Investigating the Use of Recycled Materials and Smart Technologies for the Future of Road Construction.

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ABSTRACT

The study presented here addresses the pressing need for sustainable solutions in the pavement industry amid concerns about greenhouse gas emissions, global warming, and the quest for renewable resources. While there is a growing interest in low-carbon asphalt pavement, a significant knowledge gap exists regarding the utilization of various waste materials and technologies to achieve this objective. To bridge this gap, we conducted a systematic review and scientometric assessment covering the period from 2008 to 2023, employing the VOS viewer application for analysis. Our study identifies key materials and technologies in this domain by examining co-authored country studies, publication sources, and keyword co-occurrence. It's worth noting that while we analyzed a limited number of waste materials allowing CO2 emissions reduction, other waste categories like bio-oils and polymers, with potential positive environmental or economic impacts, were not within the scope of our study. Our findings indicate that integrating recycled waste materials such as recycled asphalt pavement, biochar, or crumb rubber, along with alternative mixing technologies like warm mix asphalt and cleaner energy sources, can significantly mitigate CO2 emissions. Notably, China and the United States emerged as major contributors to research in low-carbon pavement solutions. Additionally, biomass-based fuel and electric construction equipment have shown promise in substantially reducing carbon and greenhouse gas emissions. However, several challenges must be addressed before widespread adoption of recycled waste materials and technologies in the asphalt industry. These include concerns over cost, performance, and durability, as well as issues related to standardization, regulations, availability, integration with existing infrastructure, and insufficient field and long-term data. Our review identifies critical research gaps, such as the lack of a standardized method for low-carbon asphalt pavement, limited field performance data, and the need for a comprehensive life cycle assessment approach to analyze emission reduction effects. Addressing these gaps will be crucial for facilitating a paradigm shift towards a more environmentally friendly pavement industry that embraces recycled waste materials and technologies. In conclusion, our study provides valuable insights into the current state of research on low-carbon asphalt pavement, highlighting both the potential benefits and the challenges associated with integrating recycled waste materials and technologies. This information will be instrumental in driving forward efforts to create a more sustainable and carbon-friendly pavement industry.

Keyword: - *recycled waste materials; CO2 emission; low-carbon road; waste materials; environmental impact* 1. Introduction

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The issue of global warming, exacerbated by greenhouse gas emissions such as carbon dioxide, poses a significant threat to the environment. To combat this, countries worldwide have committed to reducing emissions, with many aiming for net-zero emissions by 2050. This concerted effort underscores the global commitment to addressing environmental concerns and transitioning towards a more sustainable future. Achieving net-zero emissions is crucial for mitigating global warming and preventing further environmental degradation. In recent years, there has been a growing recognition, both in academia and industry, of the importance of adopting a holistic approach to sustainability management. This approach considers environmental, economic, and social factors, reflecting the interconnectedness of these aspects in sustainable development. In the context of road construction, integrating sustainability criteria is

essential for supporting national growth and development by providing access to essential facilities and promoting eco-friendly practices. Asphalt pavement, due to its durability, affordability, and versatility, is widely used as a road pavement material globally. However, conventional asphalt production and use have significant environmental consequences, including greenhouse gas emissions, air pollution, and depletion of natural resources. To address these issues, there is a growing emphasis on utilizing recycled waste materials and implementing new recycling techniques in asphalt pavement construction. These sustainable practices encompass a broader range of materials, including recycled, bio-based, and industrial byproducts, such as fly ash and slag. Moreover, advancements in materials science have led to the development of novel sustainable materials, such as geopolymer additives and carbon-neutral materials. Despite the widespread use of concrete and asphalt in pavement construction, these materials have been found to have adverse environmental effects, contributing to issues such as greenhouse gas emissions and pollution. Additionally, traditional asphalt pavement faces challenges such as cracking, rutting, and deformation, necessitating regular maintenance and repairs. Moreover, conventional asphalt production can be costly and reliant on scarce natural resources, further highlighting the need for sustainable alternatives.

