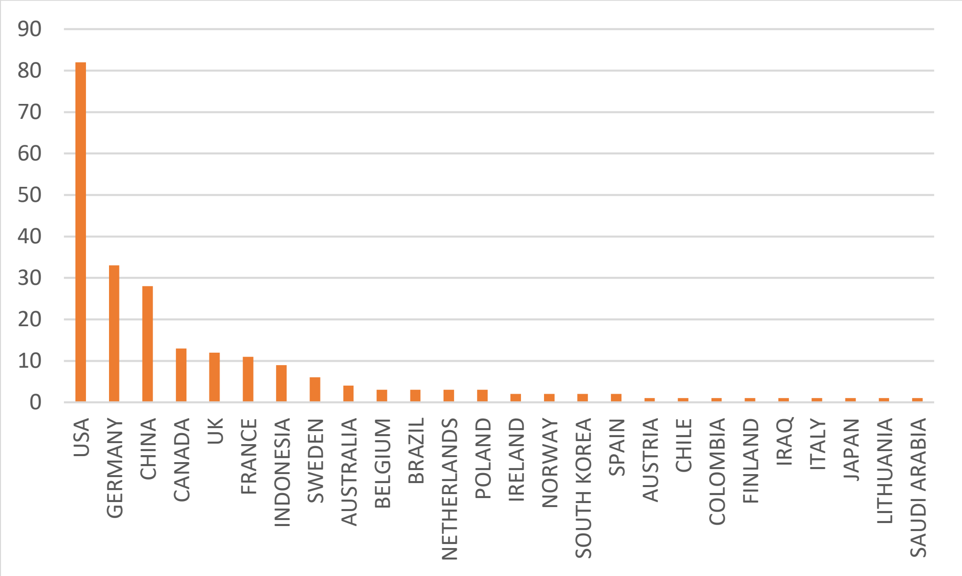
Source : Biblioshiny (Bibliometrix)

4.7 Scientific production by country

The geographical distribution of scientific production reveals a strong concentration of research activity in a limited number of countries. The United States clearly dominates the dataset, with 82 publications, representing the highest frequency among all countries. Germany ranks second with 33 publications, followed by China with 28 publications. Canada and the United Kingdom account for 13 and 12 publications, respectively, while France contributes 11 publications.

Other countries show a more limited contribution. Indonesia accounts for 9 publications, followed by Sweden with 6. Australia contributes 4 publications, while Belgium, Brazil, the Netherlands, and Poland each account for 3 publications. Ireland, Norway, South Korea, and Spain each contribute 2 publications. Several countries, including Austria, Chile, Colombia, Finland, Iraq, Italy, Japan, Lithuania, and Saudi Arabia, are represented by only one publication. On the whole, the results indicate that research on heavy-duty transport decarbonization is strongly concentrated in North America, Europe, and Asia, with the United States playing a particularly prominent role. The presence of countries from different geographical regions nevertheless highlights the international character of the research field.

Fig.4 . Scientific production by country



Source : Authors' elaboration based on Biblioshiny results.

4.8 Evolution of scientific production by country

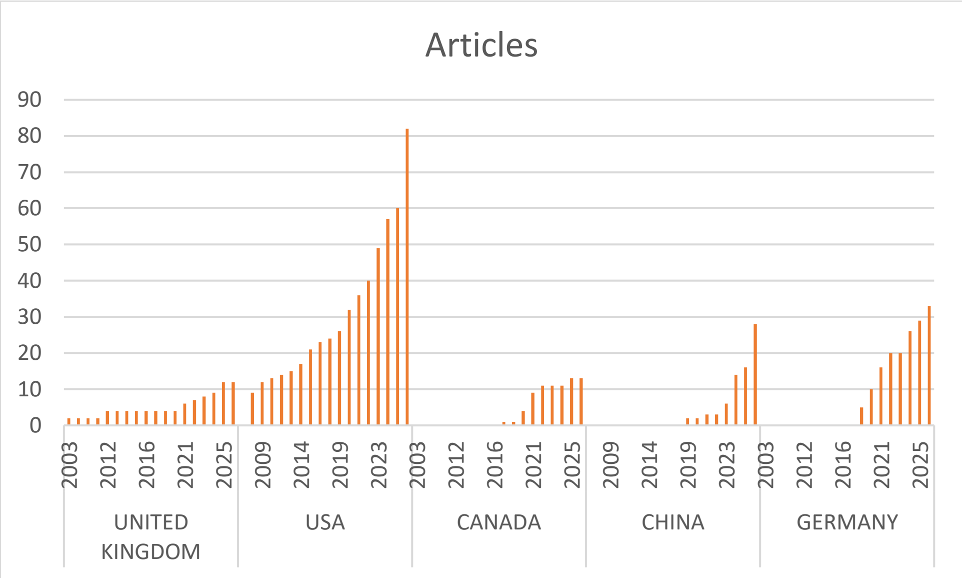
Figure 4 illustrates the evolution of scientific production in the five most productive countries over the study period. The United States clearly maintained the leading position throughout the period, with its scientific production increasing from 9 articles in 2007 to 82 articles in 2026. This sustained growth indicates the strong and long-standing contribution of US-based researchers to the literature on HDV decarbonization.

