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A Comprehensive Overview of the Utilization of Recycled Waste Materials and Technologies in Asphalt Pavements: Towards Environmental and Sustainable Low-Carbon Roads

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Abstract: Given the prevailing concerns about greenhouse gas emissions, global warming, and the growing demand for renewable resources, the pavement industry, among others, is actively engaged in researching and exploring low-carbon materials and technologies. Despite the growing interest in low-carbon asphalt pavement, there is still a significant knowledge gap regarding the use of various waste materials and technologies to achieve this goal. This study aims to close this gap by conducting a systematic review and scientometric assessment of the existing studies on the use of waste materials and technologies for low-carbon asphalt pavement. The study spans the years 2008 to 2023, and the scientometric analysis was conducted using the VOS viewer application. The study identifies materials and technologies in this area by examining co-authored country studies, publication sources, and keyword co-occurrence. It should be noted that a limited number of waste materials that allow CO₂ emissions reduction was analyzed in this study. However, other waste categories, such as bio-oils and polymers, which can provide positive either environmental or economic impacts on the production of paving materials, were not considered in the scope of the study. Based on the current review, it was found that integrating recycled waste materials like recycled asphalt pavement, biochar, or crumb rubber with alternative mixing technologies such as warm mix asphalt and cleaner energy can significantly reduce CO₂ emissions. China and the United States were identified as key research contributors to the low-carbon pavement. Furthermore, biomass-based fuel and electric construction equipment lower carbon and greenhouse gas emissions by 36–90% and 67–95%, respectively. However, before various recycled waste materials and technologies can be widely used in the asphalt industry, various challenges need to be addressed, including cost concerns, performance and durability concerns, standardization and regulations, availability, integration with existing facilities, and insufficient field and long-term data. The review identified critical research gaps, such as the absence of a homogeneous and reliable standard method for low-carbon asphalt pavement, limited field performance data, and a life cycle assessment approach in analyzing the emission reduction effects. The reviews will aid in the paradigm shift to a more carbon-friendly pavement industry that uses recycled waste materials and technologies.

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

Global warming has become a significant environmental issue due to its negative impact on the planet, which is primarily caused by greenhouse gases like carbon dioxide. To address this issue, most countries have agreed to lower their greenhouse gas production and have set targets for net-zero emissions by 2050 [1]. Over 125 nations have established or are studying long-term net-zero emanations objectives, demonstrating a global commitment to addressing environmental change and moving towards a more environmentally friendly future. It is critical to achieve net-zero emissions to limit global warming and prevent further environmental damage [2,3]. In recent years, both academia and industry have recognized the value of a holistic approach to sustainability management, which includes considering environmental, economic, and social factors [4]. Thus, sustainability criteria are required in the context of road construction and used to support national growth and development, since they offer access to occupation, communal, health, and education facilities [5]. By replacing conventional materials with alternative ones, integrating sustainability initiatives into road construction can help reduce impacts and contribute to sustainable development. As a result, consideration of sustainability criteria in road construction and use is critical. Because of its durability, low cost, and versatility, asphalt pavement is the most utilized road pavement material worldwide. Traditional asphalt production and use, on the other hand, have serious environmental consequences, including greenhouse gas emissions, air pollution, and the biodiversity loss of natural resources [6,7]. As a result, the utilization of recycled waste materials and the creation of new recycling techniques in asphalt pavement has grown in importance. The use of sustainable asphalt pavement materials includes a greater range of materials, such as recycled, bio-based, and materials derived from industrial byproducts, such as fly ash from coal power plants or slag from steel manufacture, which can likewise be utilized as alternative materials. Furthermore, advances in materials science and engineering have resulted in the creation of novel sustainable materials, such as geopolymer additives for asphalt concrete and carbon-neutral materials [6,8].

Pavement construction is a significant construction activity that frequently involves the use of both concrete and asphalt, two of the most commonly used road pavement materials. Unfortunately, it has been discovered that these materials have negative environmental effects, contributing to issues such as greenhouse gas emissions and pollution. Furthermore, conventional asphalt pavement materials and technology face several challenges and limitations, since conventional asphalt pavement production and use have significant environmental consequences, such as greenhouse gas emissions, pollution, and natural resource depletion [9,10]. Furthermore, conventional asphalt pavement is subject to cracking, rutting, and deformation due to its exposure to variables such as severe traffic loading and environmental conditions, and it frequently requires regular repair and maintenance to preserve its durability and performance [11]. Furthermore, traditional asphalt pavement can be costly to produce and maintain, particularly in areas with extreme weather and high traffic density [10]. Furthermore, natural materials are scarce because the availability of high-quality asphalt aggregates, such as natural sand and gravel, is limited in some areas, resulting in higher transportation costs and greater environmental impacts [9,11]. With the development and implementation of recycled waste materials and technologies, these issues can be addressed, and a more durable and environmentally friendly transportation system can be promoted. The continuous asphalt pavement construction necessitates a significant number of materials, technology, and fuel, resulting in significant CO₂ emissions. Given the critical need to reduce CO₂ emissions, it is critical to lessen the carbon emission level of asphalt pavement and implement effective emission reduction materials and technologies, as this will aid in the achievement of sustainable development goals while reducing the ecological impact of asphalt pavement construction and maintenance. According to a 2017 report by the International Road Federation and World Road Statistics, the world’s road networks span a total length of 32 million kilometers [12]. Meijer et al. [13], on the other hand, predicted that between 3 and 4.7 million kilometers of new highways would be
constructed by 2050. This highlights the importance of addressing the sustainability repercussion of road construction and maintenance to reduce carbon emissions and promote conservation-oriented development [12]. In the context of road construction, sustainability is defined as the ability to design, build, operate, and maintain road infrastructure in a way that achieves a balance between meeting current needs and preserving future generations’ abilities to meet their own needs [14]. This includes reducing the environmental impact of pavement production and maintenance, as well as increasing social equity and ensuring economic viability [15]. Sustainable road construction entails employing resources and techniques that reduce resource use, carbon footprint, and depletion of natural resources. It also entails building roads that promote safe and efficient transportation while minimizing negative effects on local populations and the environment [14,15].

Sustainable asphalt pavement practices are important for reasons such as:

- Environmental protection: Using recycled waste materials and technologies in asphalt pavement can significantly minimize the negative environmental effects of road construction and maintenance, such as emissions of greenhouse gases and fossil fuel-based resource depletion. It also encourages waste management and reduces the need for dumping sites [16,17].

- Cost-effectiveness: Sustainable asphalt pavement practices can save money in the long term by reducing the need for expensive repairs and replacements over the pavement’s lifespan. Using recycled materials in asphalt pavement, for example, minimizes the need for virgin materials, which can reduce production costs [16,18]. Beyond cost-effectiveness, it is critical to examine the larger benefits of employing recycled products. Recycling aids in the conservation of natural resources, the reduction of energy use, and the reduction of trash output. It also helps to promote a circular economy, which promotes sustainability and reduces dependency on natural resources. Thus, while the initial costs of employing recycled products in road building may be greater, recycling can be a viable and sustainable alternative when considering the long-term environmental advantages and potential cost savings due to lower demand for virgin materials. Recycling technology advancements and quality control procedures can increase the cost-effectiveness and performance of recycled materials in road construction.

- Performance enhancement: Sustainable asphalt pavement practices can increase durability and performance, which lower the need for upkeep and repair. For instance, warm-mix asphalt technology can enhance the compaction of the asphalt pavement, leading to better performance and durability [19,20].

- Social responsibility: Sustainable asphalt pavement practices can foster social responsibility by minimizing the detrimental consequences of road construction [21].

Greenhouse gases can be released at different phases of road construction, including the production of materials like bitumen and aggregates, as well as hauling, production, restoration, and demolition [2,12]. As a result, eco-friendly pavements should be prioritized. Green pavements are designed, built, and maintained to lower greenhouse gas production while meeting environmental and sustainable development standards. Selecting materials with lower carbon indexes, minimizing consumable usage, sourcing materials from local suppliers, and recycling wastes rather than dumping them to decrease the carbon footprint in road construction [19,22]. The carbon footprint of pavements can be reduced by adopting sustainable practices such as using lower-carbon materials, reducing waste, and using production technology assisting to address carbon emissions and promote sustainable development. Incorporating sustainable waste materials and technologies in the development of environmentally friendly asphalt pavement is critical for promoting sustainability and proper land use, as well as addressing carbon emission issues and conserving natural resources [8,14]. Furthermore, as technology advances, it becomes increasingly important to shift away from traditional materials that have significant environmental consequences, particularly in developing countries [23]. To that end, various low-carbon materials and processes based on sustainable technology have been developed [12]. As a result, it is
critical to comprehend the current and potential future applications of various materials and technologies, as well as their modifications for low carbon emissions in the asphalt pavement industry. Thus, this review aims to provide a comprehensive review and scientometric investigation into the literature on the sustainable application of different waste materials and technology for low carbon emissions in the pavement industry. The goal is to find gaps and challenges in the existing studies, as well as to provide insights for future research in this area.

2. Methodology

This study is a systematic review and scientometric assessment of the published literature on the sustainable use of various waste materials and technology for low carbon emissions in the asphalt pavement industry. However, a limited number of waste materials that are involved in the CO₂ emissions reduction were analyzed throughout the manuscript. Other products within specific waste categories (such as biochar, bio-oils, polymers, etc.,) can provide positive either environmental or economic impacts on the production of paving materials, but these are out of the scope of the present study. For the systematic review, the authors used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach, and for the scientometric analysis, we employed the VOS viewer software, version 1.6.19. The systematic literature review allows for a thorough and structured analysis of all existing literature on a specific topic, whereas the scientometric assessment provides a quantitative assessment of the defined literature’s significance and impact. The synergy of these two approaches improves the accuracy of accessing the research area and evaluating scientific development [14,24].