The adoption of sustainable asphalt pavement practices offers several advantages, including environmental protection, cost-effectiveness, performance enhancement, and social responsibility. By minimizing negative environmental impacts, reducing long-term costs, and improving durability, sustainable practices contribute to a more environmentally friendly and economically viable transportation infrastructure. Moreover, sustainable pavements can help reduce greenhouse gas emissions associated with road construction and maintenance, thereby promoting conservation-oriented development. In conclusion, sustainable asphalt pavement practices play a crucial role in addressing environmental concerns and promoting sustainable development in the pavement industry. By incorporating recycled waste materials and adopting innovative technologies, it is possible to reduce carbon emissions, conserve natural resources, and enhance the overall sustainability of road infrastructure. This review aims to provide a comprehensive overview of the literature on sustainable pavement practices, identifying gaps and challenges and offering insights for future research in this field.

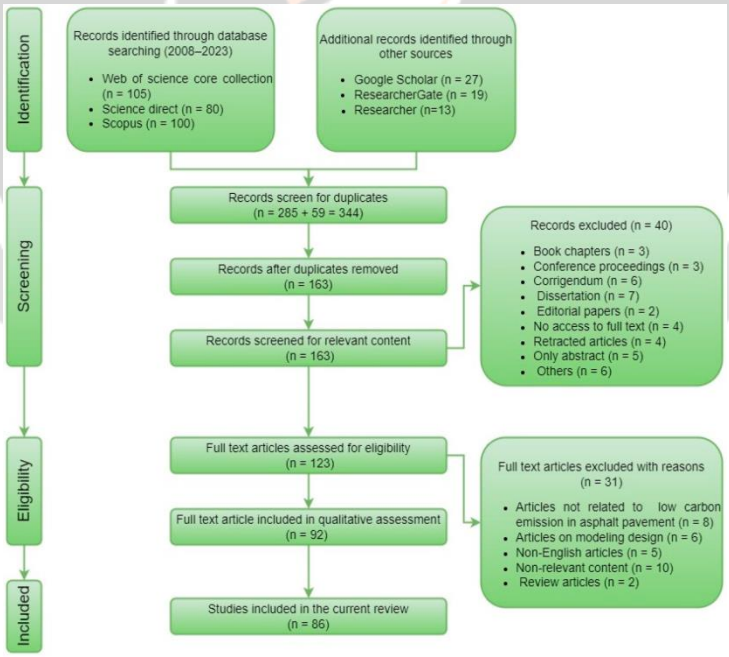

Figure 1. Study PRISMA workflow for article selection.

The methodology employed in this study integrates a systematic literature review with scientometric analysis to comprehensively assess the sustainable use of waste materials and technology for low carbon emissions in the asphalt

pavement industry. The systematic review, conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach, allows for a structured analysis of existing literature on the subject. Meanwhile, the scientometric analysis, facilitated by the VOS viewer software, offers a quantitative evaluation of the significance and impact of the literature under consideration. This combined approach enhances the accuracy of assessing the research area and evaluating scientific development.

The systematic literature review commenced with the development of well-defined research questions to ensure focus and relevance. The PRISMA framework guided the review process, promoting transparency and repeatability. The study aimed to evaluate recycled waste materials and technology for low-carbon-emission asphalt pavement production, comparing their performance and durability to traditional materials while also examining policies promoting eco-friendly alternatives. A thorough search strategy was employed, utilizing reputable repositories such as Web of Science, ScienceDirect, and Scopus, supplemented by additional sources like ResearchGate and Google Scholar. Relevant articles were identified using specific keywords, and duplicates were removed to ensure data integrity. Following the initial screening, a total of 86 articles meeting the inclusion criteria were identified for further analysis. These articles were then subjected to detailed scrutiny and analysis using Microsoft Excel and Open Refine software. The collected data were tabulated and analyzed to extract meaningful insights, facilitating a qualitative assessment of the literature. Through this process, the study identified a growing trend in research focusing on the use of recycled waste materials and technology for low-carbon-emission asphalt pavement production.

