

Review

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Advancing Efficiency and Sustainability in Road Construction: A Bibliometric Review of Recent Innovations and Challenges

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Review

Advancing Efficiency and Sustainability in Road Construction: A Bibliometric Review of Recent Innovations and Challenges

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Abstract

A This paper presents a comprehensive review of recent advancements and challenges in road construction, focusing on efficiency improvements, digitization, and innovative technologies. The construction industry, particularly the road construction sector, has been identified as one of the least digitized sectors globally, lagging behind other industries in terms of efficiency improvements. To address this issue, researchers have proposed various approaches to enhance road construction processes. Key areas of focus include: Automation and digitization of construction monitoring tasks, including progress tracking, quality control, and quantity analysis; Implementation of Industry 4.0 technologies and Lean-based flow optimization principles. Integration of virtual reality, camera modeling, and artificial intelligence to optimize road construction; Development of cellular automation models to simulate road construction traffic flow in urban networks; Application of artificial neural networks to optimize fuel use in on-road construction equipment; Digitization, BIM-accelerating planning and approval processes. In terms of construction materials and technology-implementation of discrete flow distributors in hydraulic systems for multi-functional road construction machinery; Exploration of alternative materials and stabilization techniques, such as lateritic soils and enzyme-based stabilizers. The review highlights the potential for significant improvements in road construction efficiency, environmental impact, and cost-effectiveness through the adoption of these technologies and methodologies. However, challenges remain in terms of implementation, standardization, and adaptation to specific project requirements. The research indicates a trend towards more efficient, sustainable, and technologically advanced road construction practices, with a focus on overcoming traditional inefficiencies and environmental concerns. Future research should continue to focus on addressing these challenges and developing comprehensive, adaptable solutions for the road construction industry, while leveraging the latest findings in this area.

Keywords: road construction; efficiency; sustainability; environmental impact

1. Introduction

Road construction is a critical area of construction sector, due to its fundamental role in establishing infrastructure helping to grow economy and its impact on society and environment. Roads are essential for economic development as they facilitate logistics: access to markets and providing connections between facilities. Improved road infrastructure can lead to increased GDP and economic performance [35]. The “Belt and Road Initiative” has shown, that infrastructure construction can promote economic growth and improve income distribution along the route, even more so in developing countries [41]. Multiple factors contribute to economic growth: expenditure on road construction supports the private sector with funds, promotes production and stimulates economy. That increases profit and through them increase taxes as well, which boosts government. Access through roads increase property values, and property taxes grow, which enable local

authorities to invest more in infrastructure [33]. Similarly, lack of new developments or delays, overruns on those projects might lead to losses, missed opportunities and degrading of a society [2].

Construction is one of the least digitized sectors, and road construction is particularly lagging behind [12]. While other sectors worked systematically to improve their efficiencies, standardizing processes, automate them where appropriate led to significant improvements in their productivity in past decades. A study was published on implementation of Industry 4.0 technologies and Lean-based flow optimization principles [3]. Advanced project management and modeling techniques [10], use of BIM (Building Information Modeling) enhances overall efficiency [9]. BIM modules can be leveraged to accelerate approval processes [25]. Determining factors of inaccurate estimates – local wishes, defective estimations, long processing times during planning and scope changes, market condition changes and unforeseen conditions- help reducing cost overruns [27]. Thoroughly detailed scheduling on activity level helps developing more realistic schedules and prevent overruns [19]. Transportation of road construction material contributes to cost significantly. Planning routes, decreasing stops, accelerations and idle times reduces cost, and Artificial Neural Networks could be leveraged for optimization [5]. Further optimizing machinery – coordination simultaneously operating machines through hydraulic pumps. Decreasing the number of pumps drives improvement in efficiency [18].

Technological innovation can improve the quality and durability, as well as contributing to lowering the carbon-footprint. Research into new materials like self-healing concrete, prefabricated and recycled plastic roads, and solar roads can lead to more durable and sustainable roadways [38]. These innovations can reduce maintenance costs, increase the lifetime of the road and thus reduce the overall lifecycle costs. Before new technologies are widely implemented, they need to be rigorously tested to minimize risks. Programs like Germany's duraBAST provide a platform for such testing [44]. Road infrastructure and urbanization are interconnected, with road network expansions significantly influencing socio-economic development from urban to rural areas [26].

Road construction has significant environmental impacts, including CO₂ emissions and resource consumption [42]. Research into sustainable construction practices, such as recycling materials and using energy-efficient technologies, is crucial for mitigating these impacts [39]. Comparative lifecycle analyses of construction methods help in understanding the environmental impacts and promoting eco-friendly practices [7]. Incorporating reclaimed asphalt pavement (RAP) and recycled concrete aggregates (RCA) significantly reduces the environmental impact [21] by conserving natural resources and minimizing waste [11] and also studied in earlier paper [14]. Lateritic soil – due to its availability and affordability is one of the most popular building materials in tropical and sub-tropical regions. Binders require most of the energy, thus contributing mostly to cost and also to CO₂ emissions. Using low-energy and alternative pozzolan geopolimer binders for soil/gravel stabilization improves efficiency through cost and carbon emission reduction [28]. While producing pozzolan requires high temperature (1400°C) their alternative binder needs only 100°C. Enzymes used for soil stabilization is also an opportunity [36].

