sustainability

Review

A Comprehensive Review of Biochar Utilization for Low-Carbon Flexible Asphalt Pavements

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Abstract: A large amount of biomass waste is produced globally, and its production and improper management are major environmental issues. Pavement industries consume large amounts of natural resources and adversely impact the environment. Thus, the utilization of waste materials, such as biochar from biomass, has been prioritized as an innovative and sustainable strategy. However, there is currently a paucity of knowledge regarding the utilization and performance of biochar in flexible asphalt pavements. Thus, the purpose of this study was to provide a comprehensive literature review of studies conducted between 2010 and 2022 on the advancement and application of biochar in flexible asphalt pavement production. This review also highlights biochar production materials (feedstocks) and processes. This review further evaluates the viability of biochar as a carbon-neutral material utilized in producing asphalt pavements. Owing to its exceptional and variable physicochemical properties, biochar has demonstrated improved performance for a variety of applications in flexible asphalt pavements. According to the review, for optimum performance, a particle size < 75 µm is recommended as a modifier for asphalt binders and mixtures with a content range of 5–10 wt.% of the binder, while a particle size of 1–5 mm is recommended as a filter layer. In addition, the review concluded that as a carbon-neutral material, biochar has many possibilities that can aid in reducing CO_2 emissions. The challenges and future perspectives, underlying study niches, and future research suggestions for biochar application in the flexible asphalt pavement industry are also highlighted. As a result, this review will contribute to the increased sustainability and eco-friendliness of flexible asphalt pavements by encouraging the transition to carbon-negative and emission-reducing pavements. The current review will assist researchers in identifying research gaps that will encourage the high-potential, sustainable, and multifaceted application of biochar in the pavement industry for greater environmental benefits.

Keywords: flexible asphalt pavement; sustainability; biochar; carbon-neutral material; CO_2 emission; biomass

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1. Introduction

Pavements are one of every nation's most valuable resources, making many fundamental social services accessible. Pavements increased by approximately 12 million kilometers between 2000 and 2017 [1]. By 2050, the construction of newly surfaced pavements is predicted to reach 25 million kilometers worldwide [2]. This is an incredible rate of road expansion, in terms of both length and territory. However, as the nation grows, its population also grows. This leads to an increase in traffic loads and vehicles. These increases in traffic loading and environmental conditions lead to early pavement deterioration and performance. Thus, to mitigate these issues and improve performance, various construction methods and materials have been utilized to improve the asphalt binder and mixture properties [3,4]. With recent sustainable development and environmental protection being key objectives in every construction, finding a solution to the question of where and how to dispose of the significant amount of waste produced is a global concern, and the amount of waste produced is continuously rising [5,6]. Thus, to solve these critical issues, the 2030 Agenda contains a few Sustainable Development Goals (SDGs), including SDGs 11 and 12, which promote circular and sustainable manufacturing and use, and nine of the primary goals are to reduce waste [7,8]. There are numerous economic benefits to utilizing this secondary raw material. It makes a major contribution to sustainable resource monitoring by reducing reliance on natural resources and adverse environmental effects [7,9,10]. One of the key initiatives for the future toward a sustainable environment is the application of biomass in flexible asphalt construction.

Biomass waste is one of the major contributors to waste generation, and the process of burning biomass to generate energy is a method for generating bioenergy. The lignin found in plant biomass has a high energy content, which facilitates the thermal conversion of the carbohydrate component of the biomass into biofuels or biomaterials [11]. Over the past decades, concerns regarding carbon emissions related to global warming have increased [12]. Furthermore, it is widely acknowledged that biomaterials have no greenhouse gas emissions owing to the naturally occurring CO_2 exchange [13]. This is because they are made from renewable resources, have lower costs as they are produced locally, are more ecologically friendly, and require less energy than conventional products. Recently, biomaterials have become one of the main topics of focus in the pavement industry [12]. Thus, interest in using biomaterials to build pavements has grown because of the need to find alternative renewable technologies for asphalt pavement construction and maintenance [14]. Biofuels are created from biomass through a variety of intricate chemical processes. The dominant process might change significantly depending on the operating temperature, and typically, several of these processes occur simultaneously during the process [15]. These methods involve the volatilization of waste in the absence of air to produce syngas, liquid, or bio-oil, as well as a solid product (biochar) as the primary end product [16]. Biochar is a permeable solid carbon substance formed when biomass is thermochemically converted in an inert atmosphere at relatively low temperatures. Thermochemical conversions, such as gasification, pyrolysis, and hydrothermal processes, are commonly used to produce biochar [15]. Biochar has a porous structure with a large specific surface area and many surface functional groups; it is also inexpensive to produce and has less influence on the environment [17]. It is nonflammable, has low thermal conductivity, high carbon content, and is chemically stable [18]. It contains nitrogen, hydrogen, and inorganic components. Both H/C and O/C ratios significantly influence the characteristics of biochar [19]. Furthermore, biochar is highly resistant to biological and chemical deterioration [20]. It is a renewable and sustainable substance that is capable of reducing carbon emissions [21,22].

Figure 1 shows an overview of the published articles retrieved through the Scopus data repository and mapping on the application of biochar or hydrochar using VOSviewer software [23]. Most studies have used biochar or hydrochar as adsorbent materials in wastewater treatment, photocatalytic materials for wastewater treatment, sustainability, circular economy, anaerobic digestion, heavy metal removal, and soil stabilization [24–28]. The physicochemical characteristics of biochar, including its surface area, ability to exchange cations, ability to retain water, and the size and distribution of pores, are significantly influenced by the type of biomass utilized as feedstock [18]. Greenhouse gas emissions can be mitigated by converting biomass into biochar, and more carbon can be captured [17]. An estimated 140 gigatons of biomass waste is produced globally each year because of agricultural and forestry operations [29]. Numerous types of waste biomass, such as wood waste, agro-waste, municipal/industrial sludge, organic waste, and manure, are potential feedstock sources that can be processed into biochar [29]. According to the literature, producing biochar from waste biomass lowers the operational costs associated with the disposal of these waste products [30].

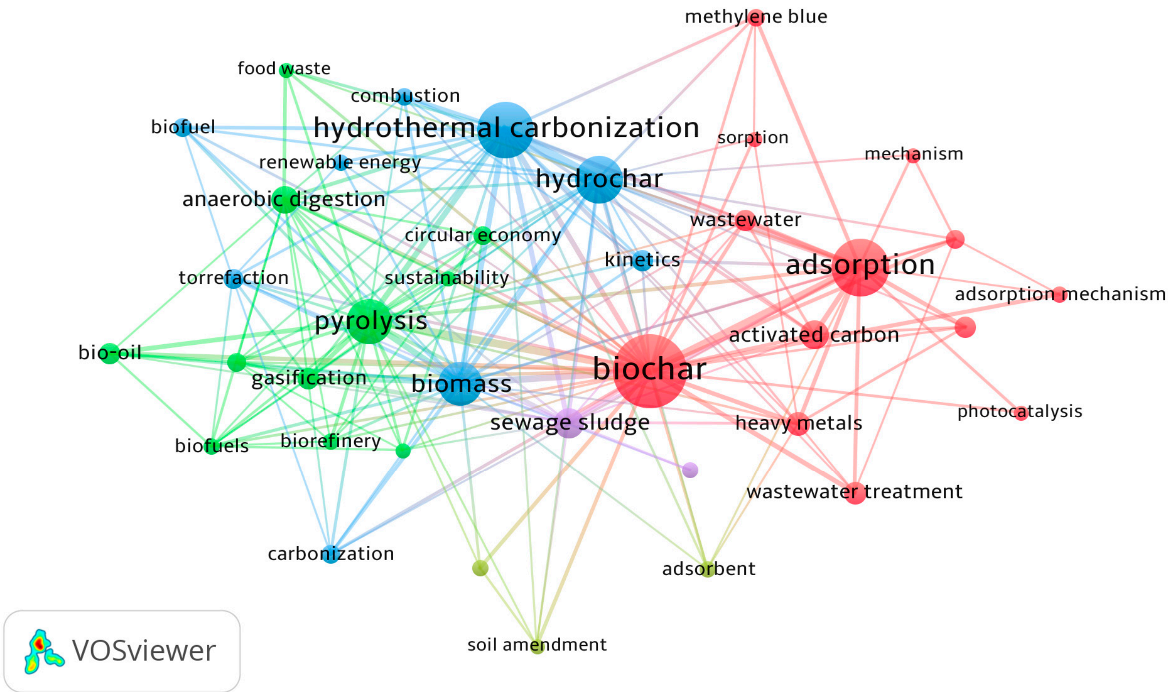

Figure 1. VOSviewer mapping visualization of biochar-related studies and applications.

However, the biomaterials used in the pavement industry for biochar applications have received little attention in the literature. Therefore, this study provides a systematic literature review on the application of various materials for biochar application in flexible asphalt pavement construction. This review also highlights biochar production materials (feedstocks) and processes. In addition, this review further evaluates the prospect and viability of biochar as a carbon-neutral material to produce asphalt pavements. It also discusses motivations, challenges, and future research directions, focusing on sustainability.

2. Methodology

In this study, a systematic literature review (SLR) was utilized, which is a comprehensive and detailed research approach that is systematically and particularly used to support the selection and screening of relevant articles [3]. It is a primary analytic method that determines, collects, validates, and translates all pertinent data related to a certain field of study, study objectives, or research approach. The SLR discussed in this study started in early October 2022. Figure 2 depicts the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) patterns for the study review employed in this investigation; thus, choosing research questions relevant to the study's objectives is required for this to be feasible. The use of PRISMA in pavement engineering is encouraged because it encourages scientific proof decision-making, aids in the identification of research gaps, allows for the evaluation of different approaches and materials, simplifies systematic reviews, and improves field knowledge. This can result in improved pavement design performance and durability, improved future research, better selection of the best approaches for specific applications, increased credibility of the findings, and a better understanding of asphalt pavements. Furthermore, the following conditions and assumptions were used for this study's PRISMA-based systematic review on the utilization of biochar in asphalt pavements: (a) papers must be peer-reviewed and relevant to the application of biochar in asphalt pavements. (b) A thorough search strategy was used. (c) Data from selected studies were extracted consistently and methodically. (d) The quality of studies performed in the paper must be evaluated using standard methods. (e) Appropriate statistical methods were used to generate and analyze the extracted data.