2. Methdology

The scientometric analysis, facilitated by the VOS viewer software, provided a quantitative evaluation of the collected data. This involved analyzing various parameters such as country contributions, author keyword co-occurrences, referenced sources co-citation, and publication sources. By visually representing the data in network maps, the scientometric analysis allowed for a comprehensive understanding of the research landscape and key trends in the field. Figure 2 illustrates the flowchart for the scientometric analysis approach, highlighting the systematic process employed to evaluate the literature.

The integration of qualitative and quantitative analysis methodologies enabled a holistic assessment of the research area. By combining the insights gained from the systematic literature review with the quantitative findings of the scientometric analysis, the study was able to provide a comprehensive summary of the current state of research on the sustainable use of waste materials and technology in asphalt pavement production. This approach not only facilitated the identification of research gaps and areas for further investigation but also highlighted the significance of policies promoting eco-friendly alternatives in the pavement industry.

Overall, the methodology outlined in this study represents a robust and systematic approach to evaluating research in the field of sustainable asphalt pavement production. By employing a combination of qualitative and quantitative analysis techniques, the study was able to provide valuable insights into current research trends, key contributors, and areas for future exploration.

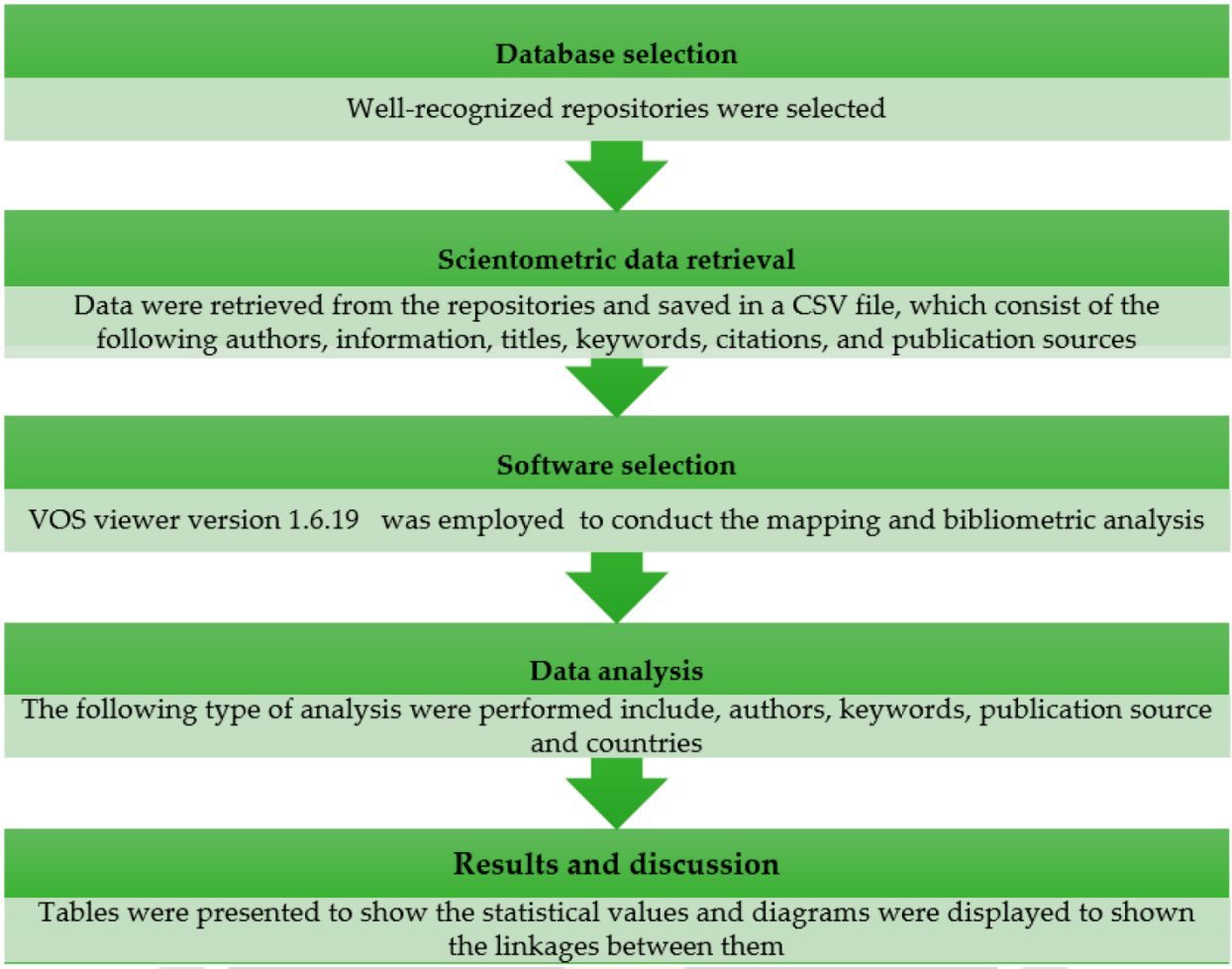

Figure 2. Flowchart for the VOS viewer scientometric methodology.

3. Results and discussion

The methodology outlined in Figure 2 provides a systematic approach for conducting scientometric analysis on the topic of recycled waste materials and technology for low-carbon-emission asphalt pavement. By employing Excel sheets, the annual publication pattern from 2008 to 2023 was plotted and assessed. Notably, there has been a consistent increase in attention to this area, which can be attributed to technological advancements and a growing interest in reducing carbon emissions in asphalt pavement. This trend aligns with global initiatives aimed at achieving net-zero greenhouse gas emissions by 2050 [1]. The annual publication rate has shown a steady rise, with 9 articles in 2020, 11 in 2021, and 13 in 2022, as depicted in Figure 3. Additionally, Figure 4 highlights the major countries contributing to this field, with China, the United States, and Italy leading in terms of publications. This is likely influenced by their status as major carbon emitters, as well as their focus on sustainable development and renewable energy. Moreover, the analysis delved into the types of publications available on sustainable and low-carbon-emission asphalt pavement. Journal articles were found to be the primary source