Pulp mill fly ash (PFS) dramatically improves soil strength and stiffness due to its self-cementing properties and that its application minimizes the bioavailability of toxic metals, making it suitable for sustainable construction and reducing industrial waste. The findings suggest that PFA can be effectively implemented as a green binder in road and pavement applications, supporting both ecological and economic benefits [8].

Planning considerations in urban areas also popular areas of research, reducing congestions through certain simulations might be an important consideration [37]. As cities expand their borders forming urban agglomerations with neighboring settlements road development establish the connection between them [40]. The improvement in infrastructure increases the inflow of the population [16]. Smart roads in the 'Smart Age' leverage latest innovations in this area [34].

2. Materials and Methods

Our analysis aims to consolidate the current state-of knowledge of road construction, based on bibliometric analysis of scientific articles published until mid-2025. Similar reviews were published in this topic from a slightly different perspective [1,26,32]. This review focuses on the following questions:

Q1: What is the current state of academic inquiry into road construction efficiency, automation, and digitalization? Which publications, researchers, institutions, and countries are most active in this area, and how are collaborative relationships and research topics interconnected within the scholarly community?

Q2: Which major topics and recurring issues define the scientific studies on efficiency, automation, and digital transformation in road construction? How can these topics be systematically grouped into foundational drivers, essential and interdisciplinary concepts, emerging research directions, and niche or marginal areas within the field?

Q3: Given recent advancements and ongoing developments, which future directions and research opportunities are likely to shape the evolution of road construction efficiency, automation, and digitalization in the coming years?

We used the Preferred Reporting Items for Systematic Reviews (PRISMA) method. Limitations: Web of Science and Scopus were used only as sources. Only English publications were considered. Uneven number of reviewers voted when deciding about articles to include, a team of 3.

Search query used: ALL=(("efficiency" OR "effectiveness" OR "productivity" OR "performance") AND ("sustainability" OR "sustainable" OR "eco-friendly" OR "green") AND ("road construction" OR "road building" OR "pavement" OR "infrastructure") AND ("materials" OR "resources" OR "techniques" OR "methods") AND ("waste reduction" OR "energy efficiency" OR "cost savings" OR "environmental impact")) which had 2097 results. Refined query and further filtered on years of publication for last 10 years. Final query used: ALL=("efficiency" and "road construction" or "high speed road network" or "motorway construction") with 519 results (Figure 1). The final analysis and visualization were performed using R (bibliometrix) and VOSViewer.

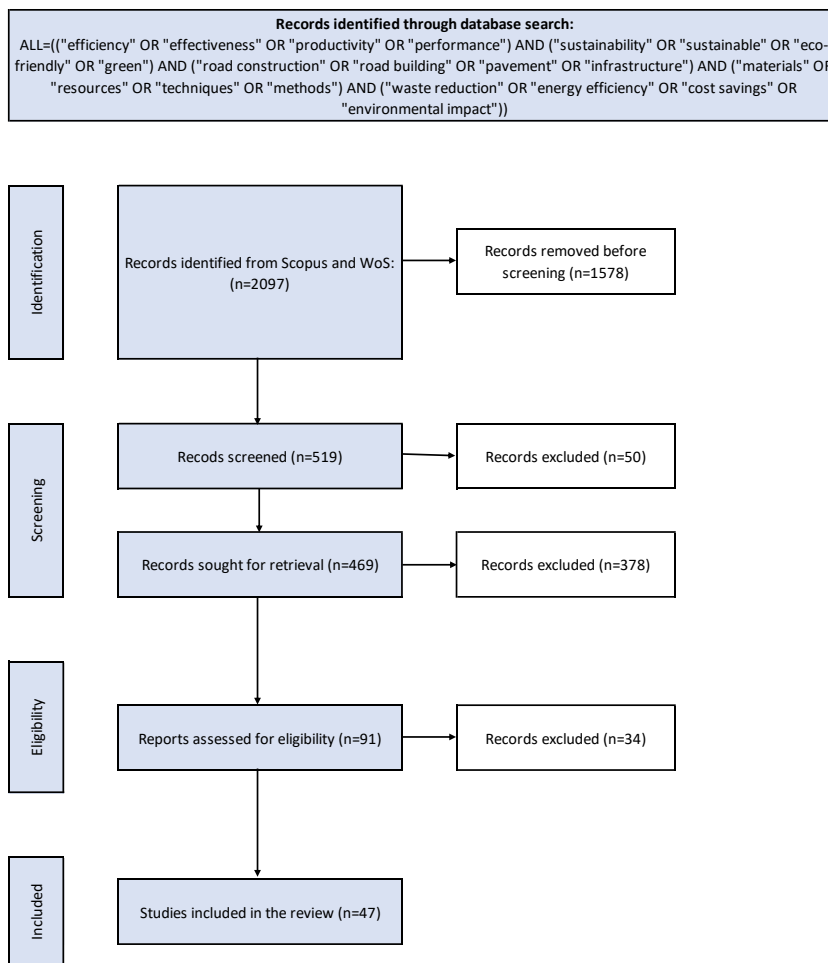


Figure 1. Process of papers selection.