2.1. Qualitative Analysis Using the PRISMA Approach

The integration of scientometric analysis and a systematic literature review can be a very effective tool in research [23,25]. The systematic literature review is a secondary investigation approach that involves locating, selecting, analyzing, and interpreting all available information on a specific research question, field of study, or research approach. The PRISMA structure is a generally recognized framework for conducting a systematic literature review, and it can aid in making the review process transparent and repeatable [25,26]. Thus, it is critical to develop well-defined research questions to ensure that the systematic review is centered and relevant to the purpose of the study. The systematic literature review in this study began in early April 2023 and was carried out per the PRISMA pattern, as shown in Figure 1. However, for this approach to be successful, well-defined research questions that are directly related to the study objective are required. This ensures that the review process is focused and pertinent, resulting in a thorough and accurate literature review.

Study Question

The growing interest in low carbon in asphalt pavement production has stimulated studies into the use of various recycled waste materials and technologies to reduce carbon emissions in the pavement industry. This study’s primary goal was to evaluate the various materials and technologies employed to work towards a carbon footprint of zero in asphalt pavement construction. To make the literature review process easier, study questions were created to guide the structure of the review. As a result, developing relevant research questions and determining the best method for answering them is a critical element of the literature analysis [23]. The purpose of this review was to assess and elucidate recycled waste materials and technology for low-carbon-emission asphalt pavement production, as well as to evaluate the various materials that can be used and how technology can help to reduce carbon emissions, as well as to investigate how these materials’ performance and durability compare to traditional materials. Finally, policies and regulations that promote the use of eco-friendly materials and technology are investigated. Table 1 shows the research questions developed for this review.
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**Table 1. Study objectives and questions.**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>To investigate, identify, and assess the current state of research and knowledge, as well as to evaluate different sustainable and recycled materials and technologies that can reduce carbon emissions in asphalt pavement in various contexts, and to render suggestions for future studies.</td>
<td>What are the recycled waste materials and technologies that can be used in asphalt pavement production and construction to minimize carbon emissions while maintaining or improving both durability and performance?</td>
</tr>
</tbody>
</table>

During the research process, credible published articles were consulted to locate research papers relevant to the review’s area. The search strategy employed in this study utilizes three repositories’ sources: Web of Science, ScienceDirect, and Scopus. These data repositories were selected because they provide thorough, vast, and reliable systematic records, with substantial data compilation and significant scientometric assessments. Other data were acquired from other resources, like “ResearchGate” and “Google Scholar”. This study examined diverse uses of recycled waste materials and technologies for low-carbon asphalt pavement from 2008 to April 2023 to help reduce carbon emissions and improve sustainability. On 11 April 2023, the data collection was completed. To conduct the literature review, the authors used two keywords in the document search: “low carbon in asphalt pavement” for TITLE-ABS-KEYS and recycled waste materials for zero carbon emission in asphalt pavement” for TITLE-ABS-KEYS. They also searched for relevant articles using the “Title” field. There are, however, a limited number of systematic literature review articles and studies evaluating recycled waste materials and technology for low-carbon emission asphalt pavement production. Following that, a process of sorting and removing duplicate content was carried out. This included removing book chapters,
abstracts, retracted articles, editorial papers, corrigendum conference proceedings, and inaccessible full texts or dissertations. Many duplicates were identified and removed due to using three online repositories and two added sources, and the selected papers were re-scrutinized for content significance. The final step was to analyze the most appropriate data for the study. The analysis focused on a specific set of papers and studies with substantial relevance, contributions, reliable studies, and findings. To identify appropriate research and collect data, the process of inclusion and exclusion was used. Initially, several papers were selected for review from a specific repository. To filter the papers for the full review, inclusion criteria based on the quality and well-recognized relevance of the documents were used. Using the predicted time between 2008 and March 2023, a total of 344 documents were identified, but after applying the criteria across all categories, the number was reduced to 86 articles that were relevant to the study. This reflects a growing trend among researchers to investigate the use of recycled waste materials and technology for low-carbon emission asphalt pavement production. The collected documents were then inputted into Microsoft Excel in a tabularized format that included the entire document as well as cited references, allowing for the creation of plots and charts. The data were properly saved and analyzed using the Open Refine software, version 3.7.3, which is a useful tool for dealing with ambiguous data, eliminating irrelevant information, converting formats, and removing duplicates.

2.2. Quantitative Scientometric Analysis Using VOS Viewer

A scientometric analysis is the scientific, quantitative, and analytical study of scientific activity and progression indices at the field, regional, group, or national level. The data for analysis come from research papers and academic journals in well-known databases [14,27]. The collected data’s findings were analyzed using the VOS viewer software, version 1.6.19, a simple and free program that enables the generation and exploration of reliable scientometric analysis maps in a lucid and user-friendly format. The figures show a network of elements depicted as circles, with varying sphere sizes indicating each component’s importance and the network demonstrating the level of proximity between the components. The components are divided into groups based on the distance between groups and the color combinations used [28]. The scientometric analysis tool was used to assist in the evaluation process as part of a quantitative research approach that involved analyzing a large volume of scientometric data. Conventional literature reviews are limited in their ability to connect different literature components thoroughly and accurately, particularly in the context of co-occurrence, co-citation, and science mapping, which are more complex aspects of contemporary research [12]. Popular search engines were used in this study to look up published articles on the subject. Sources with the highest publications, keyword co-occurrences, citations, and existing study areas for the use of recycled waste materials and technology for low carbon emission in the asphalt pavement were identified through a scientometric analysis. Several methods were used to exclude irrelevant papers from the systematic literature review, and scientometric analysis data were collected using a reliable database. To visually evaluate the literature, the collected data were saved in CSV format and analyzed using the VOS viewer software, version 1.6.19. Figure 2 depicts the flowchart for the scientometric analysis approach. This scientometric analysis-based systematic review aimed to provide a summary of the present state of studies on the utilization of recycled waste materials and technology for low carbon emission in the pavement industry. The PRISMA method was used to identify significant findings, assess their validity, and collect data for methodological assessment for scientometric analysis parameters, research gaps, and potential. Country contribution, author keyword co-occurrence, referenced sources co-citation, and publication source were the unit analyses chosen for this study.
3. Results and Discussion

3.1. Descriptive Data Assessment

To evaluate the descriptive data, an Excel work sheet was used to plot and assess the annual publication pattern on recycled waste materials and technology for low carbon emission in the pavement industry from 2008 to 2023. Figure 3 shows a consistent increase in attention to the use of recycled waste materials and technology for low-carbon emission asphalt pavement. This trend can be attributed to advancements in technology and growing interest in reducing carbon emissions in asphalt pavement; most nations have agreed to reduce CO₂ emissions and have been dedicated to realizing net-zero greenhouse gas goals by 2050 [1]. Notably, the annual publication rate has increased steadily, with 9 articles published in 2020, 11 in 2021, and 13 in 2022.

Furthermore, as shown in Figure 4, 15 countries from around the world are the major players that took part in the study of recycled waste materials and technology for low-carbon-emission asphalt pavement. China leads the way in terms of publications, with 14 (16%), followed by the United States with 12 (14%), and Italy with 10 (11.6%). These findings could be explained by the countries that are the largest producers of carbon emissions, their bioeconomy policies that prioritize production and modern technological advancement, as well as their heavy investments in renewable energy sources and construction industry strategies, which encourage eco-friendly and sustainable construction resources [29]. Furthermore, both countries have strong economies and active clean energy research and development initiatives. Poland, the United Kingdom, and Switzerland each contributed four articles, while Switzerland contributed three. Columbia, Hong Kong, Egypt, and Australia each contributed two articles. Each of the remaining countries, including Chile, published only one article.
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.

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

The study examined the various types of publications available to provide a comprehensive knowledge of the research landscape on the use of recycled waste materials and technology for low-carbon emission asphalt pavement. Figure 5 depicts the types of publication on sustainable and low-carbon asphalt pavement. The findings showed that journal articles accounted for 59% of all publications. This implies that academic journals are the primary source of information for researchers and scholars interested in this topic. Conference papers accounted for 22% of all publications. These findings indicate that conferences and other academic meetings are important forums for exchanging ideas about the
use of recycled waste materials and technology for low-carbon-emission asphalt pavement. Journal reviews, book chapters, and conference reviews were the least common types of publications, accounting for 12%, 5%, and 2% of total publications, respectively. This finding suggests that there is a limited number of comprehensive reviews and book chapters on the subject, which may present opportunities for additional research and analysis.

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

3.2. Quantitative Scientometric Analysis

In this section, the VOS viewer was used to evaluate and depict the scientific publication features such as authors’ keywords, publication source, and publication country source. The study concentrated on bibliographic coupling, which investigates the connections between sources based on shared references.