of information, accounting for 59% of all publications, followed by conference papers at 22%. This suggests that academic journals and conferences serve as vital platforms for disseminating research findings and exchanging ideas in this domain. However, there appears to be a limited number of comprehensive reviews and book chapters on the subject, indicating potential areas for further research and analysis. This descriptive assessment provides valuable insights into the research landscape and the dissemination channels used in this field. Moving on to the quantitative scientometric analysis, the VOS viewer was employed to evaluate scientific publication features such as authors' keywords, publication sources, and publication countries. Keyword co-occurrence analysis revealed significant terms in the research domain, with "carbon footprint," "sustainable

development," "recycling," "sustainability," and "environmental impact" being among the most frequently used terms. This reflects the overarching goal of achieving low-carbon emission and sustainability in asphalt pavement through the exploration of various recycled waste materials and technologies. Figure 6 visually represents these keyword co-occurrences, highlighting the prevalence and interconnections between different terms. Additionally, the color-coded clustering demonstrates the thematic associations and relative importance of various keywords in the research literature. Further analysis focused on the countries contributing significantly to research on sustainable and low-carbon-emission asphalt pavement. China, the United States, Italy, and Spain emerged as the main contributors, with their efforts driven by a commitment to sustainability, investments in renewable energy, and initiatives promoting green transportation infrastructure. The impact of these countries' research is evidenced by their citation counts and influence within the field, as illustrated in Figure 7. This network visualization provides a clear representation of the collaborative links and knowledge exchange among different countries, aiding researchers and policymakers in identifying key stakeholders and potential collaborators. Lastly, the study examined the sources of publication in this field, identifying leading journals such as the "Journal of Cleaner Production" and "Construction and Building Materials." These journals have played a pivotal role in shaping the research landscape and facilitating knowledge dissemination on sustainable and low-carbon-emission asphalt pavement. Figure 8 provides a visual mapping of publication sources based on their influence and co-citation patterns, highlighting the prominent position of certain journals within the research community. Overall, this comprehensive analysis offers valuable insights into the research trends, key contributors, and dissemination channels in the field of sustainable and low-carbon-emission asphalt pavement, laying the groundwork for future studies and collaborations.