Germany also shows a marked increase in scientific production, particularly after 2019. Its contribution rose from 5 articles in 2019 to 33 articles in 2026. Similarly, China experienced a substantial expansion in recent years, increasing from 2 articles in 2019 to 28 articles in 2026. This rapid growth highlights the increasing involvement of Chinese research institutions in this research field.

Canada entered the field more recently, with its contribution increasing from 1 article in 2018 and 2019 to 13 articles in 2025 and 2026. The United Kingdom shows a more gradual increase, reaching 12 articles in both 2025 and 2026.

The results reveal a clear geographical expansion of research on heavy-duty transport decarbonization. While the United States remains the dominant contributor, Germany and China have experienced particularly strong growth in recent years. The increasing scientific production of these countries, especially after 2020, is consistent with the growing international research interest in transport decarbonization and alternative propulsion technologies.

Fig.5 . Evolution of scientific production by country



Source : Authors' elaboration based on Biblioshiny results.

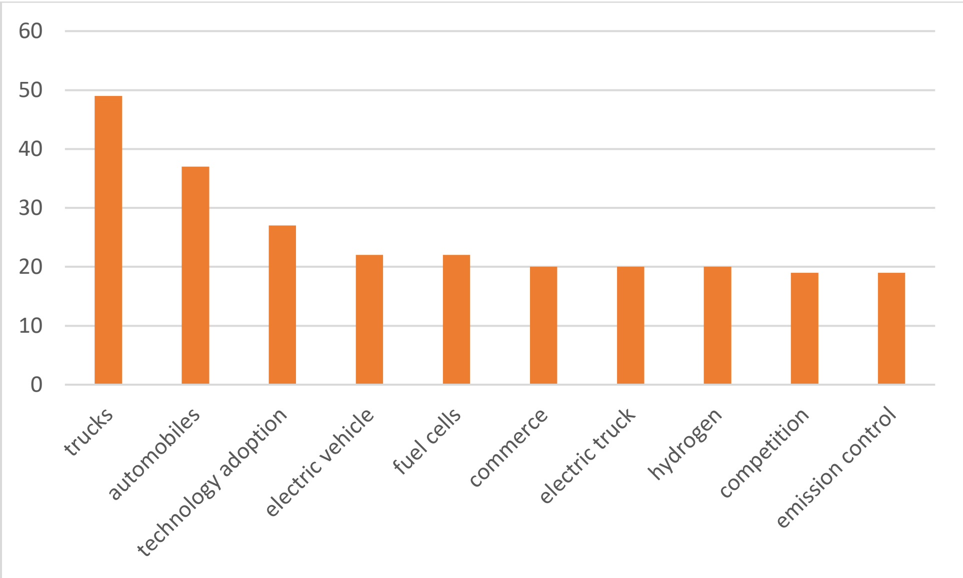
4.9 Most Frequent Words

The analysis of word occurrences highlights the main concepts characterizing the selected literature. "Trucks" is the most frequently occurring term, with 49 occurrences, confirming the central position of heavy-duty road transport in the selected research corpus. It is followed by "automobiles", with 37 occurrences, and "technology adoption", with 27 occurrences.

Other frequently occurring terms include "electric vehicle" and "fuel cells", with 22 occurrences each, followed by "commerce" and "electric truck", with 20 occurrences each. The terms "hydrogen", "competition", and "emission control" also appear frequently, with 20, 19, and 19 occurrences, respectively.

The frequency distribution reveals three major dimensions within the literature: HDV and trucks, alternative propulsion technologies such as BET, fuel cells and hydrogen, and market and environmental dimensions related to technology adoption, competition, commerce, and emission control. This combination reflects the multidisciplinary character of research on the decarbonization and technological transition of heavy-duty road transport.