3.2.1. Keywords

This section explains the significance of keywords in research analysis and displays the findings of a keyword co-occurrence analysis in a specific subject area. The investigation type chosen was co-occurrence, and the analysis unit was all keywords. The minimum occurrence limit for keywords was set at 10, and 34 out of 972 terms met the requirement. Table 2 shows the 34 most used terms in published articles in the subject field, with carbon footprint, sustainable development, recycling, sustainability, and environmental impact ranking highest. In the pursuit of low carbon emission and sustainability in asphalt pavement, numerous recycled waste materials, such as waste materials, fly ash, geopolymers, and slag, as well as diverse methods such as recycling, emission control, and energy utilization, have been investigated. Figure 6 depicts a graph-based visualization map of keywords. Based on the number of occurrences, the graph depicts co-occurrences and linkages. The size of each keyword bubble shows its prevalence, indicating how frequently it appears in the study documents. The bubble’s location reflects its co-occurrence with other keywords in the research. The chart also demonstrates that prominent keywords have bigger circles than others, implying that they have practical value in the asphalt pavement sector for low carbon emission. It also depicts the word clusters to show their co-occurrence across diverse publications. Also, Figure 6 depicts a color pattern clustering based on the co-occurrence of several terms in publications. The colors utilized (green, blue, yellow, and red) show the presence of four clusters, and the levels of keyword density are reflected in the different colors. For example, green and red represent the highest occurrences the of keywords, while blue and yellow represent the lower occurrences of the keywords.
Table 2. Keywords frequently used in asphalt pavement studies for low-carbon emission.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Keyword</th>
<th>Occurrences</th>
<th>Total Link Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Carbon footprint</td>
<td>42</td>
<td>157</td>
</tr>
<tr>
<td>2</td>
<td>Sustainable development</td>
<td>37</td>
<td>155</td>
</tr>
<tr>
<td>3</td>
<td>Recycling</td>
<td>33</td>
<td>141</td>
</tr>
<tr>
<td>4</td>
<td>Sustainability</td>
<td>31</td>
<td>137</td>
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<tr>
<td>5</td>
<td>Environmental impact</td>
<td>30</td>
<td>136</td>
</tr>
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<td>6</td>
<td>Concrete</td>
<td>29</td>
<td>130</td>
</tr>
<tr>
<td>7</td>
<td>Pavement</td>
<td>27</td>
<td>126</td>
</tr>
<tr>
<td>8</td>
<td>Emission control</td>
<td>26</td>
<td>121</td>
</tr>
<tr>
<td>9</td>
<td>Greenhouse gases</td>
<td>24</td>
<td>114</td>
</tr>
<tr>
<td>10</td>
<td>Life cycle assessment</td>
<td>24</td>
<td>108</td>
</tr>
<tr>
<td>11</td>
<td>Fly ash</td>
<td>23</td>
<td>105</td>
</tr>
<tr>
<td>12</td>
<td>Geopolymer</td>
<td>21</td>
<td>101</td>
</tr>
<tr>
<td>13</td>
<td>Greenhouse effect</td>
<td>20</td>
<td>98</td>
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<td>14</td>
<td>Gas emission</td>
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<td>95</td>
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<tr>
<td>15</td>
<td>Life cycle analysis</td>
<td>20</td>
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<td>16</td>
<td>Global warming</td>
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<td>Climate change</td>
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<tr>
<td>18</td>
<td>Aggregate</td>
<td>18</td>
<td>76</td>
</tr>
<tr>
<td>19</td>
<td>Mixtures</td>
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<td>75</td>
</tr>
<tr>
<td>20</td>
<td>Energy utilization</td>
<td>17</td>
<td>61</td>
</tr>
<tr>
<td>21</td>
<td>Roads</td>
<td>16</td>
<td>59</td>
</tr>
<tr>
<td>22</td>
<td>Waste disposal</td>
<td>16</td>
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</tr>
<tr>
<td>23</td>
<td>Binders</td>
<td>15</td>
<td>52</td>
</tr>
<tr>
<td>24</td>
<td>Asphalt mixtures</td>
<td>14</td>
<td>52</td>
</tr>
<tr>
<td>25</td>
<td>Roads and streets</td>
<td>14</td>
<td>50</td>
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<tr>
<td>26</td>
<td>Mechanical properties</td>
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<td>Construction materials</td>
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<td>Slag</td>
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<td>Soils</td>
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<td>Mixtures</td>
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<td>Inorganic polymers</td>
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<td>32</td>
<td>Demolition</td>
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<td>33</td>
<td>Blast furnace</td>
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<td>39</td>
</tr>
<tr>
<td>34</td>
<td>Air quality</td>
<td>10</td>
<td>35</td>
</tr>
</tbody>
</table>

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

3.2.2. Countries

It is an intriguing finding about the countries that have published a considerable number of publications about sustainable and low-carbon-emission asphalt pavement. The countries were selected based on the minimal threshold of two documents by applying bibliographic coupling analysis and selecting the unit of analysis as countries, as shown in Table 3. China, the United States, Italy, and Spain appear to be the main contributors in terms of publications, with 14, 12, 10, and 9 articles, respectively. The reasons for these
countries’ contributions to low-carbon road infrastructure vary, but some common features include a strong commitment to sustainability, investments in energy from renewable sources, and sustainable transport infrastructure for green activities. Furthermore, the application of recycled waste materials and the utilization of energy-efficient technologies such as solar highways and electric motorways have been driving forces in these countries’ efforts to reduce carbon emissions from transportation. It is worth noting that the four countries that have published the most articles on the topic of sustainable and low-carbon emission asphalt pavement (China, the United States, Italy, and Spain) have also garnered the most citations. This indicates that the research carried out by these countries had a substantial impact on the field. Furthermore, as illustrated in Figure 7, the mapping of nations linked by citations provides a visual depiction of the influence of these countries on the review subject. The size of the bubble corresponds to a country’s impact on the study issue, with China having had the highest impact, followed by the United States, Italy, Spain, and Canada. This information could help academics and policymakers identify key participants and interested parties in the field and collaborate with them to enhance research and development in this area.

### Table 3. Key contributing countries based on the number of articles published.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Country</th>
<th>Documents</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>China</td>
<td>14</td>
<td>449</td>
</tr>
<tr>
<td>2</td>
<td>United States</td>
<td>12</td>
<td>243</td>
</tr>
<tr>
<td>3</td>
<td>Italy</td>
<td>10</td>
<td>187</td>
</tr>
<tr>
<td>4</td>
<td>Spain</td>
<td>9</td>
<td>103</td>
</tr>
<tr>
<td>5</td>
<td>Canada</td>
<td>8</td>
<td>153</td>
</tr>
<tr>
<td>6</td>
<td>Germany</td>
<td>7</td>
<td>204</td>
</tr>
<tr>
<td>7</td>
<td>United Kingdom</td>
<td>6</td>
<td>87</td>
</tr>
<tr>
<td>8</td>
<td>Australia</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>9</td>
<td>India</td>
<td>5</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>Czech Republic</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>11</td>
<td>Poland</td>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td>12</td>
<td>Colombia</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

#### 3.2.3. Sources of Publication

To investigate the sources of publication, the VOS viewer was applied to the acquired bibliographic data. Individual sources (papers) were used as the unit of analysis, with a limitation of at least five publications per source. As a result, just 10 of the 86 published sources met this criterion. Table 4 lists the publications that published at least five studies on the usage of sustainable and low-carbon-emission asphalt pavement between 2008 and 2023. Table 4 also shows how many citations each source received during that period. Based on the number of articles published, the investigation identified “Journal of Cleaner Production” and “Construction and Building Materials” as the two leading publication sources, with 12 and 11 papers, respectively. The category “Journal of Cleaner Production” garnered 228 citations, while “Construction and Building Materials” received 173. This study’s analysis can serve as a platform for future systematic mapping investigations into sustainable and low-carbon emission asphalt pavement. It provides a thorough assessment of the existing literature, highlights major publication sources and their citation impact, and can serve as a roadmap for future research in this field. Figure 8 depicts a plot of the distribution of research articles from sources that published a minimum of five articles in the research area. The size of the frames in the map represents the journal’s influence on the number of article papers. “Journal of Cleaner Production” and “Construction and Building Materials” are highlighted with a bigger frame, emphasizing the frequency related to the source of publication. The map also depicts four different groups, each of which is denoted by a different color (green, red, blue, and yellow). These categories are defined depending on the dimensions of the study source or the frequency with which they are mentioned in related articles. Journals are clustered among these groupings according to their co-citation
patterns in published articles. The green and red clusters are made up of three sources that are commonly cited together, while the yellow and blue clusters are made up of three sources that are commonly mentioned together. Also, the proximity of frames (journals) inside a cluster indicates stronger links between them, whereas widely distributed frames imply weaker associations. Based on the study’s analysis, it is possible to conclude that specific publication sources have carved out a prominent position in the field of sustainable and low-carbon emission asphalt pavement. These sources, along with others highlighted in the analysis, have played an important role in creating the research environment and knowledge transmission related to sustainable and low-carbon emission asphalt pavement. Their efforts are likely to provide enhanced knowledge and innovation in this field.

Figure 7. VOS viewer network of contributing countries based on the number of articles published.

Table 4. Publication sources that have at least five papers published in the field of study.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Source</th>
<th>Documents</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Journal of Cleaner Production</td>
<td>12</td>
<td>228</td>
</tr>
<tr>
<td>2</td>
<td>Construction and Building Materials</td>
<td>11</td>
<td>173</td>
</tr>
<tr>
<td>3</td>
<td>Materials</td>
<td>10</td>
<td>157</td>
</tr>
<tr>
<td>4</td>
<td>Journal Central South University</td>
<td>9</td>
<td>114</td>
</tr>
<tr>
<td>5</td>
<td>Resources, Conservation, and Recycling</td>
<td>8</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>Renewable and Sustainable Energy Reviews</td>
<td>7</td>
<td>96</td>
</tr>
<tr>
<td>7</td>
<td>Transportation Research Record</td>
<td>6</td>
<td>84</td>
</tr>
<tr>
<td>8</td>
<td>Nanotechnology Review</td>
<td>5</td>
<td>56</td>
</tr>
<tr>
<td>9</td>
<td>Environmental Research</td>
<td>5</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>Environmental Research Letters</td>
<td>5</td>
<td>74</td>
</tr>
</tbody>
</table>

Figure 8. VOS viewer mapping and network of publication sources.
4. Recycled Waste Materials and Technology for Low-Carbon Emission in the Asphalt Pavement

The significance of pavement construction cannot be overstated, especially as populations grow. Raw resources and materials used in the asphalt pavement sector, on the other hand, are depleting, with immediate socioeconomic and environmental consequences [30]. Recently, there is much emphasis on the importance of incorporating low-carbon technologies into the manufacturing of pavement materials, particularly those that contribute significantly to greenhouse gas emissions, such as asphalt binder, aggregates, and cement [3]. The primary source of CO$_2$ emissions from these materials has been identified during the production phase. Thus, to reduce these emissions, measures such as using materials with lower emission factors and reducing overall material use must be implemented. Therefore, the application of low-carbon-emitting recycled waste materials and technologies is critical in reducing the environmental impact of asphalt pavement. Because of the pavement industry’s continued growth and the corresponding increase in material demand, it is critical to prioritize the development of sustainable and low-carbon alternatives to conventional materials and technologies [8].