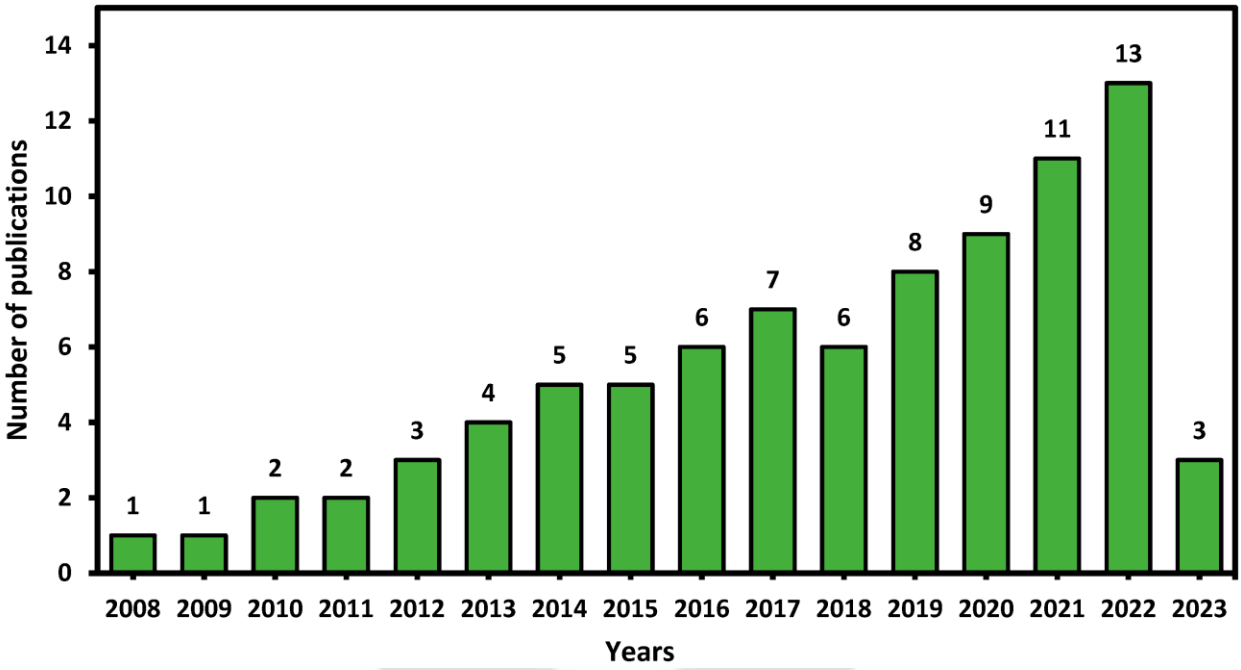

Figure 3. Yearly publication of articles on recycled waste materials and technology for low-carbon-emission asphalt pavement with a total of 86 publications considered for the years 2008 to 2023.