Fig.6 . Most Frequent Words



Source : Authors' elaboration based on Biblioshiny results.

The tree map below illustrates the frequency of the most frequently occurring keywords in the selected literature.

Fig.7 . Tree Map

Source : Biblioshiny (Bibliometrix)

4.10 Co-occurrence Network

The keyword co-occurrence network reveals three main thematic clusters within the selected literature. The first cluster, shown in blue, is mainly associated with hydrogen, fuel cells, hydrogen production, hydrogen economy, fuel-cell vehicles, and market penetration. This

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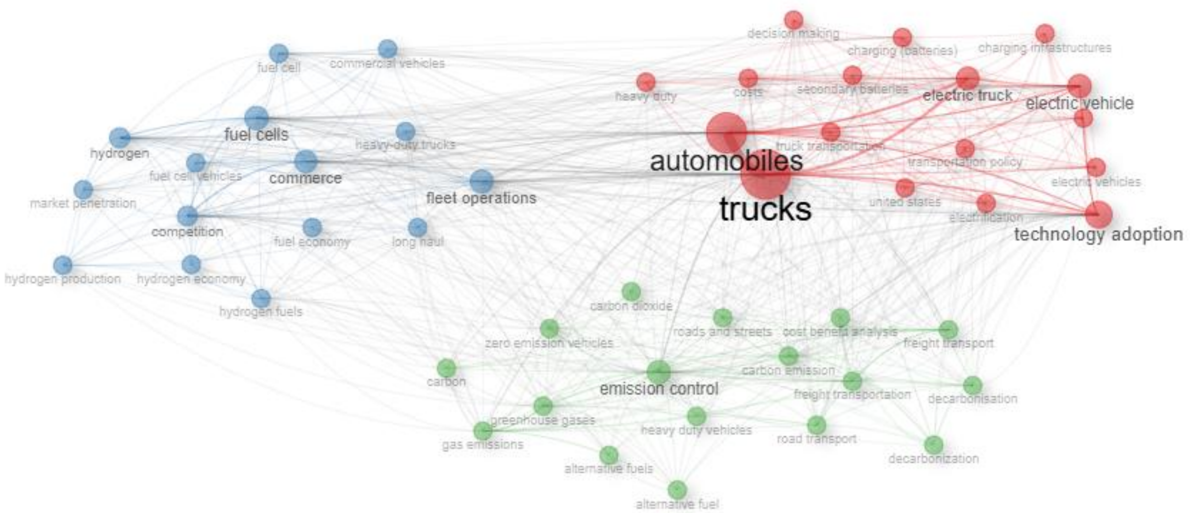
cluster reflects the research dimension related to hydrogen-based propulsion technologies and their potential development in the heavy-duty transport sector.

The second cluster, shown in red, is centered on trucks and automobiles, which are among the most prominent terms in the network. It also includes electric vehicles, electric trucks, technology adoption, charging infrastructure, batteries, costs, and transportation policy. This cluster highlights the technological and adoption dimensions of the transition toward alternative propulsion systems in road transport.

The third cluster, shown in green, focuses mainly on the environmental and decarbonization dimension of heavy-duty transport. Key terms include emission control, carbon emissions, greenhouse gases, CO_2, zero-emission vehicles, alternative fuels, freight transport, and decarbonization. This cluster reflects the environmental objectives underlying the transition toward cleaner road freight technologies.

The strong connections between the three clusters indicate that the literature does not address these dimensions independently. Instead, technological alternatives such as hydrogen, fuel cells, and electric vehicles are closely connected to questions of technology adoption, transport operations, emissions reduction, and decarbonization. Taken together, the network highlights the interdisciplinary structure of research on heavy-duty transport decarbonization, combining technological, economic, policy, and environmental perspectives.

Fig.8 . Co-occurrence Network



Source : Biblioshiny (Bibliometrix)

5 Discussion

The bibliometric findings reveal a rapidly expanding and increasingly interdisciplinary research field focused on the decarbonization of heavy-duty road transport. Although scientific production remained relatively limited during the early years of the observation period, the number of publications increased markedly after 2020, reaching its highest levels in 2024 and 2026. This evolution indicates that the decarbonization of heavy-duty road transport has progressively shifted from a relatively specialized research topic to a major area of investigation within the broader energy and transport transition. The recent acceleration in scientific production is consistent with the growing attention devoted to zero-emission HDV, alternative fuels, vehicle electrification, hydrogen-based technologies, and the infrastructure required to support their large-scale deployment. This growing research interest can be explained by the significant environmental contribution of the freight transport sector. In this context, freight trucks powered by low-emission energy sources, particularly electricity and hydrogen, have attracted increasing scientific attention as potential alternatives to conventional fossil-fuel-powered vehicles (Wanniarachchi et al., 2023).