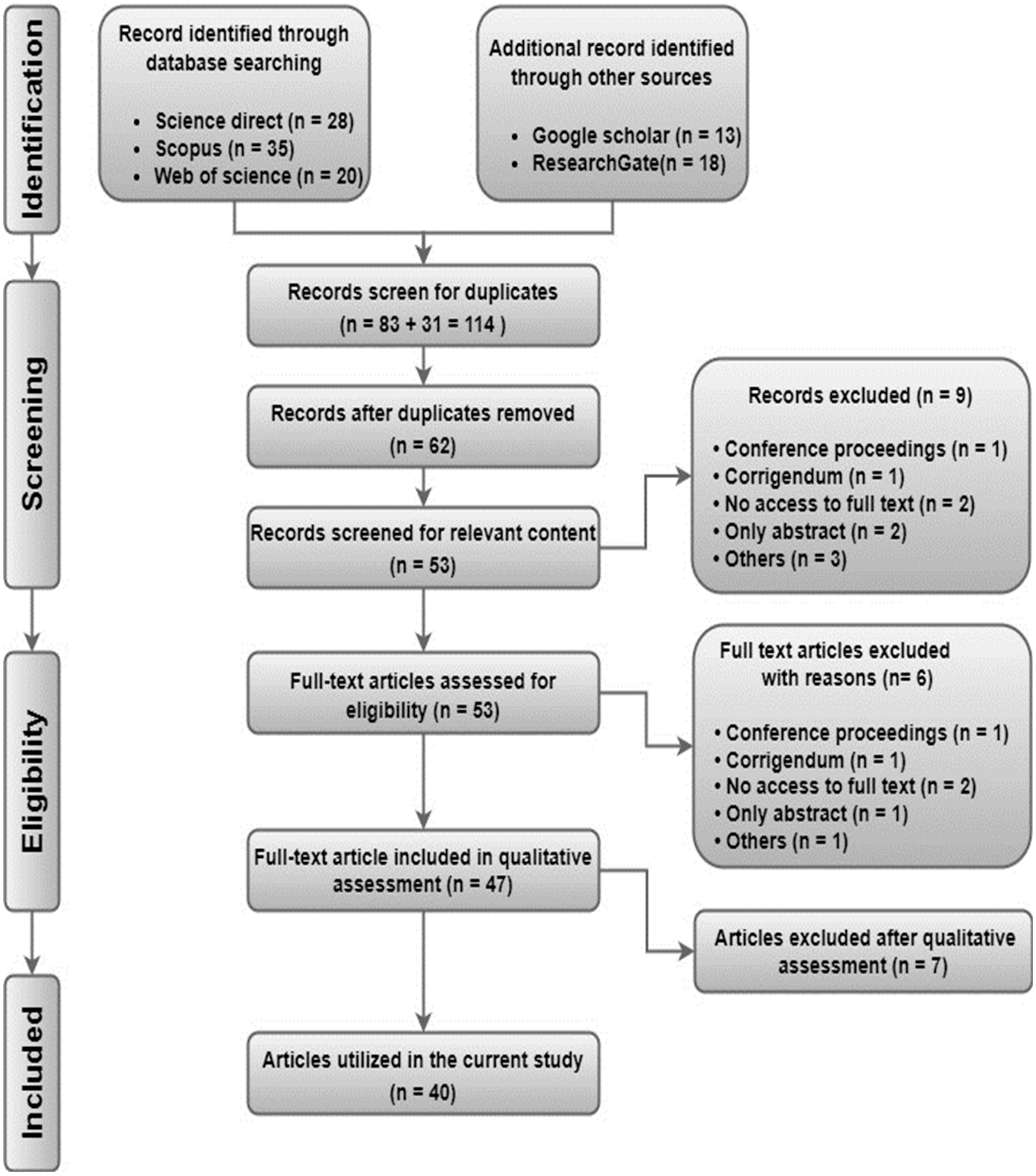

Figure 2. PRISMA study flowchart for article search and review process.

2.1. Study Research Question

With interest in the creation of sustainable and low-carbon biochar construction materials, various studies on the use of biochar have been prompted by the rapid increase in biomass waste. Thus, the main aim of this study was to establish an assessment of biochar in flexible asphalt pavement construction and assess the feasibility of biochar as a carbon-neutral material. The study questions were included in the literature review process to assist in the establishment of the review procedure. Therefore, developing questions and choosing the best strategy to respond to them is the most crucial component of any literature review. The main objective of this review is to evaluate the utilization of biochar and its viability as a carbon-neutral material in asphalt pavement applications. Table 1 lists the research objectives and corresponding questions developed in this study.

Table 1. The objectives and questions of the literature review.

	Objectives	Questions
1	To ascertain the utilization of biochar in flexible asphalt pavement and assess its influence on performance	What effect does biochar application have on the performance of flexible asphalt pavement, and how does it contribute to low-carbon pavements?
2	To assess the potential applications of biochar for a low-carbon flexible asphalt pavement	What are the prospects and applications of biochar that can be used to achieve carbon neutrality in flexible asphalt pavement

2.2. Study Scientometric Search Approach and Criteria

The approach used in this study for the primary systematic literature searches was centered on four (4) electronic databases. Databases were selected because they are some of the most comprehensive and accessible scientific resources, offering a wide range of data and promoting the improvement of competent research. Additional resources, such as "Google Scholar" and "ResearchGate," were used to yield additional records. Various biochar and hydrochar materials and their potential in asphalt binders and mixtures are still being investigated to improve sustainability and waste usage in asphalt pavement design. It is important to emphasize that the coverage of this review was from January 2010 to October 2022, and the articles-gathering process was concluded on 3 October 2022.

The following stage in the search strategy employed keywords in the article search to find scientific studies on biochar in flexible asphalt pavements. Initially, the TITLE-ABS-KEYS were made of "biochar in asphalt binder and mixtures." Consequently, the authors used the "Title" search to retrieve publications on the use of biochar in flexible asphalt binders and mixtures. The terms "biochar", bio-char", hydrochar, "asphalt binder, asphalt mixtures, asphalt mix, carbon neutrality, CO_2, and capture" were used in various combinations. All databases with advanced search options were searched using the logical operators AND/OR to join terms. In addition, the reference lists of the chosen papers were used for a secondary search to identify additional studies that met the criteria for this study.

2.3. Screening

The screening phase began with the elimination of duplicates. Numerous matches were discovered because four electronic repositories and two other sources were considered. Papers that remained after eliminating duplicates were further checked for significant content. The following forms were then eliminated: conference proceedings, corrigendum, editorial papers, no access to full text, just abstracts, and others.

2.4. Eligibility Criteria

Following the elimination of the repeated articles, the remaining articles were reviewed again for content relevancy to find the most significant articles to utilize in the SLR described in this study, and the most thorough investigation possible was conducted. This research was conducted by focusing on publications that contained scientific research, significant contributions, and enriched data. To identify pertinent research best for the studies, the collected data were compiled, and the inclusion and exclusion methods were used. A few papers were gathered from the designated repository for review. Equation (1) states that the criteria for the article inclusion or exclusion standard rate were calculated as a function of the significance ratio (S) for the included articles for a specified year (a), the overall number of suggested keywords (k), and the total number of preliminary articles in a specified year (y), and (m) represents the number of keywords linked together.

$$S^a = \frac{\sum_i^k \frac{m_i}{k}}{y^a} \tag{1}$$

In addition, Equation (2) was used to facilitate the inclusion and exclusion of articles [3]. Figure 2 depicts the inclusion criteria for articles selected for full review after filtering due to their high-quality relevance, established significance, and contribution to the study.

$$f(m_i) = \left\{ \begin{cases} included, & S^a < \frac{m_i}{y^a} \\ excluded, & (otherwise) \end{cases} \right\} \quad (2)$$

Using the projected time-lapse, this study examined 114 papers published between January 2010 and October 2022. However, we used the previously mentioned criteria for all the categories. The total number of publications relevant to this investigation was reduced to 40. This demonstrates that the use of biochar in flexible asphalt pavements is a new and growing research topic. The data were then transferred into Microsoft Excel in a table format, along with the entire document and related references, to be used in the creation of graphs and visualization. The data file was saved properly and analyzed using the Open Refine program, which is useful for cleaning up ambiguous data, converting formats, and duplications.

2.5. Descriptive Results Analysis

To analyze the descriptive results, the data for the current study were mapped in an Excel spreadsheet to evaluate and analyze the yearly publishing trend from 2010 to 2022. Figure 3 shows yearly research trends in biochar applications in flexible asphalt pavements. Owing to technological advancements, the use of biochar in asphalt binders and mixtures has seen an increase in interest from the first article on the topic in 2010, up until the present (2022). This supports the assertion that scientific studies on the topic have increased because of the guidelines and initiatives on sustainability, which have received more relevance since 2015 because of the SDG Vision 2030. Additionally, it confirms earlier studies' conclusions that emphasize the significance of SDGs, circular economy, and bio-economy policies for the increase in publications [9]. With an annual publication rate of one paper, the number of studies on biochar in the asphalt sector has steadily increased. The number of articles published in 2022 was the highest (11), followed by 2020 and 2022, with six and seven articles, respectively.

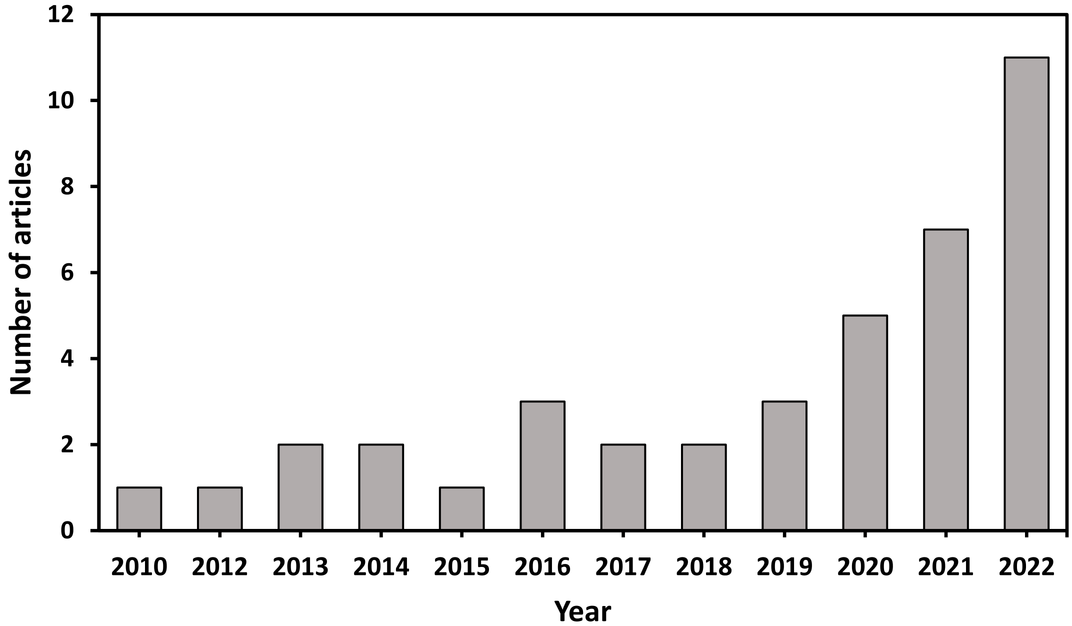

Figure 3. Annual research trends in biochar applications in flexible asphalt pavements.

It is pivotal to assess each nation's enthusiasm for different topic areas, according to the number of papers published. Thus, the industrial focus and geographic location of the articles were determined using qualitative data. The articles were categorized according to their location using content analysis, although neither term was present in the keywords. Figure 4 shows the biochar application studies on flexible asphalt pavement on a global continental scale, with the size of a sphere proportional to a country's influence on the research topic. From the analysis, it was observed that Asia, North America, and Europe had the highest number of articles (26, 20, and 18, respectively). These continents produce large amounts of waste due to their population and industrialization. Thus, they must develop strategies to reduce the effects of this enormous volume of waste, such as reprocessing or converting it into substitute resources or renewable resources. However, continents such as South America, Africa, and Australia have the least with three, two, and two research articles, respectively.