4. Recycled Waste Materials and Technology for Low-Carbon Emission in the Asphalt Pavement

he construction of pavement holds immense significance, particularly as populations grow, yet it's also associated with depletion of raw resources and environmental repercussions. Incorporating low-carbon technologies in pavement construction, especially for materials like asphalt binder and aggregates, is crucial due to their significant contribution to greenhouse gas emissions. The emphasis is on reducing emissions during the production phase by using materials with lower emission factors and overall material use reduction. This necessitates the application of low-carbon-emitting recycled waste materials and technologies in asphalt pavement construction, aligning with sustainable development goals. Waste and reprocessed materials play a pivotal role in reducing carbon emissions in pavement construction. By utilizing various waste materials such as agricultural waste, construction and demolition waste, industrial waste products, and municipal solid waste, the environmental impact of asphalt pavement can be

significantly reduced. For instance, biochar-based materials derived from renewable resources like vegetable oil and biomass can serve as alternative asphalt binders or admixtures, offering both durability enhancement and carbon reduction potential. Palm oil waste, crumb rubber from used tires, and recycled asphalt materials like reclaimed asphalt pavement (RAP) also offer viable alternatives, each contributing to lowering carbon emissions in asphalt pavement construction. The use of these recycled materials not only decreases the demand for natural resources but also reduces the environmental impact of disposal, thus promoting sustainability.

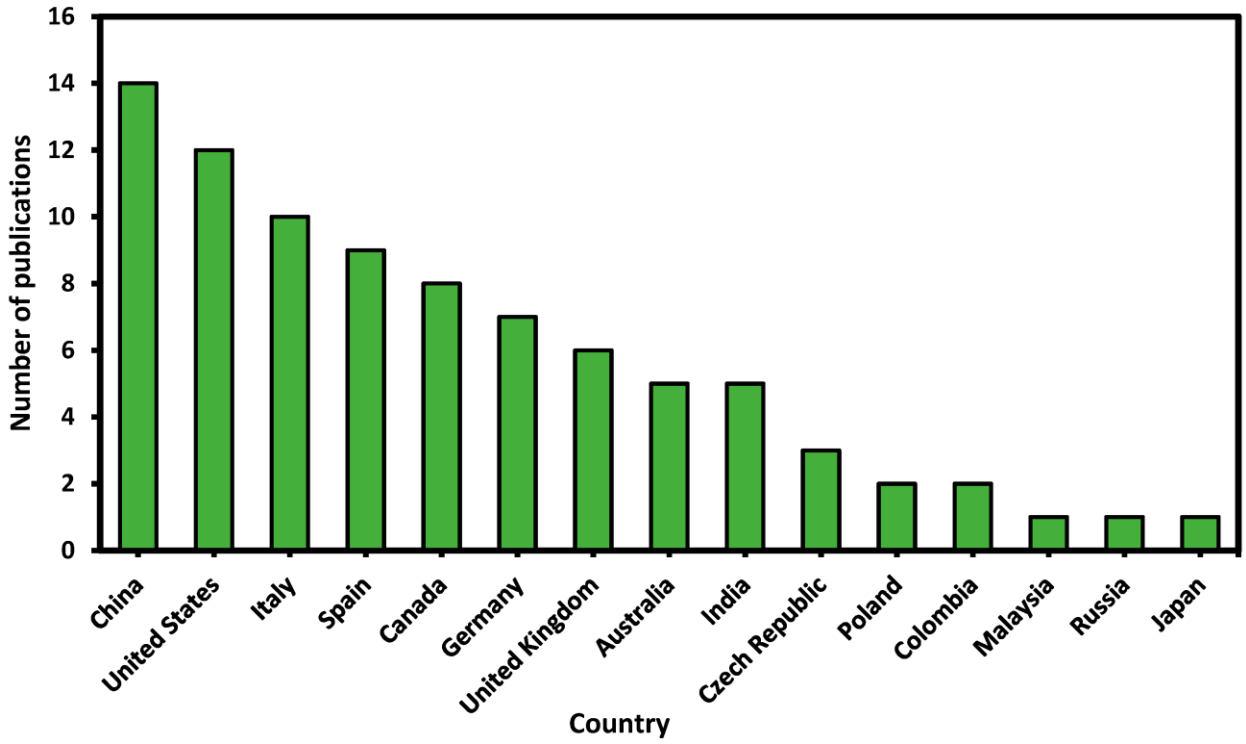

Figure 4. Published articles per country on recycled waste materials and technology for low-carbon asphalt pavement.