The citation patterns should nevertheless be interpreted in relation to the age of the publications. The higher citation rates observed for some earlier publication years may reflect not only the influence of these studies but also their longer exposure period within the scientific literature. Older publications have had more time to be discovered, cited, and incorporated into subsequent research, whereas recent publications have had a substantially shorter period in which citations could accumulate. This temporal effect is particularly important in the present study because scientific production has increased considerably in recent years. Consequently, the lower citation rates observed for publications from 2023 onward should not be interpreted as indicating lower scientific relevance or a reduced contribution to the development of the field. Rather, they partly reflect the shorter citation window available to these publications.

Conversely, the relatively high citation rates observed for some earlier years may indicate that certain studies published during these periods have had sufficient time to influence subsequent research, but citation counts alone cannot distinguish between sustained scientific influence and the cumulative advantage associated with publication age. The particularly high average citation rate observed in 2007 should therefore be interpreted with caution, especially given the relatively small number of publications contributing to this value. In the same way, the high citation rate recorded for 2021 should be considered in light of the different exposure periods of publications across the dataset. These findings suggest that citation indicators are more informative when considered alongside publication volume, temporal evolution, and the broader thematic development of the field rather than as standalone measures of research impact.

The contrast between citation accumulation and recent publication growth provides an additional insight into the evolution of the research area. While older studies have accumulated citations over a longer period, the substantial increase in scientific production after 2020 indicates that research activity has expanded rapidly in response to the growing importance of heavy-duty transport decarbonization. The comparatively low citation rates of the most recent publications may therefore coexist with a high level of current scientific activity. This distinction is important when interpreting the development of an emerging research field, as recent publications may contribute to shaping new research directions before sufficient time has elapsed for their scientific influence to become visible through conventional citation indicators.

The distribution of publications across scientific sources further confirms the interdisciplinary character of the field. The coexistence of transport-oriented, energy-oriented, environmental, and policy journals indicates that the decarbonization of heavy-duty transport cannot be addressed from a single disciplinary perspective. Rather, the literature combines transport system analysis, energy systems, environmental assessment, technological innovation, and public policy. This finding is particularly relevant because the transition of HDVs involves simultaneous changes in vehicle technologies, energy supply systems, infrastructure, operating conditions, and regulatory frameworks. Moreover, the development of the future market for HDVs technologies and fuels will depend largely on their economic performance, particularly their relative costs and competitiveness under evolving technological and market conditions (Basma & Rodríguez, 2023). Consequently, the deployment of AFPs, including BETs and FCETs, should be understood as the outcome of interactions between technological, economic, infrastructural, environmental, and policy-related factors.

The geographical distribution of scientific production reveals a strong concentration in the United States, followed by Germany, China, Canada, and the United Kingdom. This concentration may reflect differences in national research capacities, technological development, and policy support for transport decarbonization. The increasing contribution of European and Asian countries also indicates that research on heavy-duty transport decarbonization has become increasingly international and closely linked to national energy-transition strategies.

Germany provides an illustrative example of this interaction between policy, technology, and market development. Despite the fact that 99.7% of newly registered HDVs in Germany were diesel-powered until January 2019, the country has increasingly explored hydrogen and electrification as pathways toward freight decarbonization (Anderhofstadt & Spinler, 2020). Recent research identifies hydrogen as a promising option for heavy-duty applications requiring long driving ranges and high payload capacities, while emphasizing that policy instruments, particularly CO_2-based road tolls and subsidies, are important for supporting the deployment of hydrogen infrastructure (Steinbacher et al., 2026).

China also represents a major research and deployment context because of the scale of its freight transport sector and its strategic position in the global hydrogen economy. China is the world's largest hydrogen producer, accounting for approximately 30% of global production, while its transport sector represents a significant source of national energy consumption and carbon emissions (Tian et al., 2025). HDTs are particularly important in this context, accounting for a substantial share of road freight activity and transport-related emissions. However, China's hydrogen production remains largely dependent on fossil fuels, with renewable sources representing less than 1% of production, highlighting the importance of transitioning toward green hydrogen (Tian et al., 2025).