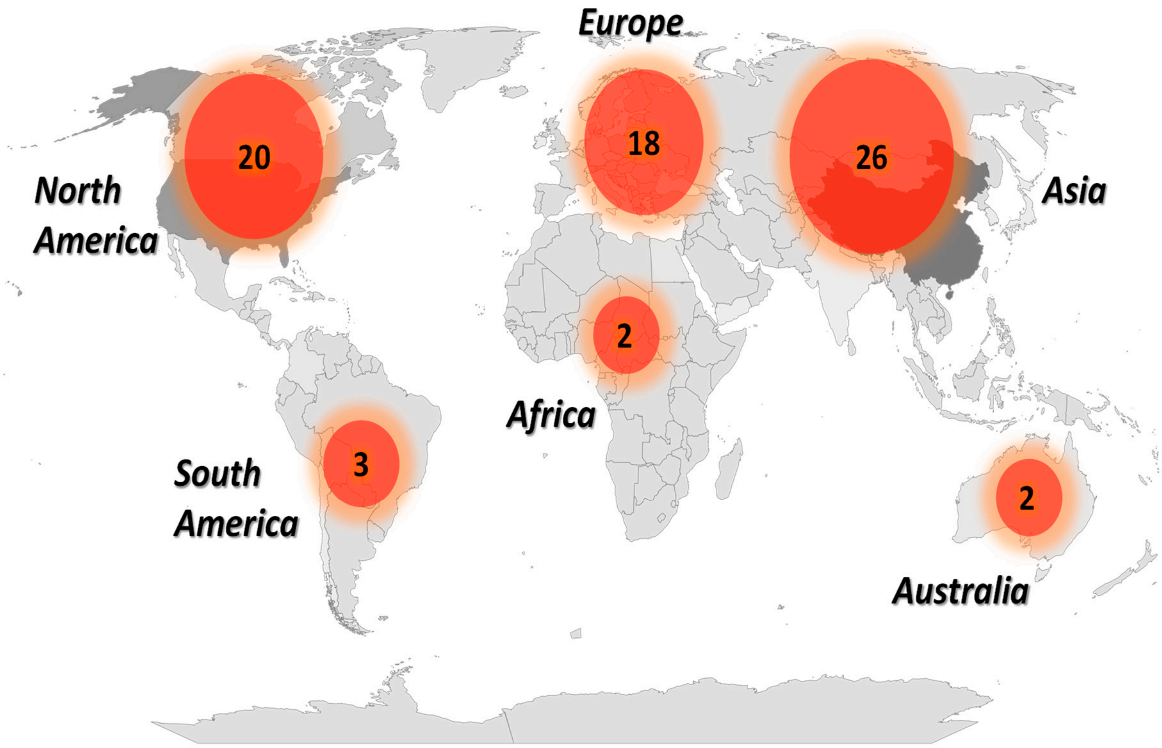

Figure 4. Biochar-related application studies on flexible asphalt pavement on a global continental scale.

Furthermore, Figure 5 shows the research on the use of biochar in flexible asphalt pavements in various countries. It is worth noting that different countries, including 23 from all over the world, participated in the study of biochar in asphalt binders and mixtures. China has the most publications with 19 (23%), followed by the United States with 14 (20%) and Canada with six (8%). This can be attributed to the countries' bioeconomy strategies, which have prioritized manufacturing and high-tech innovation [9], as well as each nation's construction sector policies, which promote environmentally friendly and sustainable materials for construction. Poland and the United Kingdom have four articles each, while Switzerland has three articles.

This review examined 40 different sources of articles. This indicates that the use of biochar in asphalt binders and mixtures is gaining popularity. Figure 6 depicts the various journal sources and the percentage of articles published. According to the collectively published articles, only four sources published more than two articles related to this study. One of the sources was the journal "Science of the Total Environment," which contained seven papers. The journal publishes papers on engineered materials and processes to ensure a safe environment. The second-most prominent journals were "Transportation

Research Record," "Transportation Safety and Environment," and "Advanced Materials Research," which had five, three, and three articles, respectively. The journals "Biochar," "Journal of Cleaner Production," and "Coating" each have two articles.

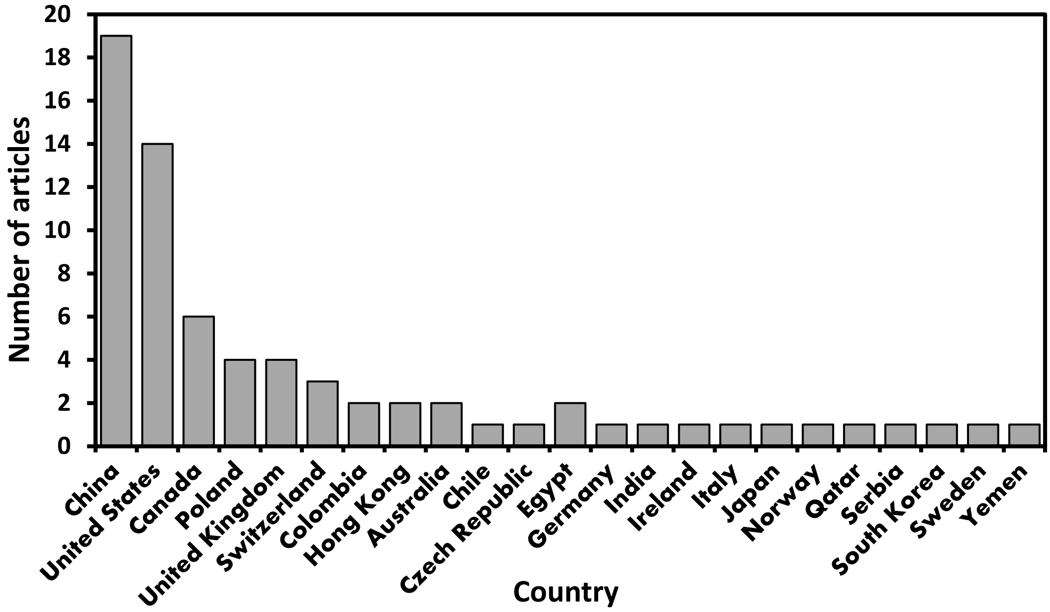

Figure 5. Studies on various biochar applications in flexible asphalt pavements across various nations.

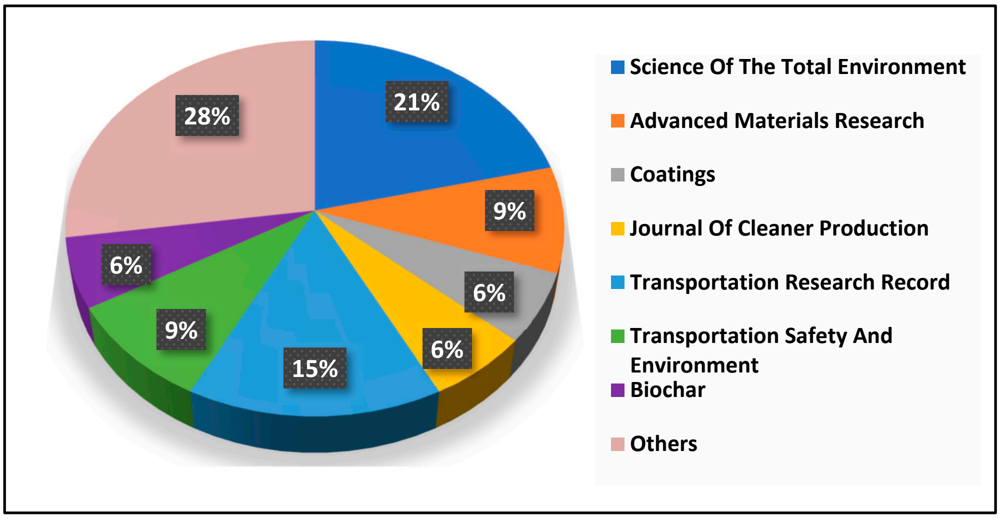

Figure 6. Journal source and percentage of articles published.

The remaining journals, accounting for 28% of the articles reviewed in this study, had at least one scientific article on biochar application related to flexible asphalt pavements that met the review inclusion criteria and were published in the following journals: Chemosphere, Bioresource Technology, Cogent Engineering, Energy And Fuels, Energy Technology, Environmental Chemistry Letters, Environmental Research, Environmental Toxicology and Chemistry, Fuel Processing Technology, Materials (MDPI), Plos One, Polish Journal Of Environmental Studies, Resources Conservation And Recycling, Revista Ambiente E Agua, Rilem Bookseries, Road Materials And Pavement Design, Sustainability Switzerland, Journal of Hazardous Materials, and Cleaner Materials.

3. Biochar

The origins of biochar can be traced back to the Amazon region, where black earth is created through cut-and-burn methods [31]. Biochar has been defined according to the European Biochar Foundation as "a porous, carbonaceous material formed by biomass pyrolysis and utilized in such a method that the embedded carbon acts as a long-term sink or substitutes for conventional carbon in industrial activity" [32]. The International Biochar Initiative (IBI) defines biochar as a solid substance produced by biomass that is converted to various biomaterials via a thermochemical process. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) has designated biochar as a negative emission technology. Biochar is a permeable carbonaceous solid produced by thermochemically converting various waste biowastes into an air environment [33], and it does not degrade easily with a high level of aromatization [32,34].

Aside from the main component "carbon," biochar consists of a variety of auxiliary components that influence how materials act and function. Biochar has a porous structure with numerous functional groups, oxidants, and charges on its surface and a large surface area. Biochar can buffer the pH and participate in cation exchange, making it an electron acceptor and donor storage material [35]. Biochar has demonstrated multifunctional roles in a variety of civil engineering disciplines, including carbon capture, soil quality improvement, wastewater treatment, contaminant removal, air quality management, and proper waste management. This is due to the presence of high levels of carbon, pore structures, augmented surface functional groups, and inorganic compounds [30]. These properties give biochar a significant degree of reactivity and are primarily determined by biomass waste and biochar production methods [36].

3.1. Biochar Sources

Biomass sources are often waste generated from crop harvesting and bioenergy production. Most of these wastes, which are transported to several countries and infrequently utilized, might serve as a reliable source to produce biochar. Animal manure is a potential source of feedstock. Most of the time, biochar is made from dairy waste and chicken litter. In addition, the use of biochar from invasive plants, food waste, and bioenergy deposits has also been studied. Biomass utilized in biochar production is classified into two types based on moisture content: wet (>30% moisture content) and dry (<30% moisture content). This classification determines the production process that is used. Wet biomass includes industrial wastewater, algae, wastewater sludge, bovine manure, and seaweed, whereas horticultural, woody, and herbaceous biomasses are dry biomass. Generally, the chemical and physical characteristics of biochar are significantly influenced by the type and nature of processed biomass.

3.2. Biochar Production Process

Biochar can be synthesized using a variety of thermochemical techniques such as pyrolysis, torrefaction, flash carbonization, hydrothermal carbonization, and gasification. Biochar can be produced for different purposes; as a result, the properties of biochar can be modified to fulfill the functions to prepare it for a specified use [37]. In general, biochar is a product ranging from partially carbonaceous biomass to completely refractory carbon, with substantial heterogeneity in physicochemical features, mostly based on biomass, production parameters, and numerous treatment methods. In addition, the properties of biochar are significantly affected by production conditions, including residence duration, temperature range, and reactor type [38]. The main thermochemical biochar production process is illustrated in Figure 7. The biomass source, moisture content, and production processes should all be compatible with maximizing biochar yield and properties.