3. Results

Earliest document found was published in 1975. Figure 2 shows the annual production of the articles. Starting to ramp up in the 2010s an average 25-35 per year produced with a peak of 49 in 2016. 2024 was also very productive year with 46 articles. There is a clear growing interest in this area.

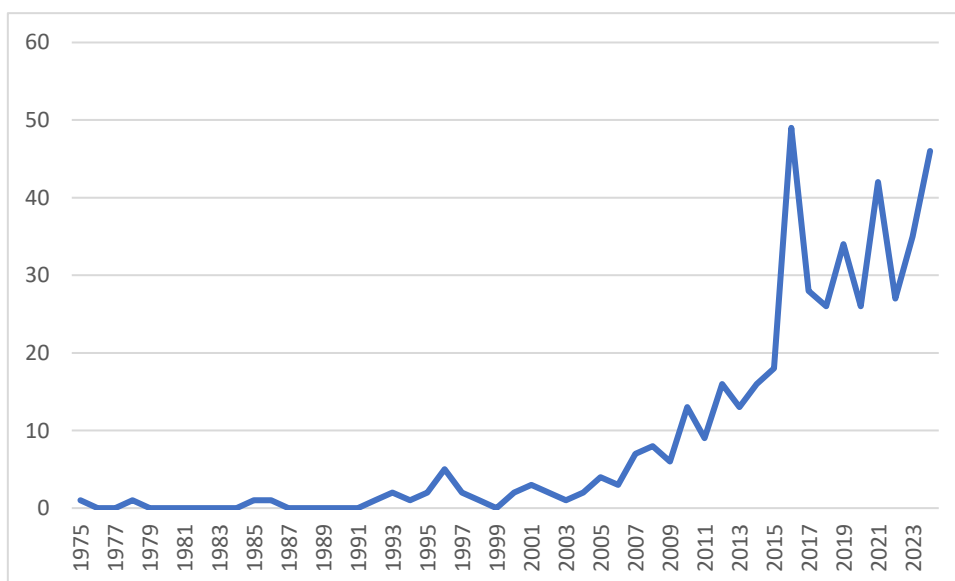


Figure 2. Quantity of annual production on Road construction until 2024 – created using R Bibliometrix.

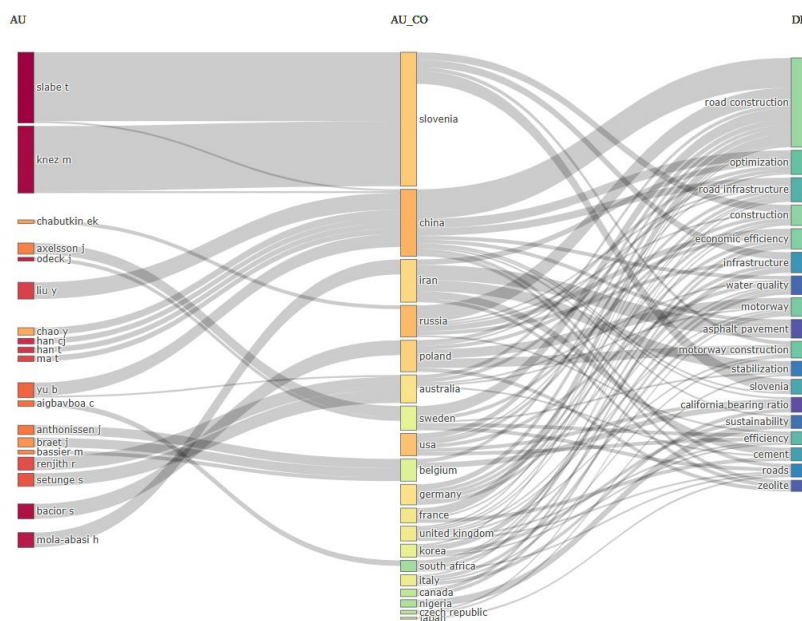


Figure 4. Three-field plot: Authors, keywords and countries – created using R Bibliometrix.

Most relevant author and their countries shown on the Sankey-diagram, (Figure 4.) and related keywords. Dominated by 2 co-authors from Slovenia. It refers to 35 findings out of which 30 belongs to one book, where different chapters referred as standalone publications in the data and 5 more really different articles from different years.