4.1. Waste and Reprocessed Materials

Generally, the utilization of mineral aggregates and the hauling of constituents in pavement-laying activities have a significant impacts on CO$_2$ emissions [3]. As a result, academics have investigated the feasibility of implementing resource-efficient economy practices in the pavement sector to address this issue. Furthermore, various geographical areas have implemented guidelines and strategies to promote the implementation of circular economy practices. One prevalent method for employing circular economy practices in pavement production is to use waste materials as a substitute for non-renewable resources or raw materials [31]. This strategy has the viability to decrease carbon emissions during material production and transportation [11,32]. Also, these wastes and reprocessed materials are utilized to achieve sustainable development goals, and they are biodegradable and cost-effective [33]. There are numerous sources from which the waste materials utilized in asphalt pavement can be sourced; for instance, agricultural waste can be processed and utilized as a replacement for conventional asphalt paving materials [34]. Also, construction and demolition waste materials obtained from tearing down old structures and roads, such as concrete, asphalt, and bricks, can be recycled into new asphalt pavement. Furthermore, industrial waste products from sectors including metal casting, tire manufacture, and roofing can be utilized in place of conventional asphalt paving components [35]. Moreover, municipal solid waste can also be processed and used as a replacement for conventional asphalt pavement materials, including glass, plastic, and paper. Additionally, waste materials produced by other industries, such as fly ash obtained from coal-fired power stations, can be utilized as alternatives to conventional asphalt paving materials [9,11]. By utilizing these waste products in asphalt paving, these sectors produce less waste and help harness sustainability. Below are some of the available literatures on various waste materials employed in asphalt pavement to reduce carbon emission.

4.1.1. Biochar-Based Materials

Asphalt pavement biochar-based materials come from renewable resources like vegetable oil, biomass materials, and bio-based polymers. These materials can be used as alternative asphalt binders or admixtures to enhance the durability of asphalt pavements. The application of bio-based asphalt pavement materials has the potential to lower greenhouse gas production while also promoting the utilization of green energy sources [36]. Biochar is a type of material created by pyrolyzing organic materials such as agricultural waste and wood chips. Biochar is also being researched for its ability to reduce carbon footprint gas emissions by adsorbing volatile organic compounds (VOCs) from asphalt and carbon dioxide from industrial processes [37]. The Intergovernmental Panel on Climate Change (IPCC) has recognized biochar as a low-carbon technology [38]. The average carbon
footprint of biochar, on the other hand, varies depending on factors such as raw material source, characteristics, and proposed utilization. The standard carbon emissions of biochar range from 2.0 to 3.3 kg of CO$_2$ equivalent per kg [39]. Despite these, biochar applications can substantially cut down greenhouse gas emissions, with estimates ranging from 3.4 to 6.4 Pg CO$_2$ equivalent. Also, the CO$_2$ extraction of biochar from the atmosphere accounts for 1.7 to 3.7 Pg CO$_2$ equivalent, or 49–59% of this reduction [37]. Ghasemi, et al. [40] examined the use of biochar made from algae as a potential carbon capture strategy for absorbing CO$_2$ from the atmosphere. The biochar was created through pyrolysis, and the researchers discovered that it has the potential to absorb CO$_2$, showing its viability as a low-cost and sustainable method of reducing carbon emissions. The study emphasizes the potential of algae-based biochar for reducing CO$_2$ levels in the atmosphere and reducing greenhouse gas emissions. Also, the potential of biochar to reduce volatile organic compound emissions from asphalt mix was studied in a study conducted by Zhou et al. [41]. Because of its inherent porosity and carbon negativity, biochar was found to effectively reduce VOC emissions by up to 50% in the study. Interestingly, the adsorption mechanisms were found to be influenced by the type of biochar used, with biochar produced from swine droppings exhibiting physical adsorption and biochar made from wood or straw exhibiting chemical adsorption. Another significant advantage of using biochar as a CO$_2$ adsorbent is its low cost, with the study revealing that it is nearly ten times less expensive than other CO$_2$ adsorbent materials [41,42]. These findings highlight the potential of biochar as a long-term and low-cost solution for carbon reduction.

4.1.2. Palm Oil Waste

These refer to the waste and residues of palm oil cultivation and processing, which are classified as solid waste and liquid waste, respectively [43]. Because of its negative environmental impacts, waste is a significant environmental issue, but there is growing interest in using it in asphalt pavement [44]. The use of palm oil waste also has the potential to help reduce carbon emissions, which is a major concern associated with conventional materials. According to Kanadasan and Razak [45] and Alnahhal et al. [46], replacing cement with palm oil fuel ash and palm oil shells can result in significant reductions in CO$_2$ emissions of up to 61% and 52%, respectively. Furthermore, palm oil ash and powder geopolymers can lower CO$_2$ emissions by up to 64%. These findings show palm oil waste releases notably lower CO$_2$ – e than conventional cement [47]. It is important to note that the total CO$_2$ – e was determined by considering the resources required for processes such as recycle, dumping, and hauling of resources within a 100-km distance [46].

4.1.3. Crumb Rubber

Crumb rubber is a recycled material made from used tires that has desirable properties such as elasticity, durability, and weathering resistance, making it useful for a variety of applications [3]. Crumb rubber is incorporated into asphalt binder through both wet and dry processes, with wet processes using a carrier oil to blend the crumb rubber and dry processes directly adding crumb rubber to the asphalt binder. The incorporation of crumb rubber into bituminous mixtures represents a promising sustainable asphalt pavement [48]. Various studies have emphasized the possibility of incorporating CR into asphalt mixtures using wet technology to reduce carbon emissions and promote sustainability in the construction industry. Farina et al. [49] examined the efficacy of incorporating crumb rubber into asphalt mixtures using the wet manufacturing method, as well as the impact on carbon reduction. When compared to the conventional mixture, the asphalt mixture with 18% CR had a carbon reduction potential of 36% to 44%, according to the findings. It suggests that incorporating 18% CR into asphalt mixtures using the wet technology method is the best way to improve mixture properties while lowering carbon emissions. Also, White et al. [50] studied the ecological effects of utilizing crumb rubber in asphalt mixtures. The study discovered that, while the use of crumb rubber increased CO$_2$ emissions during the mixture production phase, it also reduced emissions.
from natural material production. The apparent contradiction in the study stems in part from the fact that the production and use of crumb rubber have both positive and negative environmental consequences. According to the study, the utilization of crumb rubber in the pavement industry can provide a net environmental benefit, but more research is required to better comprehend the environmental impacts and identify strategies for mitigating the adverse effects while optimizing the positive ones. Furthermore, Wang et al. (2020) performed a comparison study on the environmental impacts of crumb rubber modified mixes and styrene-butadiene-styrene modified mixes and discovered that crumb rubber modified mixes decrease CO$_2$ emissions by 17% when compared to styrene-butadiene-styrene modified asphalt. The reduction can be attributed to tire recycling and the balance of the generated and prevented effects of reprocessing and co-product recovery. The study recommends optimizing crumb rubber content and manufacturing processes to maximize environmental benefits, emphasizing the need for additional research in this area.

4.1.4. Recycled Asphalt Materials

The recycled asphalt materials include reclaimed asphalt pavement (RAP), which is made by milling and crushing existing asphalt pavement and recycled asphalt shingles which are obtained from roof membranes and incorporated into the asphalt mixture. The application of recycled materials in asphalt pavement decreases the demand for natural raw materials while lowering the environmental impact of disposal. The application of reclaimed asphalt pavement in road rehabilitation can substantially decrease ecological footprint as well as carbon dioxide emissions [3]. As a low-carbon technology, recycling RAP materials is becoming increasingly significant in pavement construction. Because of their environmental and economic benefits, hot recycled asphalt mixtures are gaining popularity in pavement engineering. The degree of mixing between the virgin and RAP asphalt binders in these mixtures is critical in influencing the overall performance of the pavement [51]. Understanding the blending state of virgin and RAP asphalt binders during the design and manufacture of recycled asphalt mixtures is critical for optimizing their performance. This understanding allows for the optimization of blending procedures and binder formulas, resulting in improved durability, rutting resistance, and fatigue life. Understanding the mixing condition is important for constructing high-performance recycled asphalt mixtures, both in terms of environmental advantages and cost savings [51].

Giani et al. [52] discovered that incorporating RAP with asphalt can reduce carbon emissions by up to 6.8%. Additional research has found that increasing RAP content can result in significant reductions in carbon emissions. Furthermore, based on the research of Gulotta et al. [53], the use of RAP with warm mix asphalts (WMA) has been shown to have substantial advantages for minimizing CO$_2$ emissions (2019). Other studies, conducted by Farina et al. [49] and Saeedzadeh et al. [54], have discovered that the use of RAP does not always result in improvement, and in some cases, a higher RAP content may even result in higher environmental burdens. This could be because of the greater energy required for the mixing and compaction processes of conventional asphalt mixture when RAP is used. To account for the increased rigidity of RAP, further heating energy and extra intensity must be applied during compaction, resulting in increased energy consumption. Lime stabilization “in situ” and RAP can significantly reduce CO$_2$ emissions and contribute to sustainable construction practices in embankment construction. By reducing the need for virgin materials, lime stabilization alone can reduce emissions by 10.96%, while the integration of RAP and lime stabilization can reduce emissions by 48.27%. RAP is a low-cost, long-term alternative to traditional materials that can reduce the need for virgin materials while also lowering material-production emissions [55]. Furthermore, steel industry development is heavily reliant on electricity or coal, which contributes significantly to greenhouse gas emissions. According to Karlsson et al., using recycled steel reinforcement steel could potentially reduce emissions by 5% to 27% [56]. Recycling steel uses less energy, produces less waste, and emits less pollution than traditional steel production. The use of recycled
steel in reinforcement bars has the viability to considerably lower the environmental impact of steel production.