At the same time, China's “dual-carbon” objectives, abundant renewable-energy resources, and supportive policies are creating favorable conditions for the development of hydrogen fuel-cell heavy-duty vehicles (Cui et al., 2026). In Europe, the decarbonization challenge is equally significant. Transport accounts for almost 30% of total GHG emissions in the European Union, with HDV representing a substantial share of transport-related emissions (O'Connell et al., 2023). Although electrification has progressed rapidly in the light-duty vehicle segment, zero-emission HDVs represented only approximately 1% of new HDV registrations in the EU in 2021, illustrating the greater difficulty of decarbonizing long-haul freight (O'Connell et al., 2023).

Long-distance HDTs and coaches are particularly challenging because of their high energy requirements and intensive operating conditions (Pardhi et al., 2022). In this context, the European transition toward low-carbon mobility, together with the development of green-hydrogen production and distribution infrastructure, provides an important basis for the deployment of hydrogen in heavy-duty transport.

Overall, the geographical distribution of scientific production reflects not only the concentration of research capabilities but also the existence of strong national and regional drivers for heavy-duty transport decarbonization. The cases of Germany, China, and the European Union illustrate that the future development of alternative heavy-duty powertrains depends on the interaction between technological progress, economic competitiveness, infrastructure availability, energy-transition strategies, and public policy.

The keyword co-occurrence analysis provides a deeper interpretation of the structure of this research field. The close connections between the three clusters indicate that the literature is progressively moving beyond a purely technological assessment of alternative powertrains toward a more systemic analysis involving technology adoption, infrastructure, economic competitiveness, and environmental performance.

The prominence of both hydrogen and electric-vehicle-related terms is particularly significant. The literature does not appear to converge on a single technological solution for heavy-duty transport. Instead, it reflects an ongoing comparison between direct electrification through BEV and indirect electrification through hydrogen and fuel-cell technologies. This technological plurality is explained by the specific operational characteristics of heavy-duty freight transport. HDTs have high energy requirements, long-distance operating patterns, payload constraints, and demanding refuelling or charging requirements. Recent studies therefore identify fuel-cell trucks (FCTs) as a potentially relevant solution for long-haul and demanding applications, particularly where battery limitations related to range, charging time, and payload become important.

However, the literature also demonstrates that the environmental superiority of hydrogen cannot be assumed independently of its production pathway. Several studies emphasize that the carbon intensity of hydrogen production is a decisive factor in determining the overall environmental performance of FCTs. Green hydrogen produced through renewable electricity can substantially reduce lifecycle GHG emissions, whereas hydrogen produced through fossil-based pathways may significantly reduce, or even undermine, its expected environmental benefits. Hydrogen should therefore not be considered merely as an alternative vehicle fuel, but rather as an integral component of a broader energy system involving renewable electricity generation, electrolysis, hydrogen production, distribution, refuelling infrastructure, and vehicle operation. From this perspective, the environmental performance of hydrogen-powered HDVs depends strongly on the source and production pathway of the hydrogen. Nan et al. (2025) indicate that, by 2040, hydrogen produced from grid electricity is expected to result in slightly lower emissions than hydrogen produced from coal, while green hydrogen remains the lowest-emission option. These findings reinforce the importance of considering the entire hydrogen value chain when assessing the potential of hydrogen FCETs as a pathway for the decarbonization of heavy-duty road transport.

The economic dimension also emerges as a central component of the literature. The frequent occurrence of terms such as “technology adoption,” “competition,” “commerce,” and “costs” indicates that the research focus has progressively shifted from determining whether alternative technologies can technically operate in heavy-duty applications toward understanding the economic and market conditions under which they can be effectively adopted. Existing studies identify several factors that influence the competitiveness of zero-emission trucks, including vehicle acquisition costs, fuel costs, infrastructure availability, operating performance, and technological progress.

This economic perspective is particularly important because technological potential does not automatically translate into market diffusion. Some studies report favourable economic and environmental outcomes for highly hybridized FCTs powered by green hydrogen, including reductions in total cost of ownership and emissions. Nevertheless, these results remain dependent on assumptions concerning hydrogen prices, renewable electricity availability, infrastructure development, vehicle costs, and technological learning. Consequently, the literature increasingly points toward a transition in which technological deployment depends on the interaction between economic competitiveness, infrastructure development, policy support, and technological maturity.