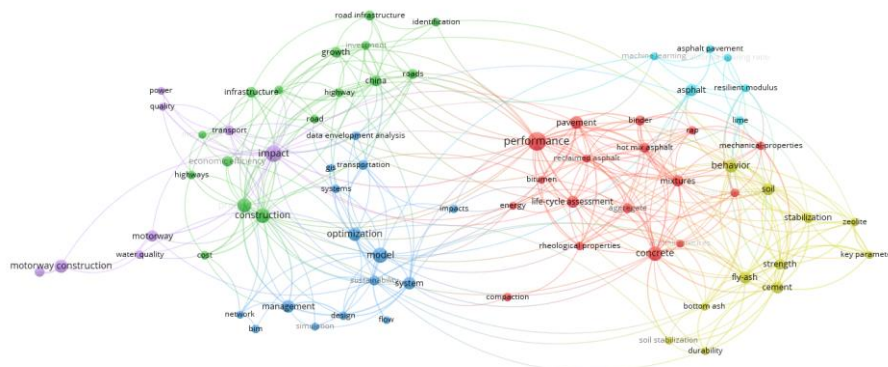


Figure 5. Keywords co-occurrence – created using VOSViewer.

In total 2311 keywords were found and 57 had at least 5 occurrences (5,5%). Road construction and efficiency and their related versions had been removed from the network view, because they were part of the search keywords, and their high occurrence is expected. Removing them helps to illustrate the other keywords better (Figure 5.). Their numbers were: performance (44), impact (32), productivity (30), concrete (28), mixtures (28) and soil (27). They form 6 clusters, have 243 links and the total link strength is 327.

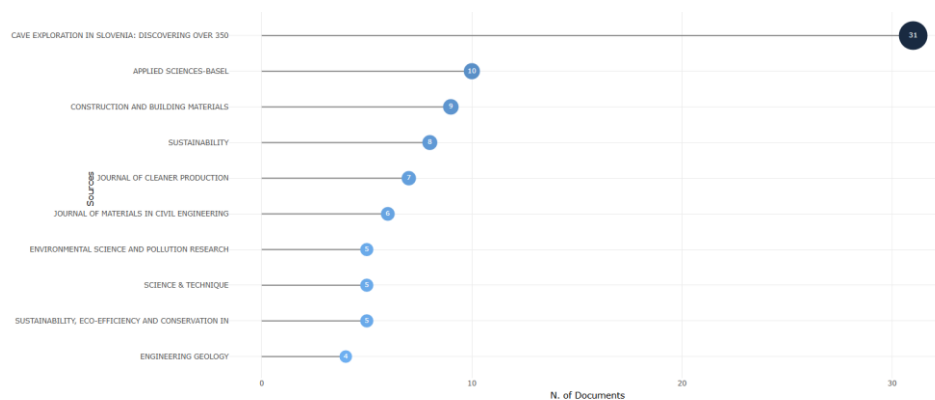


Figure 6. Most relevant Sources– created using R Bibliometrix.

The dominant Slovenian book also leads the most relevant sources' list. However, as mentioned earlier it is a book where the chapters were referred separately. Still a relevant source.

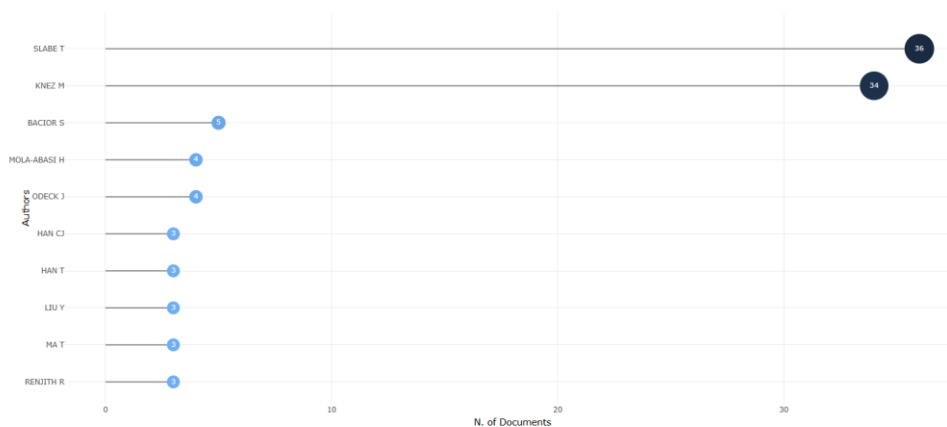


Figure 7. Most relevant authors– created using R Bibliometrix.