4.1.5. Industrial Waste Ash and Powder

In recent years, there has been increased demand in the pavement sector to lower its carbon footprint and contribute to global resources to alleviate climate change. The production of Portland cement, a key component in concrete, is a major contributor to carbon emissions in the pavement industry. Researchers have been investigating various methods, including the use of alternative materials, to decrease the carbon footprint of concrete production. The partial substitution of Portland cement clinker with industrial waste such as fly ash or palm oil fuel ash is one example of this. Using this method, carbon emissions can be significantly reduced throughout the manufacturing process. Less energy is required to produce cement by utilizing industrial waste and by-products, resulting in lower carbon emissions. This method is regarded as a viable strategy for achieving sustainability in the pavement industry. Choudhary et al. [57] researched to study the viability of using construction waste materials as fillers in asphalt concrete mixtures to reduce GHG emissions. The researchers compared four construction waste materials to conventional stone dust: concrete dust, glass waste, brick dust, and granite dust. The study discovered that limestone dust mixtures had the lowest carbon emissions, reducing them by 7% when compared to conventional stone filler. White et al. [50] investigated the feasibility of using fly ash as a replacement for Portland cement for concrete production. The researchers discovered that by substituting fly ash for a portion of Portland cement, they were capable of lowering \( \text{CO}_2 \) emissions by 29.6%, which is attributed to the fly ash having a lower carbon intensity than Portland cement. Overall, these alternatives provide environmental benefits by lowering the need for natural materials and lowering emissions from material production, resulting in a more durable and long-lasting structure. Table 5 shows the percentage distribution of pavement materials as well as \( \text{CO}_2 \) emissions.

Table 5. Pavement material percentage distribution and \( \text{CO}_2 \) emissions [58].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Material Quantity (%)</th>
<th>( \text{CO}_2 ) Emission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt binder</td>
<td>0.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Aggregates</td>
<td>74.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Cement</td>
<td>4.7</td>
<td>84.5</td>
</tr>
<tr>
<td>Quick lime</td>
<td>0.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Sand</td>
<td>17.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Fly ash</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Mineral filler</td>
<td>0.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Other benefits of employing recycled waste materials in asphalt pavement include lower environmental impact, because using recycled materials instead of virgin ones minimizes the environmental and carbon footprints of pavement construction. It also leads to cost savings, because recycled waste materials minimize the requirement for virgin resources and landfill waste management, resulting in long-term cost reductions. Furthermore, the use of recycled waste materials can increase pavement performance while reducing the frequency of maintenance and repairs. Finally, choosing recycled waste materials contributes to the circular economy by lowering the need for fresh resources and preventing waste from ending up in landfills. Table 6 summarizes the research findings on recycled waste materials for low-carbon asphalt pavement.
Table 6. An overview of the research findings on recycled waste materials for low-carbon emission asphalt pavement.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Usage and Content wt.%</th>
<th>Findings</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[59]</td>
<td>Pinewood and pig manure biochar</td>
<td>Asphalt binder modifier (5%)</td>
<td>Compared to petroleum-based asphalt, bio asphalt binder and binders modified with biochar are more energy-efficient and emit less CO2. Biochar made from wood was more effective.</td>
<td>Biochar has the prospective for the development of environmental and low-carbon asphalt pavement; however, further studies are required to fully comprehend its utilization.</td>
</tr>
<tr>
<td>[50]</td>
<td>Fly ash</td>
<td>Partial replacement of cement (0.38%)</td>
<td>Carbon emission decreased from 36% to 44% compared to conventional mixtures when using asphalt binder with 18% crumb rubber produced using wet technology.</td>
<td>There has been little research and data on the concentration of fly ash leachate in the field and its long-term use. Attention must be paid to the type and nature of rubber used, as this might result in an increase in cost due to the requirement of a higher working temperature.</td>
</tr>
<tr>
<td>[49]</td>
<td>Crumb rubber</td>
<td>Asphalt binder modifier (18%)</td>
<td>The decrease in greenhouse gas was accomplished by increasing the RAP content of asphalt binder; the prospective reduction is up to 12.4%.</td>
<td>Due to limited study on production cost and design life of the mixes, additional study on life cycle cost estimation is required.</td>
</tr>
<tr>
<td>[50]</td>
<td>Recycled asphalt pavement</td>
<td>Aggregate replacement (30%, 40%, and 50%)</td>
<td>When palm oil fuel ash was utilized to substitute OPC up to 70%, CO2 emissions were reduced by up to 32-45%.</td>
<td>Future research should concentrate on mechanical performance testing and its long-term effects on the mixture.</td>
</tr>
<tr>
<td>[56]</td>
<td>Waste wood and straw biochar</td>
<td>Cement replacement (70%)</td>
<td>Biochar was found to reduce VOC production by 50% because of its intrinsic microstructure and carbon negativity.</td>
<td>More research on the long-term and economic feasibility study of various biochar in asphalt pavement is recommended.</td>
</tr>
<tr>
<td>[56]</td>
<td>Recycled steel</td>
<td>Aggregate replacement (10%)</td>
<td>Reinforcement steel produced from reclaimed steel reduces GHG emissions by 5-27%.</td>
<td>More research on methods for detecting heavy metals while using such recycled materials in road construction is encouraged to reduce leachate development and environmental contamination.</td>
</tr>
<tr>
<td>[50]</td>
<td>Crumb rubber</td>
<td>Asphalt binder modifier (1.6%)</td>
<td>Asphalt rubber has a lower carbon footprint compared to Portland cement mixtures but a greater carbon footprint than asphalt mixtures.</td>
<td>The study was limited to dense-graded mixtures. More study using different gradations such as gap, open, and uniform grading is encouraged.</td>
</tr>
<tr>
<td>[55]</td>
<td>A recycled asphalt pavement and lime stabilization</td>
<td>Aggregate replacement and stabilization (100%)</td>
<td>CO2 emissions from the embankment section are reduced by 48.2% when both RAP and lime stabilization are used, 21.22% when only RAP is used, and 10.96% when only lime stabilization is used.</td>
<td>Further comparative studies are required to buttress the current study and additional studies are needed on life cycle cost assessment.</td>
</tr>
<tr>
<td>[46]</td>
<td>Recycled aggregate</td>
<td>Aggregate substitution (150%)</td>
<td>When compared to conventional mixes, recycled aggregate mixes reduced CO2 emissions by up to 29%.</td>
<td>Mechanical performance testing and long-term field performance studies are recommended for future research. To limit environmental impact, it is important to evaluate the environmental impact and mitigate heavy metals in waste filler before using it in road construction.</td>
</tr>
<tr>
<td>[57]</td>
<td>Brick, concrete limestone slurry dust, and glass powder</td>
<td>Filler replacement with a mass ratio of water to filler 9:1</td>
<td>Glass powder and concrete dust emit somewhat more greenhouse gases than brick and limestone dust blends, while stone dust blends emit more greenhouse gases overall. Mixes of limestone dust yield the least amount of GHG emissions of 7%.</td>
<td>More research on environmental effects and cost-benefit analyses of various biochars in asphalt pavement is recommended.</td>
</tr>
<tr>
<td>[57]</td>
<td>Palm oil fuel ash</td>
<td>Cement substitution (100%)</td>
<td>Palm oil waste-modified mixes can lower CO2 emissions by 44-64% when compared to the conventional asphalt pavement mixture.</td>
<td>More extensive rheological and performance testing are required to acquire a thorough knowledge of the microscopic and thixotropic behavior of the modified asphalt binder.</td>
</tr>
<tr>
<td>[48]</td>
<td>Crumb rubber</td>
<td>Asphalt binder modifier</td>
<td>Compared to asphalt changed with styrene-butadiene-styrene, crumb rubber-modified asphalt can lower CO2 emissions by 17.06%.</td>
<td>The percentage and selected RAP ratio must be carefully considered because they can contribute to an increase in asphalt use. Additional studies and field evaluation are required since the financial and societal impacts of the utilization of reused materials must be considered.</td>
</tr>
<tr>
<td>[52]</td>
<td>Recycled asphalt pavement</td>
<td>Aggregate replacement (10% and 30%)</td>
<td>Carbon emissions were reduced by 6.8% when RAP was combined with a hot asphalt mixture.</td>
<td></td>
</tr>
</tbody>
</table>
4.2. Mixing and Production Technology

4.2.1. Warm Mix Asphalt (WMA)

WMA is a form of asphalt production technology in which asphalt pavement is produced at lower temperatures than standard hot mix asphalt (HMA), leading to lower energy intake, lower greenhouse gas emissions, and greater construction workability [63]. WMA is made with a variety of additives that reduce the viscosity of the asphalt binder as well as the amount of energy needed to make and lay the mix. WMA has been demonstrated in studies to provide considerable environmental benefits over HMA, including lower energy use, greenhouse gas emissions, and pollutants like nitrogen oxides. WMA’s lower production temperature can potentially result in cost benefits for pavement construction [19,63]. WMA technology has gained popularity in recent years, with several publications emphasizing its ability to mitigate CO\textsubscript{2} emissions. WMA has been studied as an effective strategy to minimize greenhouse gas emissions [64,65]. These studies have emphasized the advantages of WMA technology, including lower production temperatures and lower energy usage, which can result in significant CO\textsubscript{2} emissions reductions when compared to conventional technologies. WMA technology makes use of additional additives that can be made at lower temperatures varying from 110 °C to 140 °C. According to Vidal et al. [66], this temperature reduction can result in a significant reduction in energy usage, estimated at 15% to 16%. Furthermore, as compared to conventional HMA, the utilization of these additives can lower the processing temperature, resulting in energy savings and perhaps lower carbon emissions connected with the manufacturing process. Different compounds reduce CO\textsubscript{2} emissions to varying degrees. Also, Sharma and Lee [67] investigated the influence of employing Ca(OH)\textsubscript{2} integrated zeolite modifier in asphalt mixture production and discovered it can greatly decrease CO\textsubscript{2} production from heating the pavement mixture, as well as decreasing fuel usage during the production process. Furthermore, studies by Vaitkus et al. [68] and Bueche [69] also reported a 30% to 40% reduction in CO\textsubscript{2} emission when the warm mix technology was utilized for pavement construction compared to the conventional mix.