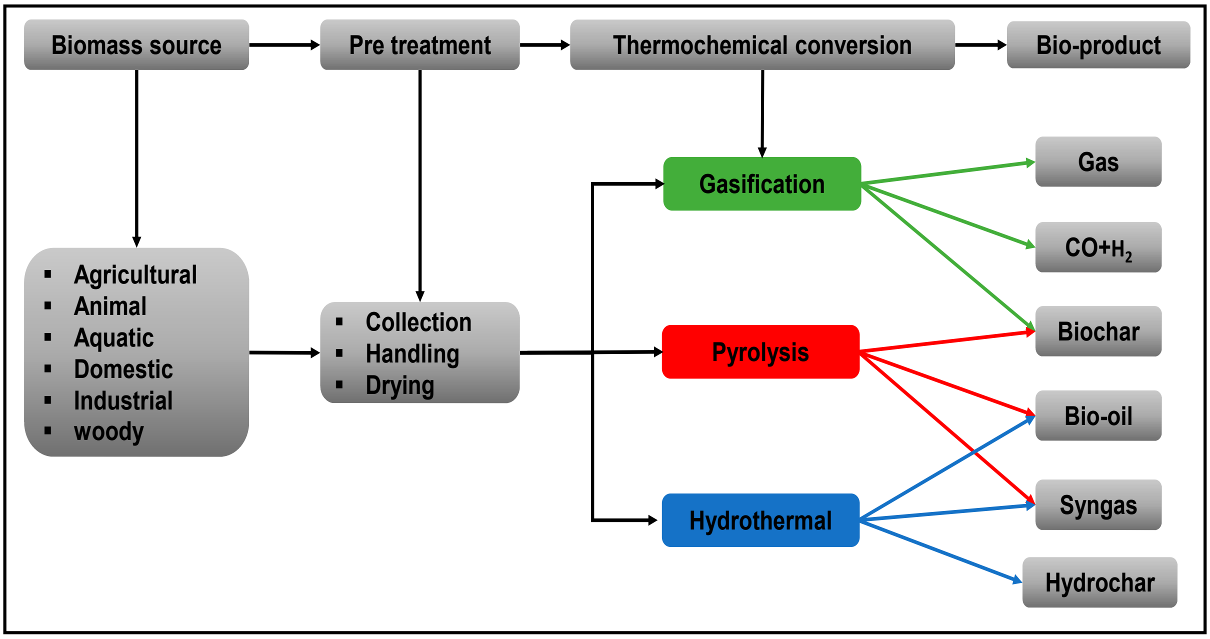

Figure 7. Biochar thermochemical production processes.

3.2.1. Pyrolysis

The term "pyrolysis" refers to the heat-induced breakdown of organic molecules in an air-limited environment at temperatures between 250 and 900 °C. This is an alternative method for producing valuable materials from biomass waste. When lignocellulosic substances are exposed to certain temperatures, reaction mechanisms such as thermal decomposition, disintegration, and linking occur, resulting in new and different product states, such as biochar, syngas, and bio-oil [39]. It is the most extensively used thermochemical method for producing biochar because of its ease of use at a technical level and its viability from an economic standpoint. The amount of biochar produced through pyrolysis is determined by the biomass type and composition as well as the pyrolysis constraints and temperature [39]. Temperature is the primary process variable influencing the properties and performance of biochar. The biochar yield decreased as the pyrolysis temperature increased. Depending on the operating conditions (temperature, heating time, duration, and pressure), pyrolysis can be classified into three broad categories based on their reaction temperature: (i) slow pyrolysis in the range of 300–550 °C with a long contact period and slow heating speed, (ii) intermediate pyrolysis in the range of 450–550 °C with a moderate contact time and heating speed, and (iii) fast pyrolysis in the range of 800–1000 °C with a short contact period and fast heating speed [39,40].

3.2.2. Gasification

Gasification is a thermochemical procedure that transforms biomass into biochar in an oxygen-deficient environment using a gasification agent, such as air or water vapor, either at ambient pressures or high temperatures above 750 °C. Approximately 85% of syngas is produced when air is utilized as the oxidizing medium, and the water gasification mode produces more H_2 with a higher heating value [38]. Gasification conditions, including temperature, characteristics of the biomass, gasification agents such as molecular oxygen, carbon dioxide, and steam, and air pressure, typically control the formation of pyrolytic gas and biochar. The production of porous structures with a greater specific surface area of biochar is facilitated by high temperatures, which encourage the emission of volatiles with increased production of biogas at the cost of a lower biochar yield [41]. A relatively low output of syngas and char was discovered, which may be the reason why the manufacture of biochar by gasification has only occasionally been reported. The production of distinct solid products in various gasification forms has been accounted for and their origins have been identified [30]. A strong carbon–alkaline interaction occurs for biomasses with high ash content and alkaline materials, such as food waste biowaste and wastewater sludge. Drying, heating, partial oxidation, and conversion are the typical order of the four processes that constitute the gasification process [42], and inlet flow, fixed bed, and liquid bed are the three primary categories under which gasification can be categorized as a gas-solid contact mechanism [39]. Generally, low yields of char and syngas are the main products of this process. Under these circumstances, biochar yields are relatively high to evaluate gasification as a practical biochar production process. However, gasification biochar is rich in pore structures, as opposed to pyrolytic biochar, which makes them a superior option as an additive in the construction industry for improving the properties and enhancing carbonation [30].

3.2.3. Hydrothermal Process

Hydrothermal technologies are seen to be a viable way to manufacture useful products from wet biomasses with less energy demand and a pre-treatment process. Hydrothermal technologies also play a crucial role because of the rising demand for environmental concerns, as the process is considered to be a carbon-neutral technology [15]. These processes can be divided into three groups based on their operation: carbonization, gasification, and liquefaction [15,38]. Hydrothermal carbonization is the most common method utilized for low-moisture, wet, and large biomass such as food waste, yard waste, and industrial wastes, and differs significantly from gasification and pyrolysis. This is because it has an advantage over other processes in that it can produce carbonized solids. The char that is created is usually referred to as hydrochar because the process is typically carried out under hydraulic pressure at low temperatures (180–250 °C) [38]. In addition, the procedure is thought to be a cheap process for dealing with biochar improvement since the biomass utilized requires less intensive drying pre-treatment [30,37]. In addition, the processing of biomass with higher moisture content is becoming increasingly rational. Temperature, residence time, pressure, and the water-to-biomass ratio are the main factors that determine the quality of the product [37]. Additionally, the hydrochar surface exhibited a higher degree of aromatization, with more oxygen-containing groups. The hydrochar production process differs from that of biochar pyrolysis. The long-chain cellulose is broken down into tiny, low-molecular-weight molecules (oligomers), then eventually into glucose that isomerizes and generates fructose [30]. It should be noted that biochar synthesized using hydrothermal carbonization differs from biochar produced using conventional pyrolysis in terms of its physical and chemical characteristics [43]. Various research noted that the yield of biochar from slow pyrolysis and hydrothermal carbonization procedures is greater than that of fast pyrolysis and gasification processes [37,38]. Besides hydrothermal carbonization, which yields hydrochar as the primary solid substance, two other methods, such as hydrothermal liquefaction and hydrothermal gasification, are also utilized to produce hydrochar, together with other by-product synthesis gas and bio-oil. The process of producing hydrochar as a viable sustainable material via hydrothermal conversions helps to generate power, decrease waste, and promote sustainability. Table 2 summarizes the major thermochemical biochar production processes.

3.3. Biochar Characteristics and Modification Methods

The physicochemical characteristics of biochar have a significant impact on its use; thus, they must be thoroughly assessed. The International Biochar Initiative has recently developed frameworks that provide defined practices and procedures for characterizing biochar materials and achieving more stable levels of yield and quality [37]. Thus, numerous characteristics of biochar have been revealed by its properties in both proximate and ultimate analyzes. Its effectiveness and performance are greatly influenced by significant physicochemical parameters, particularly cation exchange capacity, chemical size distribution, porosity, surface area, and pore size [36,39]. Biochar is composed of minerals in the ash component, as well as nitrogen, sulfur, oxygen, carbon, and hydrogen. Therefore, the characteristics of biochar differ depending on the circumstances surrounding its production and the type of biomass used. Biochar with a distinct elemental carbon content is produced when the O/C and H/C ratios are low because this causes more oxygen and hydrogen to be released during combustion [39]. To maximize yield and produce superior-quality biochar, it is essential to choose a compatible conversion process and parameters. Table 3 summarizes the proximate and ultimate studies on biomass raw materials for biochar production using different processes at various temperatures.

Table 2. Summary of major biochar thermochemical production processes.

Parameter	Production Process		
	Pyrolysis	Gasification	Hydrothermal
Biomass type	Dry	Moist	Wet
Moisture content	Low	Moderate	High
Capital cost	High	Moderate	Low
Process plant accessibility	Easily	Moderate	Scare
Operation	Simple	Mild	Complex
Biomass drying	Yes	Yes	No
Biochar yield	Low	Moderate	High
Oxygen present	Absent	Little	Absent
Energy consumption	High	Moderate	Low
Process temperature	High	High	Low
References	[37,39,44–46]	[37,39,45,47]	[38,39,44,45]

The performance of biochar can be improved by further modifying some of its intrinsic characteristics, which can be employed to suit different applications [37]. Biochar materials can undergo both pre- and post-process modifications to improve their yield and physicochemical properties. The pre-process methods might be physical, chemical, or biological, and they can vary depending on the biomass and application of the biochar [36]. However, the post-process includes modifying it physically or chemically to enhance its surface area, regenerating properties, surface functional groups, porosity, and composited nanoparticles [39]. Recently, methods such as amination, ultrasonication, microwaves, and milling have been widely used for modification. Biochar characteristics have been altered by various approaches for use in the environment. Chemical modification is the most commonly used approach [30].

Table 3. Proximate and ultimate analyzes of selected biochars synthesized from various raw materials using various production processes.

Raw Material	Production Process	Temp.(°C)	pH Value	Surface Area (m^2/g)	Dry Basis Proximate Analysis (%)				Dry Basis Ultimate Analysis (%)				Ref.
					M_C	A_C	V_M	F_C	C	O	H	N	
Rice straw	Pyrolysis	400	6.7	-	-	47.92	38.21	-	37.2	12.4	1.20	1.30	[37]
Switchgrass	Pyrolysis	500	10.8	188	-	7.80	-	-	84.4	4.5	2.6	1.1	[48]
Sugarcane	Pyrolysis	450		-	1.40	20.11	-	78.60	57.3	-	1.90	0.90	[49]
Nutshell	Pyrolysis	900	9.7	230	-	40.4	-		55.5	2.0	0.90	0.47	[50]
Bamboo	Pyrolysis	550	-	43.9	1.80	9.70	15.1	73.5	78.1	-	2.00	0.7	[49]
Wood waste	Gasification	789	-	-	25.11	1.11	79.91	19.01	49.9	43.5	5.6	0.10	[51]
Cornstalk	Gasification	800	-	342.30	-	-	-	-	70.70	-	2.10	0.70	[52]
Pinewood	Pyrolysis	450	-	166	-	5.0	8.20	-	81.4	15.3	2.99	0.3	[37]
Swine manure	Pyrolysis	500	10.48	47.51	-	48.43	10.98	-	42.68	-	-	-	[37]
Waste sea plant	Hydrothermal	200	5.31	-	-	19.43	-	-	45.42	26.30	5.14	3.60	[53]
Algae waste	Pyrolysis	300–700	-	-	-		-	-	50.5	31.0	7.6	11.0	[54]
Wetland waste	Hydrothermal	-	7.71	-	-	14.52	-	-	59.10	17.01	5.45	3.14	[53]
Municipal sludge	Pyrolysis	500	8.8	-	-	74.19	-	-	17.5	11.0	0.9	1.50	[55]
Domestic sludge	Pyrolysis	400	7.3	-	-	37.1	35.0	-	43.0	3.4	8.1	8.1	[37]

4. Biochar Applications in the Flexible Asphalt Pavement

Owing to the annual expansion of industrialization, massive amounts of biomass waste are discarded in landfills. As a result of these ongoing issues, researchers have devised strategies to incorporate biochar into flexible asphalt pavements to encourage sustainability and improve performance. Based on the VOSviewer mapping shown in Figure 8, biochar is most used in flexible asphalt pavements for bio-asphalt and to modify asphalt binders. Some studies have substituted mineral filler materials with additives or surrogates in asphalt mixtures to reduce toxicity and promote sustainability. The following is a summary of various studies and applications of biochar/hydrochar in flexible asphalt pavements, either as an asphalt binder or as a modifier of a mixture.