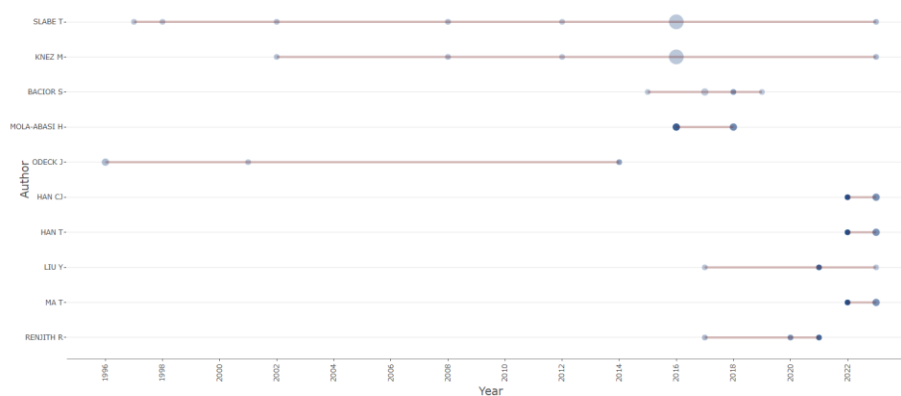


Figure 8. Author's productivity over time – created using R bibliometrix.

Slabe and Knez had been very productive over the years. Even though the most referred publications of theirs related to their book on caves and road constructions on those circumstances, Figure 8 shows their productivity over many years go way beyond the book itself. They are the only authors who have been researching and authoring specialized in road construction for many years, most of their career dedicated. Other researchers had very few in this topic.

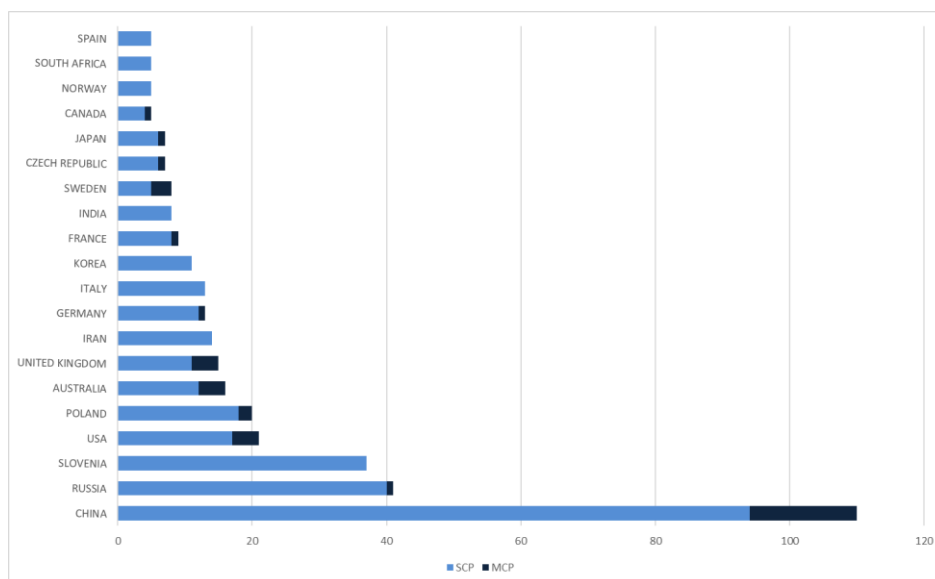


Figure 9. Corresponding author's countries, including single-country (SCP) and multi-country (MCP) publications - created using R bibliometrix.

In the countries' comparison China is most dominant, nearly three times more than the next in line, which is Russia. Slabe and Knez made their country third most productive, more than USA. Majority of the researches are single country; more international research should be encouraged.

Table 1. List of the relevant journals that have been cited mostly.

Journal	Authors	Title	Number of citations	Category
SUSTAINABLE CITIES AND SOCIETY	(Xiao et al., 2022) [45]	Exploring the coupling coordination and key factors between urbanization and land use efficiency in ecologically sensitive areas: A case study of the Loess Plateau, China	97	Management
JOURNAL OF CLEANER PRODUCTION	(Bamigboye et al., 2021) [4]	Waste materials in highway applications: An overview on generation and utilization implications on sustainability	93	Innovative materials
CONSTRUCTION AND BUILDING MATERIALS	(Zentar et al., 2021) [46]	Comparative study of stabilization/solidification of dredged sediments with ordinary Port-land cement and calcium sulfo-aluminate cement in the framework of valorization in road construction material	88	Innovative materials
WASTE MANAGEMENT	(Pecqueur et al., 2001) [31]	Behaviour of cement-treated MSWI bottom ash	84	Innovative materials
JOURNAL OF PUBLIC ECONOMICS	(Marion, 2007) [24]	Are bid preferences benign? The effect of small business subsidies in highway procurement auctions	82	Management
ENGINEERING GEOLOGY	(Obuzor et al., 2012) [29]	Soil stabilisation with lime-activated-GGBS-A mitigation to flooding effects on road structural layers/embankments constructed on floodplains	80	Innovative materials
JOURNAL OF CLEANER PRODUCTION	(Mah et al., 2018) [22]	Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia	76	Innovative materials

CONSTRUCTION AND BUILDING MATERIALS	(Fang et al., 2021)[13]	Comprehensive re-view on the application of bio-rejuvenator in the regeneration of waste asphalt materials	75	Innovative materials
CEMENT & CONCRETE COMPOSITES	(Zhao et al., 2018) [47]	Use of uncontaminated marine sediments in mortar and concrete by partial substitution of cement	70	Innovative materials