Another type of warm asphalt technology is half-hot mix asphalt (HWMA). While the production temperature of WMA mixes is in the range of 100–150 °C, HWMA technology permits asphalt pavement production at a reduction temperature of less than 100 °C [70,71]. HWMA technology employs chemical additives and foaming processes to minimize HMA mixing and compaction temperatures [70]. This method has been found to decrease energy usage and greenhouse gas emissions during the manufacturing process. Additionally, del Carmen Rubio et al. [72] assessed the environmental impact of HWMA and discovered that it can reduce CO\textsubscript{2} emissions by 58% when compared to HMA throughout the production process. Lower manufacturing temperatures and the application of chemical additives to improve workability and lower viscosity are responsible for the considerable reduction in CO\textsubscript{2} emissions. Overall, the WMA technology is a potential solution to lowering the environmental impact of asphalt production and construction while retaining the desired engineering features of the pavement.

4.2.2. Cold Mix Asphalt (CMA)

CMA is an asphalt production technology in which asphalt pavement is produced at a much lower temperature. It is made by combining aggregates and asphalt binder emulsion without the use of heat, which considerably minimizes dangerous volatile component emissions and fuel usage. Unlike HMA, the interaction between the aggregate and leftover asphalt binder occurs at room temperature [73]. However, CMA has some drawbacks, such as hurdles during compaction, the high air-void percentage in compacted mixtures, reduced initial strength, and the prolonged time required to generate completely cured specimens for best performance. Despite these constraints, CMA’s lower environmental effect makes it an appealing option to HMA in some applications [74]. Several studies have found that cold mix outperforms hot mix in terms of resource usage and greenhouse gas emissions during the production and placing stages. These benefits have been established in studies [73–75]. Goyer et al. [76] conducted a comparison study between cold mix
and standard hot mix procedures and observed that the amount of energy demand and greenhouse gas emissions for producing a 10 cm layer of pavement material were roughly double for hot mix manufacturing compared to cold mix manufacturing. These data imply that using cold mix asphalt pavement construction can greatly lower the carbon footprint of asphalt pavement construction. Also, Chappat and Bilal [77] conducted a study to assess CO\textsubscript{2} emissions from cold mixes, which were discovered to emit less CO\textsubscript{2} than other forms of asphalt. This is mostly attributed to the use of emulsion asphalt binder and that the mixing materials do not require heating, leading to lower energy demand and emissions throughout the manufacturing process. According to other studies, CMA uses less energy and emits less CO\textsubscript{2} during the production process than HMA. HMA has an energy consumption and CO\textsubscript{2} emissions of 132.3 kWh/ton and 35.5 kg CO\textsubscript{2}/ton asphalt mix, respectively, while CMA has just 37.4 kWh/ton and 7.1 kg CO\textsubscript{2}/ton asphalt mix, respectively [73]. Furthermore, the usage of cationic asphalt binder emulsion for asphalt pavement construction was discovered to have 15% to 20% less emission than conventional asphalt binder [73]. CMA has also been proven to be more energy-efficient and produces fewer emissions than HMA for the paving and maintenance of rural pavements, which account for a large fraction of the paved surface and are exposed to lower traffic loads. Because of its decreased environmental impact and cost-effectiveness, CMA appears to be an appealing solution for sustainable pavement construction [77].

4.2.3. Cold Recycling

Cold recycling includes removing an existing asphalt pavement, crushing it, and then mixing it with a recycling agent to create a new base material for road construction [78]. Cold recycling, unlike typical HMA procedures, does not require the materials to be heated to high degrees, making it a more ecologically friendly and cost-effective alternative [79]. Cold recycling technologies are classified into two types: cold in-place recycling (CIR) and cold central plant recycling (CCPR). Cold in-place recycling includes milling existing asphalt pavement, mixing it with a recycling agent, and then laying it back down and compacting it in situ. The cold central plant recycling strategy, on the contrary, requires transporting milled material to a central plant for processing, where it is combined with the recycling agent and then returned to the construction location for placement [79]. Cold recycling has major advantages over hot recycling in terms of lowering CO\textsubscript{2} emissions. One of the fundamental benefits of cold recycling is that most materials may be recycled on-site, reducing the requirement for significant vehicle travel, and thus lowering emissions [3]. Furthermore, because heat is not required for the asphalt mixture, the procedure greatly lessens energy consumption, resulting in lower fossil fuel usage and CO\textsubscript{2} emissions. According to Santos et al. [80], cold in-place recycling can decrease carbon dioxide emissions associated with raw material collection and mix manufacture by approximately 75% when compared to typical recycling procedures. Furthermore, because there is no energy demand in the production and aggregate sections, cold in-place recycling with emulsion has the lowest energy usage [3,81]. Cold recycling can also be used with other measures to lower CO\textsubscript{2} emissions from asphalt pavement; for example, reducing emissions may occur by optimizing pavement roughness by employing low rolling resistance combinations and further pavement restoration. Improving waste concrete carbonation and surface albedo can also assist in decreasing CO\textsubscript{2} emissions [3].

4.3. Energy Saving and Reduction Technology

High-energy-consuming sectors such as the asphalt pavement industry are currently promoting energy conservation and emission reduction [82]. Implementation of new energy-efficient and environmentally friendly technologies may increase construction costs, but an examination of the benefits of energy sustainability and emissions mitigation should prioritize emission reduction before taking economic reasons into account [82]. According to Liu et al. [83], the adoption of renewable energy sources, using electrical energy to power and hybrid fuel systems, are the key decarbonization approaches for road production.
machinery and equipment. These approaches are widely used to lower carbon emissions in the transportation industry.

4.3.1. Energy Reduction through Moisture Content

Moisture content, in addition to energy type, has an important influence on carbon emissions throughout the aggregate heating process, and it is relatively easy to adjust. Peng et al. [82] investigated how moisture content affected the aggregate heating procedure and carbon emissions when the asphalt binder-aggregate ratio was 5.1%, the mineral filler content was 4%, the mixing plant’s output ability was 300 t/h, and the aggregate heating temperature was 175 °C. According to the findings, the moisture content of aggregates affects the carbon emissions during the heating process. It was also revealed that the impact of moisture content on the aggregate heating process and carbon emissions increased linearly with moisture content. Thus, reducing aggregate moisture content by 1% reduces carbon emissions by 8.92%, saves energy by 9.12%, and lowers construction costs in the making of one tonne of asphalt mixture.

4.3.2. Energy Substitution and the Material Heating Process

The energy type utilized in asphalt pavement construction makes up for more than 60% of entire carbon emissions, making it an important topic for energy-saving and emission-reducing research. Converting traditional fuels to biomass-based fuels is one effective approach for reducing emissions in construction equipment. Karlsson et al. [56] discovered that using biomass-based fuel can result in a substantially higher proportion of emissions reduction, up to 90%. Another effective technology that has the potential to reduce emissions by 67% to 95% is electrified construction equipment. Similarly, a study by Fernández-Sánchez et al. [84], was conducted where a 20% biofuel blend named B20 was employed instead of diesel for off-road equipment and transportation machinery. From the studies, it was observed that biofuel reduced CO₂ emissions by 13%. Furthermore, the type of energy used has a significant impact on carbon emissions. As a result, more focus is given to altering the energy type and analyzing the consequences on energy savings and emission reduction [82,85]. Heating asphalt binder leads to about 15% of total carbon emissions because many asphalt mixture mixing units utilize coal for this purpose. Table 7 shows the benefits of switching the energy source for asphalt binder and aggregate heating and using various alternative energy sources. The table demonstrates that using alternative energy sources can significantly reduce carbon emissions during the heating process. While switching from coal to alternative energy sources would increase expenses, it would also cut sulphur dioxide and dust generation, as well as carbon emissions. Also, Table 7 demonstrates that heating the aggregate with natural gas can reduce carbon emissions. Based on the research of Peng et al. [85], the asphalt binder factory generates a large portion of CO₂ emissions due to the use of fossil fuels to heat and dry aggregates and the acquisition of power to operate the facility. Natural gas, as a replacement for heavy oil, can cut emissions by roughly 27.68% in heating aggregates and by 40.82% when compared to coal. Similarly, moving from electricity to natural gas can reduce CO₂ emissions by 65% [86]. However, [87] claims that plants that rely purely on electricity release more CO₂ than gas-powered plants, although this is dependent on the type of electricity generation. Effective CO₂ reduction strategies for cement industries include the utilization of bio-based fuel, waste as fuel, and electrical energy [56].