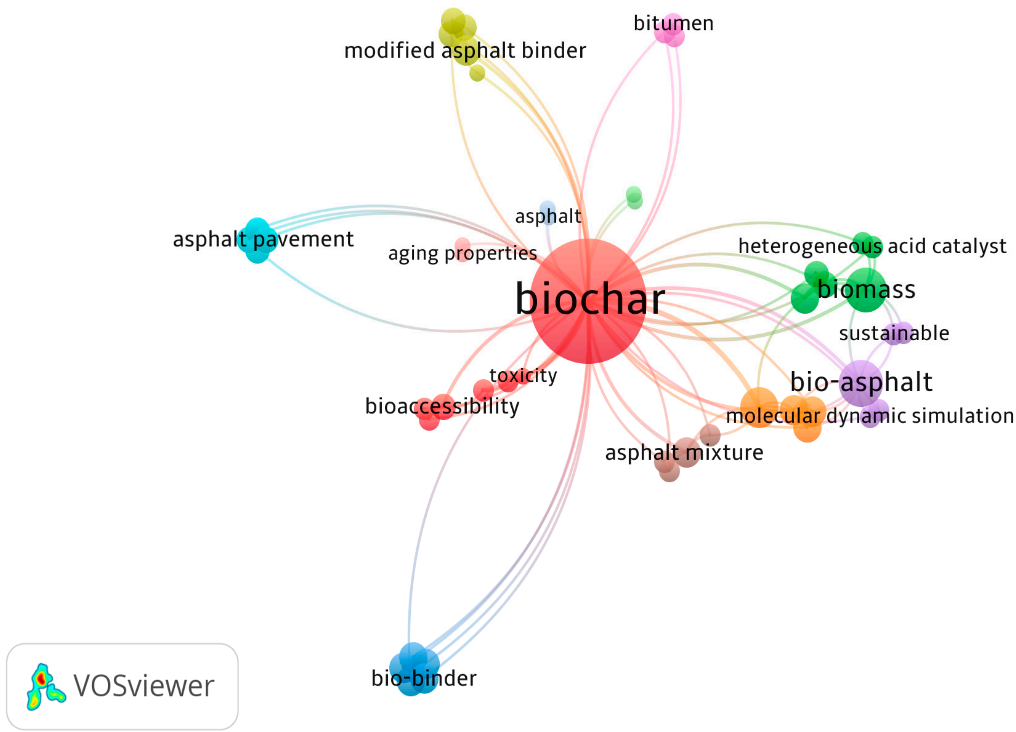

Figure 8. VOSviewer mapping visualization of biochar-related studies for flexible pavement applications.

In a study by Çeloğlu et al. [56], two forms of biochar made from the walnut crust and apricot seed shell were used to modify an asphalt binder at different concentrations (5%, 10%, and 15% per weight of the binder) at 180 °C. The results indicated that biochar improved the stiffness of the asphalt binder at high temperatures. However, this study only evaluated the conventional and rheological properties of the binders, and there was no information on the properties of the mixtures. In another study by Ma et al. [57], biochar was generated by thermally cracking straw stalks in a nitrogen environment at 450 °C, with particle sizes of 89 µm. Using a high-shear mixer, the biochar was mixed with PEN 60/80 asphalt binder at various contents (5%, 7.5%, 10%, 12.5%, and 15%). The researchers observed that adding biochar to the binder increased its resistance to rutting at high temperatures, but had no effect on its low-temperature performance. Another study by Zhou and Adhikari [58] modified a bio-oil asphalt with biochar derived from the pyrolysis of cypress waste wood in their study. The biochar had particle sizes that passed through a 75 µm sieve and were mixed into the bio-asphalt at 2%, 4%, 6%, and 8% for 60 min at 135 °C with a mixing speed of 2000 rpm. The researchers performed rheological and chemical characterization tests on the bio-asphalt and discovered that the integration of biochar improved flow-induced crystallization, high-temperature performance, and aging resistance. Furthermore, the study found that biochar had no effect on the performance of bio-low-temperature asphalt and produced SiO_2 particles in the blend.

Zhao et al. [59] explored the influence of pyrolysis on the performance of switchgrass biochar for asphalt binder modification. Finer particles produced at a lower heating rate and temperature of 15 °C/min and 400 °C, respectively, produced the optimum results. According to these findings, incorporating biochar improved the rheological properties of the asphalt binder, aging resistance, and high-temperature performance, outperforming activated carbon as an asphalt binder modifier. In a similar study, Zhao et al. [60] used slow pyrolysis to produce biochar from switchgrass with a particle size of 75 μm to modify a PG 64-22 asphalt binder at 5% and 10% dosages in another study. A biochar-modified asphalt binder was used to make modified asphalt mixtures, and the results demonstrated that the biochar stiffened the mixtures, reducing the rutting depth and moisture susceptibility. However, there was uncertainty in the results and their statistical significance; as the percentage of biochar increased, the moisture damage resistance decreased, with an improvement in the crack resistance of the asphalt mixes. Another study by Dong et al. [61] investigated the use of different types of biochar (DS-510F) in an asphalt binder. They mixed biochar with the binder in various proportions (5–15% by weight) and discovered that it improved the binder's aging resistance. The effect on low-temperature performance, on the other hand, was negligible. Moreover, FTIR analysis revealed that no chemical reaction occurred between the biochar and binder during blending.

Moreover, a study conducted by Gan and Zhang [62] examined the effect of crop straw biochar on the performance of a PEN 60/70 asphalt binder. The biochar was mixed with the binder at various ratios (2–12% by weight), and the physical and rheological properties were evaluated. The findings revealed that 6% biochar content was optimal for improving asphalt binder performance and that biochar improved performance at high temperatures but decreased it at low temperatures. Kumar et al. [63] investigated the performance of biochar derived from Mesua ferrea seed cover. The biochar had particle sizes that passed through a standard sieve of 150 μm and was used to modify two different asphalt binders. A shear mixer was used to blend the biochar with binders at various content levels (5–20% by weight). The findings revealed that increasing the biochar content in the asphalt binders improved their viscosity, aging resistance, and rutting resistance. In addition, biochar was used as a filler for an asphalt binder in a study by Wu et al. [64], and the biochar was produced by burning rice straw at high temperatures, and the mineral filler ratios in the gradation and bitumen content in the mixtures were 9% and 6%, respectively, corresponding to a mass ratio of 58.5:41.5 of mineral filler to bitumen. Biochar filler was used to partially replace the granite filler in the asphalt mastic at volume fractions of 0%, 40%, 80%, and 100%. The results indicated that incorporating biochar into the asphalt binder stiffened it and made it more resistant to flow.

Ghasemi et al. [65] recently investigated the effectiveness of biochar and hydrochar in slowing the aging process of asphalt binders. This study produced biochar and hydrochar from woody biomass and algal biomass using both pyrolysis and hydrothermal conversion. The results showed that hardwood biochar reduced the rheology- and chemistry-based aging indices by 13% and 28%, respectively, whereas algal biochar improved the indices by 45% and 35%, respectively. Moreover, Zhang et al. [66] examined the impact of waste wood pyrolysis biochar on the properties of a modified PG 58-28 asphalt binder. Using a high-speed shearing stirrer, asphalt binder and biochar with varying particle sizes were blended at 120 °C for 60 min. The results showed that adding biochar increased viscosity and that using biochar with a particle size greater than 75 μm and content less than 4% could enhance the asphalt binder's aging resistance and high-temperature performance while having little effect on low-temperature performance. Furthermore, in a similar study, Zhang et al. [67] studied the effect of biochar particle size and dosage on the rutting and fatigue performance of asphalt binders using a similar PG 58-28 asphalt binder and biochar produced from the pyrolysis of waste wood with varying particle sizes passing through a standard sieve of 75 μm and between 75 μm and150 μm. They discovered that the use of biochar improved rutting resistance at high temperatures while maintaining low-temperature fatigue resistance. They also suggested using biochar particles with a size of <75 μm and a content of 2–4% for asphalt binder modification to achieve optimal performance.

In a study by Saadeh et al. [68], a PG 64-10 asphalt binder and crumb rubber blend were modified with swine waste-based biochar produced through the hydrothermal liquefaction process. Biochar was added to 5% mass of the asphalt binder. The rheological properties of the biochar-modified binder were assessed, followed by tests for rutting, fatigue, and moisture damage resistance. The findings revealed that biochar increased the fracture resistance of the asphalt mixture before and after aging, as well as the resistance to rutting and moisture damage over time. Walters et al. [69] modified a PG 64-22 asphalt binder with a blend of biochar and nanoclay. The biochar was derived from pig manure, and the blend was created by combining the biochar and nanoclay in various ratios (2%, 5%, and 10% by weight of asphalt binder for biochar, and 2% and 4% for nanoclay). The rheological properties, aging resistance, and thermal resistance of the modified blends were tested. The study discovered that the incorporation of biochar improved the aging and thermal properties of the asphalt binder, and helped distribute the nano clay evenly across the binder. Likewise, Walters et al. [70] studied the influence of 3% and 6% swine manure biochar on the properties of PG 64-22 asphalt binder and modified asphalt binder. The researchers wanted to determine how biochar affected the aging behavior and chromium absorption capacity of asphalt binders. The integration of biochar improved the viscoelastic behavior and aging resistance of the asphalt binders, according to the results. Furthermore, biochar with a pH of 5.5 was found to absorb up to 75% of chromium from contaminated surface runoff.

In a recent study on biochar application in asphalt mixtures, Liu et al. [71] investigated the viability of utilizing biochar as a mineral filler substitute for the purification of runoff from porous asphalt mixtures. The mixture contained three biochar-based fillers with particle sizes of 3–5 mm, 1–2 mm, and 75µm, respectively. The filler was rice straw, and the filter layers were coconut and nutshells. The binding material was PG 76-22 styrenes butadiene-styrene. The study discovered that using biochar as a mineral filler reduced nitrogen and phosphorus leaching by 70–86% and 48–85%, respectively, but did not affect pollutant filtration. This study also confirmed the feasibility of using biochar to purify asphalt runoff. Qi et al. [72] assessed the influence of coconut shell and bamboo biochar on nitrogen removal in porous pavement bedding. The NO_3-N removal rates for the reference and biochar-modified pavements were 10.8% and 48.6–54.0%, respectively, while the total nitrogen removal rates were 20% and 52.6–57.7%, respectively. The study also demonstrated that biochar improved denitrification without promoting biological material leaching, and significantly increased the abundance of denitrifying bacteria. Recently, Liu et al. [73] examined the purification effects of straw-derived biochar in the removal of pollutants from porous asphalt pavements. The research included laboratory tests for static adsorption and rainfall. The filter layers significantly increased the removal rate of all suspended particles to 60–80%, according to the results. Biochar's distinct chemical properties, as well as its beneficial effect on the microscopic pore structures of porous asphalt mixtures, make it an effective purification material, particularly for dissolved contaminants such as heavy metals.