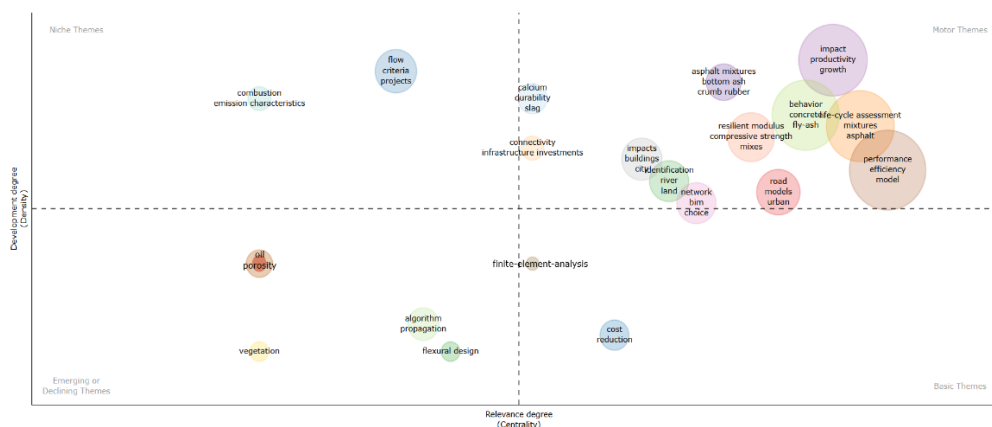


Figure 11. Thematic Map created using R bibliometrix.

The thematic map generated from bibliometric analysis divides the research landscape of road construction into four principal quadrants based on development and relevance. Motor themes, located in the upper right quadrant, encompass well-developed and highly central topics such as impact, productivity, growth, performance efficiency, and advanced asphalt mixtures. These themes reflect the current focus on innovative materials (bottom ash, fly ash, crumb rubber, compressive strength mixes), optimizing construction processes, integrating digital technologies (BIM), and enhancing sustainability through lifecycle and performance models. Niche themes, positioned in the upper left quadrant, include specialized topics like flow criteria and emission characteristics. These areas, while technically advanced, are less central to the broader field, indicating their specialized application or limited interdisciplinary connectivity. Emerging or declining themes, found in the lower left quadrant, are characterized by low development and marginal relevance. Topics such as vegetation, algorithmic propagation, and flexural design may represent either nascent research fronts or areas losing prominence. Basic themes, in the lower right quadrant, are foundational yet underdeveloped, including asphalt mixtures, recycled materials, resilient modulus, and cost reduction strategies. These themes are widely connected and represent essential research domains that require further exploration and technological advancement.

Findings of most relevant papers

The researches of the most relevant papers focused on multiple areas: use of innovative materials (binders, stabilizers), management (accelerations, efficiencies, optimizations), digitization (BIM, drones/optical recognition), other innovations (smart cities/smart roads, smart design). The most cited ones are mostly from innovative/waste material researches.

Innovative materials

This is the most interesting topic in terms of number of citations: 8 out of top 10 cited articles belong here. Binders, soil stabilizers, cement alternatives and use of waste materials from other industries like fly ash or bottom ash. Xantan Gum (XG) was used as stabilizer for road shoulders in a Sri Lanka construction case [20]. They compared it with conventional cement, fly ash and bottom ash blended binders as well. After slightly longer curing time (28 days) XG treated soil had remarkably higher unconfined compressive strength (UCS) and also higher ductility. Use of waste materials was compared by [4] in a review paper. They compared of PET (plastic bottles), waste rubber or crumb rubber (CR) which is ELT (end-of-life tires), steel slag, glass waste, construction and demolition waste

(C and D), recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), colliery spoils (CS), fly-ash (FA) which is a byproduct of coal combustion, cement kiln dust (CKD), aluminium dross, mine tailings, bio-oils (from agricultural and organic wastes) and incineration bottom ash (incineration of solid wastes). In their results PET, CR, RAP, RAS, steel slag and bio-oils were used in asphalt layers, all others were used for ground improving or in the sub layers of the pavement. C and D wastes were very efficient in landfills. These utilization of waste materials can lead to improvements in recycling rates, while effectively reducing land requirements for landfills, preserves natural aggregates against depletion and reduce cost significantly. It was also noted that waste materials must be carefully tested and free from hazardous matter to prevent the environment [4]. Incineration bottom ash of municipal solid waste incinerator (MSWI) was studied more in more details by [31]. Significant concern around using MSWI as a binder is its expansion which results in cracks and road destruction. The study identified the root cause which is the oxidation of metallic aluminium. It's difficult to extract the non-ferrous metals from the ash one solution might be treating it with cements. Portland cement can reduce expansion by 70% they found.