The strong presence of policy-related terms in the network reinforces this interpretation. Technology adoption in heavy-duty transport is not presented as a purely market-driven process. Regulatory instruments, financial incentives, carbon pricing, road tolls, infrastructure policies, and public investment can influence the relative competitiveness of alternative technologies.

Furthermore, the absence of African countries in the scientific literature highlights the continent’s relative lag in research and development related to the decarbonization of heavy-duty road freight transport. This situation points to the need for greater research attention to African contexts, where the conditions and pathways of decarbonization may differ substantially from those observed in Europe, North America, and Asia.

In this context, countries such as Morocco, which have significant renewable-energy potential and are developing strategies for the energy transition and the reduction of transport-sector emissions, provide a relevant context for investigating the conditions, opportunities, and barriers associated with the decarbonization of heavy-duty road freight transport. Future research should therefore devote greater attention to African countries and examine context-specific decarbonization pathways that account for their technological, economic, infrastructural, and policy characteristics.

6 Conclusion

This study used bibliometric analysis to examine the development of scientific research on decarbonization and technology diffusion in heavy-duty road freight transport. The results show that this research field has expanded significantly, particularly since 2020, reflecting the growing importance of heavy-duty freight decarbonization in the energy and transport transition.

The analysis highlights the interdisciplinary nature of the field. Research is concentrated around three closely connected dimensions : hydrogen and fuel-cell technologies, electrification, batteries, and technology adoption, and emissions, alternative fuels, and freight decarbonization. The co-occurrence analysis indicates that the research agenda is progressively moving from the technical performance of alternative technologies toward broader questions of technology adoption, infrastructure, cost, environmental performance, and policy support.

The findings also show that hydrogen and battery-electric technologies are the two major technological pathways receiving scientific attention, without clear evidence of a single dominant solution for all heavy-duty applications. Their potential diffusion depends on operational requirements, technological maturity, infrastructure availability, energy costs, and policy conditions. Hydrogen research, in particular, is strongly connected to FCVs, hydrogen production, infrastructure, and market penetration, indicating that its development is increasingly considered as part of a wider energy and transport system rather than simply as an alternative vehicle fuel.

Geographically, scientific production remains concentrated in the United States, Europe, and Asia, with countries such as the United States, Germany, and China occupying prominent positions. This concentration contrasts with the relatively limited representation of African countries in the literature. The geographical imbalance suggests that the current research agenda is largely shaped by the technological and policy conditions of developed and major emerging economies.

Overall, the findings indicate that the diffusion of AFPs in heavy-duty road freight is a multidimensional transition involving technology, economics, infrastructure, energy systems, and public policy. The literature increasingly recognizes that technological availability alone is insufficient to ensure diffusion. Future deployment will depend on the interaction between these factors and on the specific conditions of individual freight markets.

This study has several limitations. First, the analysis is based on a specific scientific database and search strategy, consequently, some relevant publications may not have been captured. Second, differences in terminology used to describe HDVs, alternative fuels, electrification, hydrogen, and technology adoption may have influenced the composition of the dataset.

Third, bibliometric indicators measure patterns of scientific production and influence but cannot directly measure the actual commercial diffusion or technological success of AFPs. A high level of research activity around a technology should therefore not be interpreted as evidence of its future market dominance.

The results suggest several priorities for future research. First, further studies should investigate why and under which conditions specific AFPs are adopted by heavy-duty freight operators, rather than focusing only on their technical or environmental performance. Comparative research on battery-electric, hydrogen fuel-cell, hybrid, and other alternative technologies would be particularly valuable.

Second, future research should examine the interaction between vehicle technologies and supporting infrastructure, especially the relationship between hydrogen production, hydrogen refueling networks, electricity generation, charging infrastructure, and freight corridors.

Third, more research is needed on context-specific decarbonization pathways in emerging and developing economies. The limited representation of Africa in the current literature suggests a significant geographical research gap.

Finally, future studies should increasingly use prospective and scenario-based approaches to examine alternative trajectories for heavy-duty freight decarbonization. Rather than assuming that one technology will dominate, such research could compare possible combinations of battery-electric, hydrogen, and other low-carbon technologies under different assumptions regarding energy prices, infrastructure development, technological costs, and policy support. For countries such as Morocco, this could provide a useful basis for examining the possible role and conditions of hydrogen-based heavy-duty freight transport within the broader national energy transition.

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