Table 4 summarizes the findings of several studies on the utilization of biochar in flexible asphalt pavements, with a particular emphasis on asphalt binder performance. Table 5 summarizes the findings of several studies on the utilization of biochar in flexible asphalt pavements, with a focus on the performance of the asphalt mixture. According to the summaries, the emphasis is on biochar's importance in a variety of asphalt pavement applications, such as its excellent structural and surface properties, simple preparation method, and availability of a variety of biomass alternatives. The unique physical and chemical properties of biochar can increase its effectiveness for specific applications. The combination of these superior properties makes biochar a cost-effective and ecologically friendly solution for improving the performance and promoting the sustainability of flexible asphalt pavements. Figure 9 shows the potential use of biochar in flexible asphalt pavements.

Table 4. A synopsis of research findings on biochar applications in flexible asphalt pavements with a focus on asphalt binders.

Raw Material	Biochar Process	Biochar Particle Sizes/Content, wt.%	Study Focus/ Application/Binder Type	Study Objectives	Analysis Conducted	Findings	Future Recommendation	Ref.
Crop straw	Pyrolysis	<75 µm (2, 4, 6, 8, 10, 12%)	Asphalt binder modifier (PEN 60-80)	To evaluate the viability of using biochar to improve asphalt binder properties.	Morphological and particle size analysis, as well as conventional testing, were used to characterize the binder.	- Biochar has a higher specific surface area than coal, smaller particle size, and improves binder performance at elevated temperatures.	- Studies of the surface energy adhesion and adsorption properties of biochar-modified binders, as well as a comprehensive viscoelastic study and techno-economic analysis, are required.	[62]
Swine manure	Not stated	- (3 and 6%)	Asphalt binder modifier (PG 64-22)	The evaluate the influence of biochar on asphalt binders' aging and its ability to absorb chromium from contaminated surface runoff.	DSR, RTFO, rotational viscosity, and chromium removal test.	- Asphalt binders' viscoelastic properties and aging resistance were improved by biochar. At a pH of 5.5, it has been found to absorb up to 75% of chromium.	- Analyzes on the interaction between biochar and asphalt binder with regard to thixotropic behavior. A life cycle cost analysis and mechanical performance tests are also recommended.	[70]
Waste wood	Pyrolysis	<75 µm and between 75–150 µm (2, 4 and 8%)	Asphalt binder modifier PG 58-28	The influence of biochar on asphalt binder rheological, fatigue, and rutting resistance is being studied.	DSR, RV, BBR and RTFO aging test.	- Biochar addition enhances viscosity, aging resistance, and rutting resistance of binder while maintaining fatigue resistance.	- A further investigation into the surface energy and adhesion properties of asphalt binders treated with POBA. - Furthermore, no mechanical performance testing is performed.	[66]
Rice straw	incineration	<75 µm (Filler to binder the ratio of 58.5:41.5)	Surrogate filler PG64-22	To determine and model the viscoelastic properties of biochar-modified asphalt binder via soft computing techniques.	Morphological, rheological properties and finite element (FE).	- Asphalt mixtures' resistance to rutting is improved by biochar's creation of a thick coating layer that increases blend stiffness and modulus. - FE is suitable for accurate and effective modeling.	- More studies are needed on employing biochar as a surrogate filler in asphalt mixtures, particularly on the synergetic interaction between the biochar, asphalt binder, and aggregate.	[64]
Straw stalk	Thermal cracking	<89 µm (5, 7.5, 10, 12.5, and 15%)	Asphalt binder modifier PEN 60-80	To assess the effect of biochar on asphalt binder high-temperature performance.	Penetration, rutting factor, complex modulus, and viscosity-temperature index.	- There are no chemical reactions when using biochar in asphalt modification. Biochar improves binder deformation at high temperatures while decreasing resistance at low temperatures.	- Future research is needed to investigate the environmental effects of biochar-modified asphalt, and atomistic modeling could help us better understand the molecular-level interface between biochar and asphalt.	[57]
Cornstalk	Hydrothermal	2 mm (2, 4, 6, 8 and 10%)	Asphalt binder modifier PEN 60-70	To examine the impact of hydrochar on binder chemical and rheological properties.	Rotational viscosity, storage stability, DSR test, gel permeation chromatography, and FTIR.	- The incorporation of hydrochar improves asphalt binder rheological properties. - FTIR shows that Hydrochar has improved well dispersion and aging resistance binder.	- In-depth studies are needed to understand the influence of hydrochar on asphalt binder on viscoelastic thixotropic behavior properties.	[74]
Switchgrass	Pyrolysis	<75 µm and 75–150 µm (5,10,15, and 20%)	Asphalt binder bio-modifier PG 64-22	To determine the viability and rheological properties of the carbonaceous bio-modifier before and after aging.	SEM, and DSR RTFOT and PAV.	- The addition of biochar to asphalt binder improves its rheological properties at high temperatures, as well as its aging properties.	- The study only focuses on one binder grade. As a result, more research into other binder grade and biochar materials is encouraged.	[43]

Table 4. *Cont.*

Raw Material	Biochar Process	Biochar Particle Sizes/Content, wt.%	Study Focus/ Application/Binder Type	Study Objectives	Analysis Conducted	Findings	Future Recommendation	Ref.
Waste wood	Pyrolysis	<75 µm and 75–150 µm (2, 4, and 8%)	Asphalt binder modifier PG 58-28	To investigate the influence of biochar on the rheological, fatigue, and rutting resistance of asphalt binder.	DSR, RTFO, PAV and SEM.	- Incorporating biochar improves elastic properties and rutting resistance at high temperatures while sustaining fatigue resistance before and after aging.	- To fully comprehend how biochar-modified binders affect the mechanical performance of mixes, more studies are required.	[67]
Wood chips	Pyrolysis	<75 µm (2, 4, 6, and 8%)	Asphalt binder modifier PG 58-28 modified with bio-oil	To analyze the flow-induced biochar crystallization in bio asphalt with varying aging conditions.	DSR, FTIR, XRD, molecular dynamic simulation, and optical microscope.	- Biochar improves the high-temperature performance, flow-induced crystallization, and aging resistance of bio-asphalt, with little effect on its low-temperature performance.	- Bio-based wood chips bio-oil as an alternative binder can help with the development of sustainable and renewable bio asphalt.— More studies with a variety of bio-oils are recommended.	[58]
Walnut and apricot seed shells	Pyrolysis	<75 µm	Asphalt binder modifier B 160/200 5, 10, and 15%	To evaluate the influence of various biochar on asphalt binder performance at high temperatures.	Penetration, softening point, rotational viscometer, and DSR Test.	- Biochar decreases the penetration thermal sensitivity increase with the increase in softening point and viscosity.—Biochar also enhances the viscoelastic properties of the asphalt binder.	- For future research, the mechanical and long-term performance of the biochar-modified mixture should be evaluated. —The atom-level analysis could be used to better comprehend the molecular-level interface characteristics of biochar and asphalt.	[56]
Cornstalk	Hydrothermal	2 mm (2, 4, 6, 8, and 10%)	Asphalt binder modifier PEN 60-70	To assess the viability of utilizing hydrochar bio-asphalt modifier to improve asphalt binder high-temperature performance.	Penetration, softening point, ductility, rotational viscosity, time sweep test, XRD, FTIR, and gas permeation chromatography.	- Hydrochar demonstrated good compatibility with asphalt. - Hydrochar improves binder high temperature and reduces low-temperature performance.	- The use of hydrochar in asphalt binder has the potential to be a promising bio-asphalt for asphalt pavements. —More research into rheological, low, and intermediate temperature performance is recommended.	[75]
Mesua ferrea seed shells	pyrolysis	<150 µm (5, 10, 15, and 20%)	Asphalt binder modifier PEN 60-70	To explore the potential of using Mesua ferrea seed shells biochar in asphalt binders.	Flow behavior, DSR, RTFO, and PAV test.	- The addition of biochar increased the binder viscosity's resistance to rutting deformation and decreased its susceptibility to aging. - Biochar decreased accumulated strain and non-recoverable compliance.	- Future research should examine the mechanical properties of biochar-modified binders, as well as how various biochar materials influence the flow and rheological properties of the binder.	[63]
Biochar DS-510F	Not stated	<89 µm (5, 7.5, 10, 12.5, and 15%)	Asphalt binder modifier PEN 60-80	To examine the short and long-term aging of asphalt binder modified with biochar.	DSR, BBR, and FTIR.	- Biochar enhances asphalt binder's aging resistance. - Biochar affects asphalt binder's low-temperature performance depending on the content. FTIR shows only physically blending between biochar and binder.	- More advanced rheological and performance tests are needed to gain a comprehensive understanding of the biochar behavior of biochar-modified asphalt binder thixotropic behavior.	[61]

Table 4. *Cont.*

Raw Material	Biochar Process	Biochar Particle Sizes/Content, wt.%	Study Focus/ Application/Binder Type	Study Objectives	Analysis Conducted	Findings	Future Recommendation	Ref.
Pinewood and pig manure	Pyrolysis	- (5%)	Asphalt binder modifier Pinewood bio asphalt (PG 52-28) Pig manure bio asphalt (PG58-22)	To assess the environmental impact and life cycle evaluation of using biochar-modified asphalt binder.	Conventional, DSR, and morphology tests. Energy consumption and emission test.	- Bio asphalt and biochar-modified binders are more energy efficient and emit less CO_2 than petroleum-based asphalt, with wood-based biochar being especially effective.	- Additional laboratory and field testing is required to validate the limited study on biochar-modified asphalt binder. Both academic and government efforts are needed.	[76]
Woody and Algae	Pyrolysis and Hydrothermal	- (5%)	Asphalt binder modifier PG 64-10	To investigate the effect of incorporating biochar and hydrochar on the aging resistance of asphalt binder.	DSR, FTIR, and molecular dynamic simulation test.	- According to rheology and chemistry analysis, adding biochar and hydrochar improves the aging indexes of asphalt binder.	- Future research should delve into the chemical interactions between biochar and asphalt at the atomic level using microscopic modeling.	[65]
Corn stalks	Hydrothermal	2 mm (3,6, and 9%)	Asphalt binder modifier PEN 60-70	To assess the viability of using hydrochar as an asphalt binder modifier.	Consistency, storage stability, rotational viscosity, and DSR test.	- Hydrochar improves binders' consistency but has poor storage stability. It also improves the binder's rutting and fatigue resistance.	- Some drawbacks of using hydrochar in asphalt binder have been reported, such as poor storage stability. More research is needed to address these concerns.	[77]

Table 5. A synopsis of research findings on biochar applications in flexible asphalt pavements with a focus on asphalt mixtures.