Table 7. The effect of material heating on the emissions reduction.
4.3.3. Emerging Technology and Recycled Waste Materials

Emerging technology and recycled waste materials are critical for lowering carbon emissions in asphalt pavement construction. Technological advancements have resulted in the development of new materials and heating technologies that can promote the use of clean energy and boost energy efficiency. Superconducting heating, solar heating, and infrared radiation heating are some of the new technologies being investigated, all of which increase the application of clean energy and enhance energy efficiency. Furthermore, the usage of environmentally friendly materials such as bio-based fuels, waste-based fuels, and biomass-based fuels can significantly cut carbon emissions. It is possible to efficiently reduce carbon emissions and promote green road construction by using these innovative technologies and materials in asphalt pavement construction [82,84]. Other types of emerging technology are permeable, perpetual, and smart pavement. A study conducted by Brown [88] compared the carbon footprint of perpetual pavement with that of conventional pavement. The study discovered that while perpetual pavement had a greater carbon footprint during its initial construction than conventional pavement, it had lower GHG emissions during its service life. This suggests that, despite greater initial construction emissions, permanent pavement is a more sustainable alternative for decreasing carbon footprint in the long run. Also, a study on a smart road conducted by Guerrieri et al. [89] combines technologies like recycled asphalt pavement, lime stabilization, safety restrictions, and cooperative transportation function to demonstrate a considerable reduction in CO$_2$ emissions when compared to traditional methods for road construction. The study calculated the smart road’s life cycle CO$_2$ emissions and its potential for global warming, demonstrating that smart asphalt roads could be an effective strategy for lowering carbon emissions. Moreover, Liu et al. [90] conducted a study that compared the CO$_2$ emissions produced by porous asphalt pavement with conventional impermeable asphalt pavement. The study observed that the use of porous pavement greatly lowered CO$_2$ emissions. Also, the porous pavements were discovered to have a cooling impact and might be employed to decrease urban warming.

Furthermore, changing the asphalt pavement construction techniques can also help to reduce carbon emissions during the mixing and paving of asphalt pavement; it is critical to consider using bulk asphalt binder rather than bottled asphalt [82]. This is because removing the bucket from bottled asphalt before use is a required step that can contribute to higher carbon emissions. To bypass this process, several asphalt binder mixing stations have begun to use bulk asphalt. Additionally, contemporary asphalt heating tanks use waste heat to heat barrelled asphalt, improving energy utilization efficiency. In conclusion, employing bulk asphalt binders throughout the heating process can significantly cut energy usage and carbon emissions. Using bulk asphalt instead of bottled asphalt will decrease energy usage and carbon emissions by roughly 11.36% [82]. Table 8 provides a summary of the research findings on numerous low-carbon-emission asphalt pavement technologies.
Table 8. An overview of the research findings on several technologies for low-carbon emission asphalt pavement.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Technology Utilized</th>
<th>Findings</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[52]</td>
<td>Cold recycling</td>
<td>The use of cold in-place recycling reduces the usages of aggregate, transportation, and plant consumption, all of which have advantages to CO₂ eq released (a decrease of 9% throughout the entire lifespan and 54% when only the recycling phase is included).</td>
<td>When the method is paired with additional steps such as optimizing pavement roughness and optimizing waste concrete carbonation, CO₂ emissions can be significantly reduced.</td>
</tr>
<tr>
<td>[91]</td>
<td>WMA</td>
<td>WMA has been proven to reduce CO₂ emissions by 10–40% at asphalt plants, making it a more sustainable option for pavement construction</td>
<td>More research and consistent statistics on the environmental impact and long-term durability of WMA during its life cycle, as well as its impact on worker health and safety, are needed.</td>
</tr>
<tr>
<td>[72]</td>
<td>HWMA</td>
<td>The application usage of HWMA can cut CO₂ emissions in the production process by up to 58% compared to HMA.</td>
<td>Further research on its long-term viability and performance, potential effects on worker safety and health, and cost-effectiveness, when compared to other asphalt mixtures, is needed.</td>
</tr>
<tr>
<td>[56]</td>
<td>Energy substitution</td>
<td>Biomass-based fuel and electric construction equipment significantly reduce carbon and GHG emissions, with biomass-based fuel cutting carbon emissions by 36–90% and electrical construction machinery reducing GHG emissions by 67–95%.</td>
<td>More research on the scalability and feasibility of using this construction equipment on larger scales, as well as the fiscal and life cycle analyses, are needed.</td>
</tr>
<tr>
<td>[81]</td>
<td>Cold recycling</td>
<td>When compared to conventional HMA production, the usage of cold recycling technology results in a 52% reduction in greenhouse gas emissions.</td>
<td>Research on the potential environmental impacts and economic sustainability of large-scale cold recycling technologies in the pavement industry is required.</td>
</tr>
<tr>
<td>[85]</td>
<td>Energy substitution and WMA</td>
<td>Natural gas reduces carbon emissions by 27.68% when compared to heavy oil, and it reduces emissions by 40.92% when compared to coal when heating asphalt binder. Furthermore, by adopting WMA and low-carbon asphalt mixture technologies, carbon emissions from asphalt mixtures can be reduced by 27.3% and 48.6%, respectively.</td>
<td>More research is required on asphalt pavement’s long-term durability and performance, as well as the potential impact of these technologies on pavement design and construction.</td>
</tr>
<tr>
<td>[80]</td>
<td>Cold recycling</td>
<td>Due to the use of existing materials and decreased energy usage, cold in-place recycling can lower CO₂ emissions by up to 75% when compared to conventional construction processes.</td>
<td>More studies into the most efficient and sustainable combinations of materials and technologies, as well as financial viability and long-term viability in varied geographic and environmental situations, are needed.</td>
</tr>
<tr>
<td>[82]</td>
<td>WMA</td>
<td>The study reveals that WMA has the potential to reduce CO₂ emissions at asphalt binder plants by up to 35% compared to the conventional method.</td>
<td>More research is needed to thoroughly assess the technologies and investigate their long-term performances, as well as optimize the process to achieve higher CO₂ reduction rates while maintaining mixture performance.</td>
</tr>
<tr>
<td>[86]</td>
<td>Energy substitution and WMA</td>
<td>The study indicates the feasibility to attain a 65% decrease in CO₂ emissions by replacing electricity with natural gas, whereas replacing electricity with oil or diesel can result in a 50% to 51% reduction in CO₂ emissions.</td>
<td>More research on the field adaptability and practicality of deploying this technology, as well as financial and energy cycle assessments, are necessary.</td>
</tr>
<tr>
<td>[68]</td>
<td>WMA</td>
<td>According to the study, WMA has the prospect to lower CO₂ emissions by up to 30–40% in asphalt plants while also lowering working temperatures by 30 °C.</td>
<td>Further research into the long-term durability and performance of WMA pavement, as well as the economic feasibility of the technology in various regions and asphalt gradations, is needed.</td>
</tr>
</tbody>
</table>
5. Discussion

This systematic review presents three key aspects discussed in the literature based on the reviewed articles: the factors driving the adoption of recycled waste materials and technology for achieving low carbon emissions in asphalt pavement, the perspectives and challenges encountered when implementing this technology, and recommended strategies to overcome these drawbacks.

5.1. Key Findings

The following are the key findings in adopting recycled waste materials and technology for low carbon emission in asphalt pavement, based on the articles analyzed in the systematic review:

- It was observed that the incorporation of recycled waste materials and technology in asphalt pavement can help provide considerable environmental benefits by lowering carbon emissions and reducing the total environmental footprint. Additionally, the use of sustainable alternative technologies like WMA and cold recycling reduces energy use and emissions during asphalt manufacture by lowering mixing and compaction temperatures.
- The study found a significant concentration in the field of material-related technologies application for low-carbon asphalt pavement. These technologies employ several strategies, including the use of waste material, mixing procedures, and greener energy. When considered and employed collectively, these methods have a great potential to lower CO₂ emissions, with studies predicting a reduction of up to 70% in emissions.
- To ensure the dependable and consistent use of recycled waste materials and technologies for low-carbon asphalt pavements, standardized testing techniques and performance standards should be devised. Technical compatibility investigations should also be conducted to assess the influence of recycled waste materials and technologies on current asphalt production and construction practices.
- When it comes to construction-related technologies, there is much emphasis on strategies to reduce mixing temperatures, as well as on investigating sustainable energy alternatives and improving recycling and low-carbon emission technology. WMA, HWMA, and cold mixes have been developed to replace the high-emission HMA strategy while replacing conventional energy sources with natural gas or electric sources, and biomass fuels can be considered viable measures to lower asphalt plant CO₂ emissions.
- There are currently no standardized rules or processes for the development, design, or production of larger-scale mixtures that comprise recycled waste materials and technologies for low-carbon asphalt pavement. The lack of set norms and standards may impede both interested parties and industry professionals from adopting and implementing these recycled waste materials and technologies.
- Furthermore, current studies have depended mostly on experimental trials to identify the optimum proportion of utilizing waste material and technology in mixtures, emphasizing the need for more field-based research to examine the effectiveness and durability of these mixtures in real-world contexts.
- Most research studies on emission reduction methods are limited in scope because they focus on discrete aspects rather than taking a complete whole-life-cycle approach. Furthermore, these studies frequently include inconsistencies in system boundaries and functional units, which makes assessing the efficacy of competing technologies in decreasing emissions difficult.

5.2. Motivations for Adopting Recycled Waste Materials and Technology in Asphalt Pavement to Reduce Carbon Emissions

Circular economy and resource conservation: The use of recycled waste materials encourages resource conservation while also supporting the ideas of a circular economy. Valuable resources can be saved by reusing or recycling materials such as RAP and RAS,
minimizing the requirement for new raw materials. This strategy also minimizes trash generation and landfill use, resulting in a more sustainable and efficient asphalt pavement sector.