Mixing and production technologies such as Warm Mix Asphalt (WMA), Cold Mix Asphalt (CMA), and cold recycling further contribute to carbon emission reduction. WMA, with its lower production temperatures, offers significant environmental benefits over conventional Hot Mix Asphalt (HMA), while CMA, produced at much lower temperatures, reduces energy consumption and emissions during production and placing stages. Cold recycling techniques, including cold in-place recycling and cold central plant recycling, minimize energy consumption and emissions associated with asphalt pavement construction. Energy-saving and reduction technologies, such as utilizing renewable energy sources and optimizing energy consumption during the production process, play a crucial role in reducing carbon emissions in asphalt pavement construction. Techniques like energy substitution and material heating processes also contribute to lowering emissions, with the adoption of emerging technologies and recycled waste materials further enhancing sustainability efforts. In summary, incorporating low-carbon-emission asphalt pavement technologies, including the use of recycled waste materials and innovative production methods, is essential for reducing the environmental impact of pavement construction. These advancements not only contribute to carbon emission reduction but also promote sustainability and resource efficiency in the construction industry.

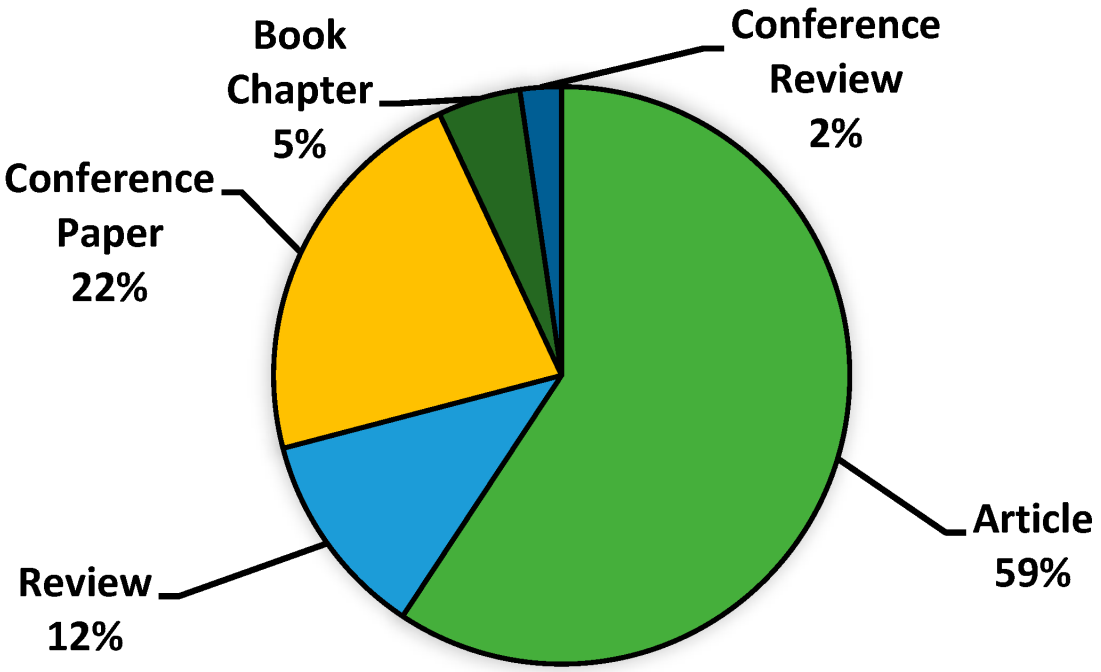

Figure 5. Publication types of publications on sustainable and low-carbon-emission asphalt pavement.