Raw Material	Biochar Process	Biochar Particle Sizes/Content, wt.%	Application/Binder Type	Study Objectives	Analysis Conducted	Findings	Recommendation	Ref.
Not stated		<75 µm (5%)	Asphalt binder and mixture modifier PG 64-10 and Crumb rubber modified PG 64-16	To evaluate the impact of using biochar as a free radical scavenger during construction to reduce UV-aging of both asphalt binder and mixtures.	DSR, FTIR, ultraviolet, oxidative, and Xenon arc aging tests, as well as overall asphalt mixture performance.	- Both the rheological and chemical aging indices revealed that asphalt incorporated with biochar had a lower aging index.	- Biochar has the potential to contribute to the creation of sustainable bio-asphalt, but more research is needed to fully understand its potential applications.	[78]
Switch Grass	Pyrolysis	<4.75 mm (5 and 10%)	Asphalt binder and mixture modifier PG 64-22	To study the performance of biochar-modified asphalt binder and mixtures.	Binder (DSR, rutting, and fatigue) Mixture (moisture damage; Superpave IDT and rutting).	- The integration of biochar into asphalt improves its rutting resistance and durability against cracking, rutting, and water damage.	- Biochar-modified asphalt binder has shown promise as a bio-asphalt solution, but more testing is required to fully assess its potential.	[59]
Coconut shell, rice straw, and nutshell	Not stated	<75 µm as filler 1–2 mm and 2–5 mm as a filter layer	As filler in asphalt mixtures PG 76-22 SBS-modified binder	To assess the influence of biochar on the purification efficiency of runoff in porous asphalt pavement.	Infiltration and leachate contamination test and Purification efficiency.	- The use of biochar reduces nitrogen and phosphorus leaching by 70–86% and 48–85%, respectively, without affecting pollutant filtration.	- The use of biochar as an environmentally friendly filler and filtration material results in the creation of environmentally sustainable porous asphalt mixtures.	[71]
Swine manure	Hydrothermal	<75 µm (5%)	Asphalt mixture PG 64-10	To assess the impact of biochar on the mechanical properties of the asphalt mixture.	Rutting, fatigue, and moisture damage tests. Semi-circular bending.	- Biochar improves the permanent deformation, fatigue, and water resistance of the mixture. Biochar improves the mixture of energy strain values.	- More testing and field evaluations, as well as large-scale design and product life assessment, are required.	[68]

Table 5. *Cont.*

Raw Material	Biochar Process	Biochar Particle Sizes/Content, wt.%	Application/Binder Type	Study Objectives	Analysis Conducted	Findings	Recommendation	Ref.
Bamboo and coconut shell	Not mentioned	<3 mm (3–6% *w*/*w*)	Asphalt mixture bedding course	To improve nitrogen removal from permeable pavements by using bamboo and coconut shell biochar.	Nitrogen mass balances and Denitrification test.	- Biochar increases nitrogen removal rates by 52.6–57.7% while decreasing the effectiveness of blank controls by 20%. It also improves denitrification without causing organic matter to leach.	- It is suggested that more studies be done on environmental impact and techno-economic analysis of using different biochar in asphalt mixtures.	[72]
Straw	-	-	Porous asphalt mixtures surrogate filler and purification material	To assess the viability of employing biochar as a filler in porous asphalt mixtures for water purification.	Static adsorption, and pollutant removal.	- Biochar has been shown to increase the removal rate of suspended solids to 60–80% and to improve the ability to absorb dissolved contaminants.	- To fully understand and implement the use of biochar, more laboratory testing, field evaluations, large-scale design, and life cycle assessment are required.	[73]
Switchgrass	Pyrolysis	<75 µm (5 and 10%)	Asphalt binder and mixture modifier PG 64-22	To study the performance of asphalt mixtures modified with biochar derived under controlled environments.	DSR, resilient modulus test, asphalt pavement analyzer test, and semi-circular bend fracture test.	- The use of biochar-modified asphalt binder results in environmentally sustainable and performance-enhanced asphalt pavement.	- The integration of biochar into asphalt binder production will result in a low-carbon and sustainable asphalt pavement with improved performance.	[60]

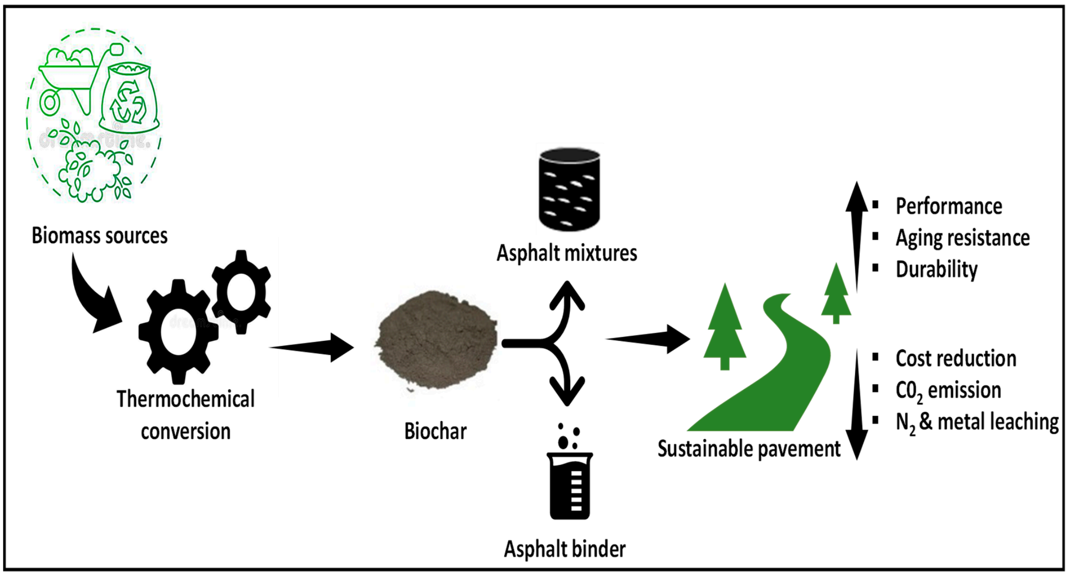

Figure 9. Application potential of biochar in flexible asphalt pavements.

5. Biochar Interaction with Asphalt

The performance and grade of modified asphalt are determined by the level of interaction between the modifier and the asphalt binder [79]. The nature and extent of this molecular interaction can have a significant influence on the properties of modified asphalt, making it an important factor to consider when evaluating the effectiveness of biochar-modified asphalts. As a result, different analytical techniques were used to investigate the biochar-asphalt binder interaction [75]. In a study conducted by Martínez-Toledo et al. [80], confocal fluorescence laser microscopy imaging was utilized to provide useful insights into the modification of asphalt binders with biochar. The imaging results allow for an assessment of the success of the modification procedure as well as the distribution and particle size of the biochar particles within the binder. It was used to investigate the distribution of oat hull-based biochar in an asphalt binder at dosages of 2.5, 5, and 7.5%. Figure 10 depicts the fluorescence images of the pristine binder and biochar-modified binder at various dosages. The imaging results showed that for all dosages of biochar modification, the distribution was uniform throughout the binder, with no cluster formation. This homogeneous integration of the two materials indicated that the modification procedure used to incorporate biochar into the asphalt binder was successful. Furthermore, the images revealed that the maximum size of the biochar particles was approximately 30 μm, even though the biochar fraction was separated using a 75 μm sieve. This is due to the efficiency of the downsizing process, which used a grinder and a specific processing time to produce finer-size biochar particles. The homogenous dispersion of the biochar particles in the binder, as well as the small particle size, are critical factors in determining the efficiency of the modification process.

Similarly, Ma et al. [57] modified asphalt binders with biochar at dosages of 5, 7.5, 10, 12.5, and 15% and performed microstructural analysis using SEM. The SEM images of all asphalt samples containing varying amounts of biochar had their SEM images magnified 100 times for detailed examination, and the results are shown in Figure 11. The surface of the plain binder was smooth, as shown in Figure 11a. The biochar-modified asphalt binders revealed a more dispersed and well-structured distribution of biochar in the binder. However, when compared to the pristine binder, the biochar binder is stiff due to its fibrous structure with many pores. The stiffening zone is defined by the optical micrograph as the area of the asphalt binder is encircled by biochar modifier particles. The presence of this stiffening zone raises the complex modulus of the asphalt binder [57,81]. Furthermore, the SEM images of the biochar-modified asphalt binder showed the presence of stiffening zones, which are marked with red lines for visual clarity. The porous structure of biochar tends to have a direct impact on the specific surface area, which increases the interaction of the biochar with the asphalt constituents as well as the compatibility of the biochar with the asphalt binder [57]. Because of their fibrous nature, biochar particles efficiently fill gaps in the asphalt and form a skeleton-like structure, which improves the overall performance of the modified asphalt binder. These findings are in line with the prior study by Hu et al. [75], which found an increase in the softening point, viscosity, and complex modulus of biochar-modified asphalts, as well as a decline in phase angle and penetration.

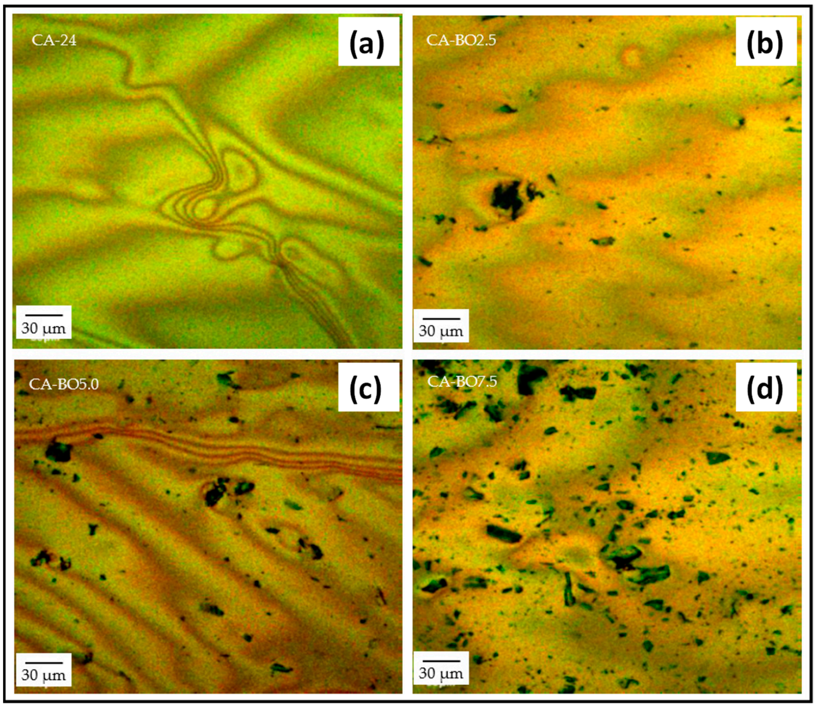

Figure 10. Fluorescence images of the effects of biochar content on asphalt binders: (**a**) pristine binder, (**b**) 2.5%, (**c**) 5%, (**d**) 5977.5% Ref. [80] From MDPI, and used under Creative Commons CC-BY license.

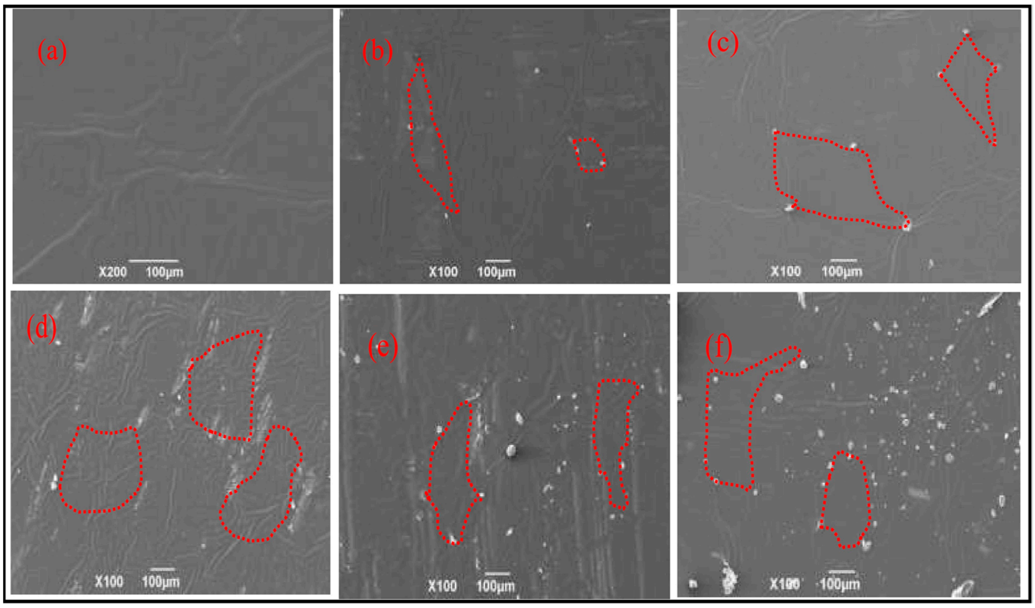

Figure 11. SEM images of asphalt binders modified with varying amounts of biochar: (a) pristine binder, (**b**) 5%, (**c**) 7.5%, 620, (**d**) 10%, (**e**) 12.5%, and (**f**) 15% (From Elsevier Ref. [57] and used with permission).