Environmental sustainability: Improving the environmental sustainability of asphalt pavements is the fundamental motivator for combining recycled waste materials and technologies. Conventional asphalt binder and mixtures generate considerable amounts of CO₂ and have detrimental effects on the environment. It is possible to lower the carbon footprint and alleviate the environmental impact of asphalt pavement construction and repairs by utilizing recycled waste materials and technologies. Also, by using alternative energy sources during heating and construction, the asphalt sector may contribute to reducing climate change and improving air quality.

Environmental and regulatory compliance: Government and transportation agencies’ increasingly stringent environmental laws and sustainability goals are encouraging the utilization of recycled waste materials and technologies in asphalt pavement. The application of low-carbon materials and technologies complies with these legislative criteria and assists agencies in meeting their sustainability goals. It also helps infrastructure projects’ reputations by displaying a commitment to environmental conservation and sustainable development.

Asphalt pavement performance: According to studies, using recycled waste materials and technologies enhances the performance and durability of asphalt pavements. Incorporating RAP and RAS, for example, into asphalt pavement has been demonstrated to improve mechanical performance as well as resistance to permanent deformation. Similarly, bio-based modifiers have been demonstrated to improve asphalt binder-aggregate adhesion, resulting in increased pavement durability and lifespan. Thus, the determination to produce sustainable, high-performance asphalt pavements motivates the aim to achieve sustainable practices.

Climate change mitigation: The pressing need to lower carbon emissions and mitigate the effects of climate change is a major key incentive for combining recycled waste materials and technologies in asphalt pavement. The extraction and modification of fossil fuel-based asphalt binders contribute to greenhouse gas emissions throughout the production and use of conventional asphalt products. It is possible to drastically reduce carbon emissions related to asphalt pavement construction and maintenance by using low-carbon materials and technologies, such as bio-based binders or recycled materials.

5.3. Perspectives and Issues Encountered When Implementing Recycled Waste Materials and Technology

Cost factors: When compared to conventional asphalt materials, recycled waste materials and technologies may have greater initial costs. The extraction, processing, and treatment of some recycled waste materials, such as RAP and bio-based additives, might be more expensive than conventional asphalt materials. The cost-effectiveness of sustainable alternatives must be thoroughly analyzed, considering their performance benefits, life-cycle costs, and techno-economic analysis. Thus, innovative funding strategies and incentives can assist in overcoming the initial cost hurdles associated with the adoption of recycled waste materials and technologies.

Technological limitations and compatibility: The compatibility of recycled waste materials and technologies with current asphalt production and construction practices may be difficult. Integrating recycled waste materials and low-carbon-emission technology into pavement construction practices may demand improvements to existing production methods and equipment. For example, the use of WMA involves changes in mixing and compaction temperatures, which may influence the long-term durability and mechanical properties of the asphalt pavement. Equipment compatibility, facility modifications, and the requirement for additional quality control measures can all cause issues. To overcome these constraints and enable widespread acceptance of recycled waste materials and technology, technological advancements and innovations are necessary.
Performance and durability: Ensuring that the performance and durability requirements are met is one of the key problems noticed in effectively applying recycled waste materials and technology for low carbon emissions in asphalt pavement. When compared to conventional materials, sustainable alternatives have distinct physiochemical and performance characteristics. Thus, to guarantee that these materials meet or surpass the performance standards defined for asphalt pavements, it is pivotal to extensively examine their long-term performance in terms of permanent deformation, fatigue life, water damage, and long-term usability.

Inconsistent performance outcome: The performance of asphalt pavement produced from recycled waste materials and technologies can vary based on numerous aspects, including material quality, source, and processing. As a result, it is critical to create standard performance requirements and testing procedures to ensure the dependable and consistent use of recycled waste materials and technologies in asphalt pavements.

Material availability and consistency: The availability and consistency of sustainable resources can be challenging. The availability of bio-based binders or specific recycled materials, for example, may be limited or vary locally. Material property and quality inconsistencies can have an impact on the dependability and predictability of low-carbon asphalt mixtures. To overcome these issues, efforts should be made to establish dependable supply chains, quality control procedures, and material requirements. Furthermore, the availability of relevant recycled waste materials and technologies can vary locally, influencing the total expense and effectiveness of sustainable and low-carbon asphalt pavements.

The review highlights the challenge in implementing carbon-reduction efforts, with a recognized gap between research and practice. While many researchers have recommended techniques to reduce carbon emissions, there is a paucity of practical applications in research investigations. As a result, more study is needed to address the practical execution of these methods, with an emphasis on carbon estimation and the development and implementation of mitigation strategies to ameliorate the existing situation.

6. Conclusions

Based on the systematic review and scientometric analysis using PRISMA and VOS viewer, the following conclusions were drawn about recycled waste materials and methods for low carbon emission in asphalt pavement:

The study aided in the identification of numerous recycled waste materials that might be employed in asphalt pavement to reduce carbon emissions. Among the materials identified are RAP, crumb rubber, recycled aggregate, biochar, palm oil fuel ash, and bio-based binders. These materials can help to lessen the environmental consequences of asphalt pavement production and maintenance.

For the low-carbon-emission technology, the study examined various methods aimed at decreasing carbon emissions in manufacturing and using different strategies targeted at lowering carbon emissions in the manufacturing and use of asphalt pavement. These featured energy-efficient manufacturing approaches like cold mix and warm mix asphalt technologies, which reduce production temperatures and energy requirements. Innovative construction approaches, such as cold recycling and alternative energy sources during heating and production, were also identified for their potential to lower overall carbon emissions.

Currently, most studies in the field are primarily focused on three primary areas: waste materials, reduced asphalt mixing temperature, and energy replacement. These locations are being targeted because they can dramatically reduce CO$_2$ emissions. However, the integration of numerous materials and technologies tends to result in a significant decrease in CO$_2$ emission.

More studies and investigations are needed to include a broader range of components such as base layers, subgrade, and surface treatment of asphalt pavement structures, which would encourage a more comprehensive and integrated approach to sustainable and low-carbon asphalt pavement development, addressing the current emphasis on pavement-related issues such as mixtures and performance.
From the scientometric analysis carried out using VOS viewer, the study identified the distribution of research publications, interaction networks, and emerging trends in the field of recycled waste materials and technologies for low carbon emissions in asphalt pavement.

The rapid pace of scientific research necessitates the use of qualitative systematic and scientometric analyses, which bring significant benefits. The qualitative systematic and scientometric analyses provide significant benefits by combining data from the literature, providing practical recommendations, incorporating creative results, identifying research gaps, and improving collaboration. These papers are critical resources for professionals and academics interested in learning more about sustainable and low-carbon asphalt pavement.

Overall, this study provides important insights into recycled waste materials and technologies for low carbon emission in asphalt pavement construction and emphasizes the importance of employing recycled waste materials and technologies to reduce carbon emissions in the asphalt pavement industry. Furthermore, the findings contribute to the body of knowledge in this area and may affect future research and development efforts in the sector.

7. Future Studies and Research Niche

In contrast to conventional asphalt pavement materials and production processes, the use of recycled waste materials and technologies for low-carbon asphalt pavement is distinguished by its superior sustainability and decreased environmental footprint. Nonetheless, due to the embryonic nature of these recycled waste materials and technologies, further research in the following sectors is recommended.

- Based on the review’s findings, scientometric analysis, and discussions, future research should investigate broadening the focus beyond carbon emission studies in most developed countries like China and the United States. Furthermore, more research in underdeveloped nations is required to address the obvious lack of studies in that environment.
- To have a thorough grasp of worldwide low-carbon-emissions asphalt pavement, researchers must widen their investigations to include nations other than the ones currently researched. This approach would allow for a more realistic assessment of the effectiveness, obstacles, and possible possibilities associated with low-carbon-emissions asphalt pavement on a worldwide scale.
- There is a gap between experimental and field performance when it comes to implementing carbon mitigation techniques in asphalt pavement. As a result, to confirm the reliability of the findings, more study is required to focus on the practical implementation of these ideas. Thus, further detailed studies are required before broad full-scale field performance and application.
- Most previous studies focused on adopting one sustainable material or technology for low-carbon asphalt pavement at a time. It is both encouraging and critical to use and combine a variety of waste materials and technology techniques in the asphalt paving sector to improve performance, harness sustainability, and reduce carbon emissions.
- Despite the comprehensive investigation of asphalt pavement CO₂ emissions, the prevalence of uncertainties in assessment boundaries, data, and techniques makes cross-comparisons difficult, and needs the development of general evaluation standards, as well as the inclusion of susceptibility and uncertainty assessments, in future studies.
- It is highly advised to use advanced technology such as artificial intelligence for the modeling, and optimization in the field of sustainable and low-carbon technology. These techniques are extremely useful in assessing the CO₂ emissions and energy demands of various strategies, both independently and when integrated with other relevant technologies.
- More studies on field investigations in various geographies and climatic situations to validate laboratory research findings about the environmental and economic benefits
of using sustainable and low-carbon technologies in asphalt pavement, as recorded in the existing literature, are encouraged.

- Further investigation and testing of WMA technology integration with other asphalt technologies, such as RAP and bio-asphalt technologies, are needed to address and reduce the CO₂ emissions and energy consumption associated with the traditional construction process.
- More in-depth examinations and evaluations of road construction techniques/processes, as well as waste materials, are required for low-carbon emission roads. Furthermore, more research is needed on the ultimate physio-mechanical reactivity of asphalt binders and asphalt mixtures to pavement material components.
- The present study considered only a limited number of waste categories/products that allow CO₂ emissions reduction. However, other waste products within specific waste categories (such as biochar, bio-oils, polymers, etc.) can provide positive either environmental or economic impacts on the production of paving materials, but these are out of the scope of the present study.

In summary, future studies should focus on correlating the findings of large-scale field experiments. Given that numerous approaches for sustainable and low-carbon technology in asphalt pavement, as defined in the existing literature, are still in the pilot phase, more standard assessments are required to determine their suitability for general deployment.


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