5. Discussion

The systematic review delves into three primary themes prevalent in the literature surrounding recycled waste materials and technology implementation for reducing carbon emissions in asphalt pavement. Firstly, it emphasizes the environmental benefits of incorporating such materials and technologies, like warm mix asphalt (WMA) and cold recycling, which substantially lower energy consumption and emissions during asphalt manufacturing processes. Secondly, the review underscores the concentration of research on material-related technologies, highlighting the potential for significant CO2 emissions reduction, up to 70%, through their collective application. Thirdly, it identifies critical challenges, including the absence of standardized testing techniques and performance standards, technological compatibility issues, and the lack of standardized rules governing the development of mixtures incorporating recycled waste materials. Despite the promising findings, the study points out the need for more comprehensive investigations across various pavement components to promote a holistic and integrated approach to sustainability in asphalt pavement construction. Motivations driving the adoption of recycled waste materials and technology in asphalt pavement to mitigate carbon emissions are multifaceted. They encompass circular economy principles, resource conservation, and compliance with increasingly stringent environmental regulations. The pursuit of environmental sustainability and improved pavement performance further incentivizes the integration of recycled materials and technologies. Additionally, the urgent need to mitigate climate change underscores the importance of reducing carbon emissions throughout the lifecycle of asphalt pavement, driving the exploration of low-carbon alternatives.

However, several challenges impede the widespread implementation of recycled waste materials and technology. These include initial cost factors, technological limitations, and compatibility issues with existing asphalt production practices. Ensuring performance and durability standards are met remains a significant concern, compounded by inconsistent outcomes and material availability issues. The review highlights a gap between research recommendations and practical applications, emphasizing the need for further studies focused on carbon estimation, mitigation strategies, and real-world implementation. Overall, the study underscores the critical role of recycled waste materials and technology in reducing carbon emissions in asphalt pavement construction while advocating for concerted efforts to address existing challenges and bridge the gap between research and practice.

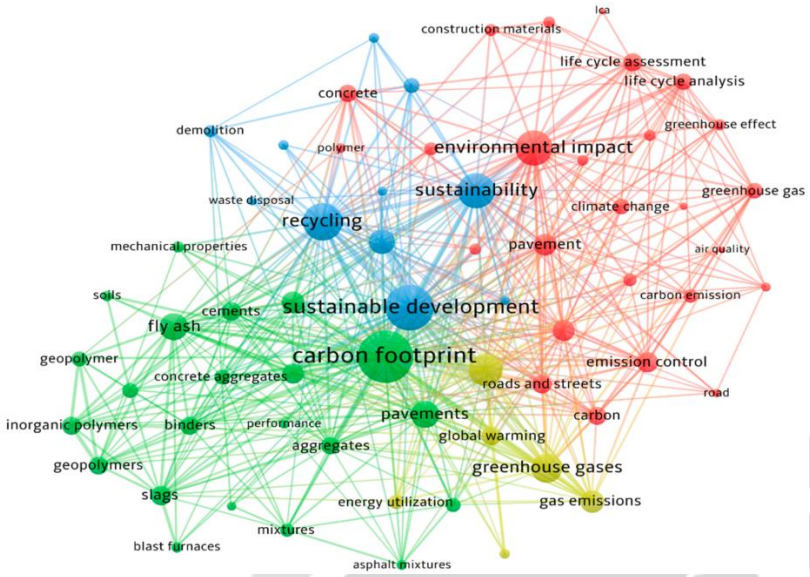

Figure 6. VOS viewer mapping of authors' keyword analysis sources.

6. Conclusion

Based on a comprehensive systematic review and scientometric analysis utilizing PRISMA and VOS viewer, this study highlights the potential of recycled waste materials and innovative technologies to mitigate carbon emissions in asphalt pavement construction. It identifies a range of recycled materials, including RAP, crumb rubber, and biochar, alongside low-carbon technologies such as warm mix asphalt, that offer promising avenues for reducing environmental impact. While current research primarily focuses on waste materials and temperature reduction in asphalt production, there is a pressing need for broader investigations encompassing various pavement components to foster a more integrated approach to sustainability. The findings underscore the importance of qualitative analyses in advancing knowledge, guiding future research efforts, and promoting collaboration within the asphalt pavement industry to achieve significant reductions in carbon emissions and enhance environmental stewardship.

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