Alternative cement (Calcium Sulfo Aluminate - CSA) was compared to Ordinary Portland Cement (OPC) by [46]. CSA is green, low carbon and environmentally friendly: limestone demand is 35-40% lower than OPC, and production temperature is 200°C lower, which results in 33% lower CO₂ emission, while its nearly as strong: compressing strength could be reached by CSA is 78-98% that of using OPC.

The performance of three-layer reinforced concrete plate constructions was performed by [6], analyzing their load-bearing capacity, crack resistance, and deformation with varying reinforcement percentages and concrete grades. They found, that reducing the structural weight by using a lightweight, self-sealing expanded clay concrete middle layer can significantly improve energy efficiency and economic benefits. Experimentally tested 16 plate samples to show how factors like concrete grade and reinforcement affect their strength and durability, aiming to optimize construction materials for transport buildings and road construction.

Composite cationic bituminous structures, a novel material offering several advantages over traditional hot and cold asphalt paving was studied [43], such as usability in various weather conditions, reduced bitumen usage, quicker road reopening, and enhanced durability. The study develops price formation schemes and estimated specifications for road works with this technology, demonstrating significant economic and ecological benefits, including cost reductions and more durable road surfaces compared to conventional methods. The findings highlight the potential of this composite technology to improve working efficiency and environmental impact in road repair projects.

Management

SoS –System-of-systems concept had been studied for improved road construction by [3]. According to their findings, on-site execution and coordination such as improved planning, communication, analytics based on IoT (Internet of Things), use of BIM (Building Information Management) could raise productivity by 20-25%. Potential waste reduction, improvement in machine movements resulting in reducing fuel consumption can save some 31%. The application of SoS could be mostly applied in the planning phase. Detailed activity-based scheduling model was developed by [19]. Matlab algorithms (DADER and DP) were used during planning of the construction. The duration of the project without applying the model was 3913 days and with the model it was reduced to 2431days. Total cost remained nearly identical, but the acceleration is significant – down to 60%. Further schedule optimization is possible through accelerating approvals [25]. In their quantitative study Common Data Environment (CDE) as a digital platform was compared to conventional methods. Using CDE was considered to have high value added, especially in terms of transparency and traceability which were identified as most concerning in the conventional methods. Implementation of CDE cross-country and public participation is a future research topic, use of BIM might be an opportunity. Promising added values in planning and approval processes were predicted in this context.

A novel hybrid approach combining egalitarian bargaining game theory, data envelopment analysis (DEA), and sustainable network design to evaluate, select, and schedule urban road construction projects, with an application to the Isfahan city network. The proposed model integrates sustainability (economic, social, and environmental aspects) and controls undesirable shocks in network performance across multiple periods, using a meta-heuristic genetic algorithm to efficiently solve large-scale instances. Results from both simulated and real-world cases demonstrate that the method enhances network efficiency, sustainability, and stability while optimizing project selection and timing within technical and financial constraints [23].

An evaluation method was developed for municipal road construction quality that incorporates carbon emissions to ensure environmentally friendly construction [15]. This method uses an improved genetic algorithm (GA) combined with a spanning tree constraint approach to optimize the assessment of road construction flow parameters, considering factors like material quality and environmental impact. Experimental results demonstrate that this method is accurate, reliable, and achieves lower carbon footprints compared to existing methods, aligning with the priority of environmental protection in infrastructure development

For cost reduction in planning fuel consumption might be an improvement area identified by [5]. They developed a model using artificial neural networks focusing on optimal driving speed, route and also on road conditions. Mitigating idle time and reducing the number of stops also contribute to reducing fuel consumption.

Digitization

Research interest for BIM, 3D models, use of GPS, UAVs (Unmanned Aerial Vehicles) - drones had been in past 5 years. Significant challenge for implementing digitization and computerization is the high costs and long-term investment particularly in small and medium companies, and in developing countries [32]. RTK drone survey was used to quickly and homogeneously determine the amount of earthwork [12]. Data was collected through the survey and tracking was performed in BIM. While through this study the process worked well and results were accurate, it was noted that the availability of available data (3D IFC databases) and terrain obstacles such as water and vegetation might impact negatively the effectiveness of the method. Data collection is possible on the ground as well using UGVs (Unmanned Ground Vehicles). Pavement layer change classifier measures pavement construction progress automatically [30]. In their study the UGV was equipped with a laser distance sensor, accelerometer, gyroscope and GPS sensor. The authors selected various scenarios and different sensors and algorithms to compare and select the best combination. The best combinations' highest accuracy was 97.88%. This real-time automated monitoring can help companies to move from tedious and time-consuming manual methods.

Other important considerations

Beyond these major categories road maintenance, pollution management was the main focus of the Slovenian authors Slabe and Knez. Runoff monitoring from Slovenian motorways has shown persistent contamination, with seasonal peaks of salts in winter and heavy metals in summer, playing a key role in pollutant wash-off. These results led to the construction of treatment facilities, though their efficiency depends on proper maintenance and flow conditions. In karst regions, where runoff directly affects drinking water sources, systematic monitoring and protection measures are critical. Motorway construction also advanced karstological knowledge, uncovering numerous caves and geomorphological features that deepen understanding of karst development and heritage.

Green road construction practices in Ghana were analysed [17], using a quantitative approach and structural equation modeling (SEM) to identify four key components: sustainable design, materials and resources, stormwater management, and energy efficiency. Results reveal stormwater management as the most significant component, followed by the use of locally sourced materials and energy efficiency measures, with sustainable design focusing on educating workers about environmental hazards. The findings provide a framework for stakeholders to implement sustainable road construction practices, contributing valuable empirical evidence to the literature on green infrastructure in developing countries.

4. Discussion

The comprehensive bibliometric review and analysis of recent scholarly articles identify significant opportunities to enhance efficiency, sustainability, and cost-effectiveness in road construction. There is an evident trend toward adopting alternative, recycled, and bio-based materials across the literature. These materials contribute to lowering the overall carbon footprint by extending the lifecycle of roads, utilizing locally sourced materials to minimize transportation-related emissions, and turning waste into valuable construction inputs. Such innovations not only conserve scarce natural resources but also promote environmentally responsible construction practices that align with global sustainability goals.

Digital transformation emerges as a critical enabler of improved road construction productivity. Technologies such as Building Information Modeling (BIM), advanced scheduling models, and intelligent monitoring systems including drones and unmanned ground vehicles (UGVs) hold promise for productivity increments of up to 20-25%. Artificial Intelligence (AI) applications, particularly in optimizing fuel and resource consumption, integrate seamlessly with these digital tools, reinforcing sustainability while enhancing operational efficiencies. However, broad adoption of these technologies is often hindered by high upfront costs, lack of standardization, and challenges unique to specific geographic and organizational contexts. Small and medium enterprises (SMEs), especially in developing regions, face pronounced barriers that impede their ability to leverage these advancements, underscoring an urgent need for accessible, scalable solutions.

The management of road construction projects benefits substantially from integrated approaches combining lean principles, Industry 4.0, and system-of-systems methodologies. Enhanced planning, communication, and real-time analytics can reduce waste, improve machine coordination, and shorten project durations without increasing costs. The application of hybrid analytical models incorporating sustainability dimensions reveals that economic, social, and environmental factors can be harmonized for resilient and efficient road network development. Concurrently, innovations in material science—from bio-rejuvenators and self-healing concretes to novel binders and composites—demonstrate potential for improving road durability, reducing maintenance cycles, and mitigating environmental impacts.

Despite these promising insights, critical implementation challenges persist. These include the need for rigorous testing and standardization of innovative materials and technologies to ensure reliability and safety, and the development of comprehensive, adaptable guidelines that accommodate diverse project contexts. Additionally, greater international collaboration and knowledge exchange are necessary to bridge gaps between research and practice, particularly in regions where infrastructure development is rapidly expanding but access to cutting-edge technologies remains limited.

Future Research Agenda

Building on the findings, the future research agenda in road construction should encompass several prioritized dimensions:

Standardization and Validation of Innovative Materials and Technologies: There is a clear need for robust, standardized testing protocols and performance benchmarks addressing the long-term behavior of alternative materials, bio-based stabilizers, and digital construction technologies under diverse environmental and operational conditions.

Affordable Digital Solutions for SMEs: Research should focus on developing cost-effective, modular digital and AI-driven tools tailored to the resource constraints of SMEs, emphasizing ease of integration, scalability, and impact on productivity and sustainability.

Cross-disciplinary and International Collaboration: Encouraging collaborative, multi-institutional studies that bring together expertise from civil engineering, materials science, computer science, environmental science, and economics will foster holistic solutions. Particular attention is needed to include developing country perspectives and customize innovations accordingly.

Lifecycle and Circular Economy Models: Advancing comprehensive lifecycle assessment methods and circular economy frameworks tailored for road construction materials and processes

will enable quantification of environmental impacts and identification of trade-offs, supporting decision-making for sustainable infrastructure.

Policy and Socioeconomic Impact Studies: Investigations into the wider economic, social, and regulatory effects of adopting new road construction paradigms—including urbanization impacts, labor market influences, and legal frameworks—will help align technological gains with societal benefits.

Smart Infrastructure and Resilience: Further exploration of smart road systems leveraging Internet of Things (IoT), sensor networks, and real-time data analytics can enhance infrastructure resilience, maintenance, and user safety. Research should address the integration challenges and environmental footprints of such systems.

Adaptive Project Management Methodologies: There is opportunity for research into innovative project management approaches that incorporate uncertainty, variability in material performance, and dynamic stakeholder needs, utilizing advanced modeling and optimization techniques.

By addressing these agenda items through targeted research efforts, the road construction field can accelerate its transformation toward more efficient, environmentally responsible, and economically viable infrastructure development globally.

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