Using a similar study, Ma et al. [57] used FTIR spectra to analyze the molecular interactions between biochar and asphalt as well as to evaluate the effectiveness of the biochar-modified binder. Figure 12 shows the combined FTIR spectra for the biochar, pristine (matrix) binder, and biochar-modified binders. It can be observed that the methyl bonds (CH_3), which are a type of carbon-hydrogen bond in organic compounds, have peaks at 2953 cm^{-1}, 1460 cm^{-1}, and 1380 cm^{-1}. The peaks at 2920 cm^{-1} and 2850 cm^{-1} represent methylene single bonds (CH_2), which are the vibrations of the carbon–hydrogen bonds of organic compounds. In addition, the benzene ring (C=C) is represented by a peak at 1600 cm^{-1}, indicating the presence of aromatic compounds in the binder. This is significant because aromatic compounds contribute to the viscosity, stiffness, and aging resistance of asphalt. The faint peak at 2720 cm^{-1} is attributed to the CH of the fatty aldehyde. Fatty aldehydes are unsaturated fatty acids that can help asphalt resist aging.

It was also observed that the biochar-modified asphalt has similar transmittance as the pristine binder's characteristic peaks, indicating that the main components of the biochar-modified binder were aromatic and hydrocarbon compounds, which is consistent with previous research on biochar-modified binders [75]. Furthermore, the transmittance peaks of the biochar-modified asphalt were altered in the minimal wavenumber direction compared to the plain asphalt binder. This shift indicates that the absorption frequency decreased as the wavelength increased. This is because, for the FTIR spectra, the band frequency is described by the weight of the atoms in a group and the constant bond formation between atoms [57]. This is because the internal chemical nature of biochar-modified asphalt is distinct from that of plain asphalt binder. The presence of biochar in a modified binder alters its chemical composition and molecular structure, thereby affecting its properties.

As a result, the shift in the absorption peaks observed in the FTIR spectra of the biochar-modified binder indicates changes in the internal chemical environment of the asphalt compared to the pristine binder [63]. This can cause changes in the properties of the modified binder, such as its stiffness, viscosity, and aging resistance. FTIR spectra can provide useful information about these changes and aid in determining the effectiveness of biochar modification [57].

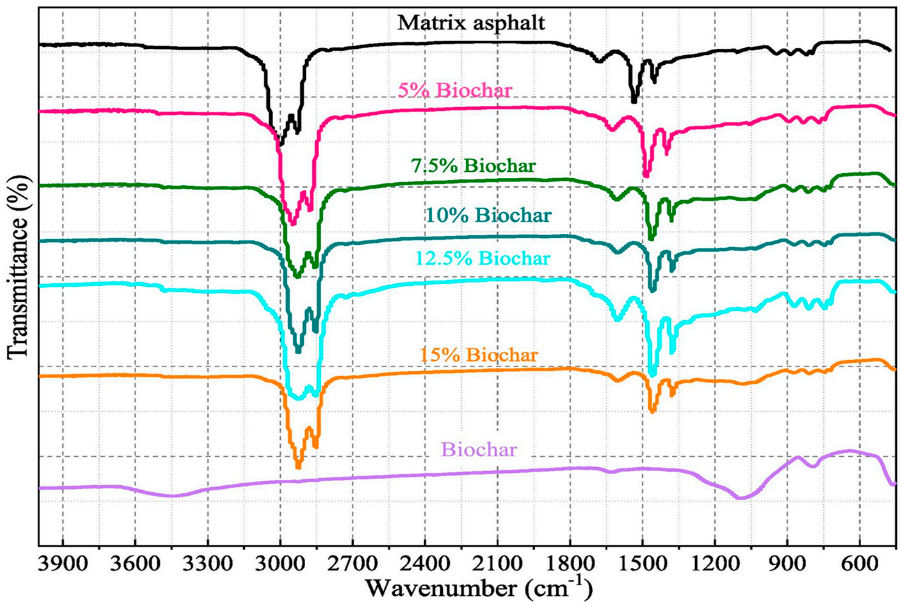

Figure 12. Combined FTIR spectra of biochar, pristine (matrix) binder, and biochar—modified binders (From Elsevier Ref. [57] and used with permission).

6. Biochar as a Carbon-Neutral Material for Flexible Asphalt Pavement Applications

The most significant greenhouse gas in the world is carbon dioxide. In addition to being used by plants for photosynthesis, they absorb heat to maintain climate change. The planet's natural greenhouse effect is weak without CO_2, and the temperature drops below zero. On the other hand, a high quantity of CO_2 in the environment increases the global temperature, causing it to warm and eventually cause global warming [82]. Based on the International Energy Agency, world CO_2 emissions surged by 53% between 1990 and 2020, reaching around 31.5 gigatons, causing global warming and endangering environments [83]. A previous study reported that approximately 35 billion tons of CO_2 are emitted annually into the atmosphere by businesses and fossil fuels worldwide [84]. The Global Alliance for Buildings and Construction estimates that building and construction operations are responsible for approximately 40% of energy-related CO_2 emissions [85]. To attain realistic global carbon neutrality targets, it is essential to take remarkable measures to innovate construction design and promote the use of low-carbon emission building materials, such as biomass. Biomass generation, processing, and utilization have increased as industrial activities have increased with a surge in the global population, which has increased carbon emissions. Therefore, finding new ways to advance the use of biomass to satisfy demand is necessary to achieve reduced carbon emissions, which will also help the environment. Thermochemical processes are one of the many approaches to increase the utilization of biomass and produce a usable and multifunctional by-product called biochar, which waste biomass serves as the main raw material for its production.

The IPCC has identified biochar as a low-emission technology [86]. However, depending on the locations and characteristics of the feedstocks and the intended applications, the average CO_2 footprint of biochar ranged from 2.0 kg to 3.3 kg of CO_2-eq per kg of biochar [87]. Biochar technology, in general, can reduce gas emissions by 3.4–6.4 Pg CO_2-eq, with CO_2 extraction from the air accounting for 1.7–3.7 Pg CO_2-eq (49–59%) of the reduction [88]. The idea of carbon neutrality was developed in response to the need to keep global warming below 1.5 °C since the temperature rise is mostly caused by CO_2 emissions [89]. Thus, the optimal action is to reduce CO_2 emissions with the understanding that any remaining emissions will be eliminated by environmental factors [90]. If all CO_2 emissions are neutralized by reducing atmospheric CO_2 via carbon scavenging techniques, the goal of reducing carbon emissions will be achieved [91]. Moreover, the use of bio-related materials can help promote a circular economy [92,93]. The primacy of using renewable energy and how it will help achieve carbon neutrality cannot be overemphasized. Thus, biochar can provide a paradigm shift and revolutionize the process.

Volatile Organic Compounds (VOCs) are among the most harmful substances and contain a significant level of toxic components that are inevitably produced during the production, mixing, transportation, and laying processes of asphalt pavement, thus posing health risks to humans and the atmosphere [22,94]. The utilization of common emission reduction agents, such as metal oxide materials, organic polymer materials, inorganic salts materials, inorganic materials, inorganic porous materials, and composite materials, has been shown to reduce the VOC content in asphalt binders and mixtures [95]. However, their applicability is constrained by the fact that most of them are hazardous, and the results of the reaction between them and the asphalt binder and mixtures are still unclear and require further research [95,96]. To address this issue, researchers have proposed the use of biochar to remove VOCs from asphalt [95].

A recent study by Ghasemi et al. [65] utilized biochar produced using algae to simulate the viability of utilizing biochar to absorb atmospheric CO_2. Another study by Zhou et al. [21] evaluated the effect of biochar on the removal of VOCs from asphalt mixtures using various biochar sources. The results demonstrated that biochar could minimize VOC emissions by 50% owing to its inherent porosity and negative carbon content. They also found that the type of biochar used determined the adsorption mechanism. For instance, the process between VOCs and biochar made from pig manure exhibits physical adsorption, whereas biochar from wood or straw exhibits chemical adsorption [21,97].

Furthermore, biochar is nearly ten times cheaper than other CO_2 adsorbent materials, resulting in a significant cost advantage [98]. Biochar in asphalt binders and mixtures can better adsorb VOCs by increasing the specific surface area, the number of surface chemical functional groups, and pore volume and decreasing pore size [99]. Several studies related to the utilization of biochar have focused on either lowering the content and toxic effects of VOCs in asphalt binders and mixtures or enhancing their performance. Although biochar has great potential as a VOC scavenger, only a limited number of studies have examined the synergetic influence between the ability of biochar to remove VOCs and its potential to enhance asphalt binder and mixture performance. Therefore, additional pertinent studies are required to fully harness the carbon-neutral potential of biochar materials in the asphalt pavement industry.

7. Discussion

Based on the articles examined in this systematic review, the following section provides three elements of the literature's content: the motivations for using biochar technology in asphalt binders and mixtures to produce sustainable asphalt pavements, the perspectives and challenges observed in effectively employing this technology, and recommendations to alleviate such limitations.

7.1. Key Findings

Biochar has numerous benefits when it is used in asphalt mixtures. Its application areas for porous asphalt include asphalt binder and mixture modification, CO_2 scavengers, filler substitutes, water purification, and nitrogen and contaminant removal.

- It has been discovered that utilizing biochar can positively impact the environment by lowering the carbon emissions generated by natural resource exploration and usage. By integrating biochar as a paving material, waste disposal and landfilling problems can be addressed.
- Most of the methods employed in the literature for utilizing biochar in the asphalt industry are still in the laboratory and pilot phases, and additional testing is required before they can be prevalently used. In addition, limited research has been conducted on the application of biochar in the asphalt pavement industry under real axle loading conditions over a specific period or using full-scale field pavement testing.
- Moreover, no standard criteria or specifications for the formulation, design, and production of biochar-modified asphalt binders and mixtures on a large scale have been established to encourage stakeholders and professionals to use biochar asphalt pavement construction. This is because most research has mainly utilized laboratory tests to determine the optimal amount.
- The review, data analysis, and graphical representations and mapping will assist innovative scholars in establishing scholarly connections, developing joint projects, and working to increase the use of biochar in flexible asphalt pavement construction.
- This review describes the various approaches that can be employed to utilize biochar in asphalt binders and mixtures, supported by experimental evidence and results based on guidelines and methodologies.

7.2. Motivation, and Potentials of Employing Biochar in the Pavement

Recently, premature flexible asphalt pavement failures have occurred because of the sudden rise in traffic density caused by urban development, prompting the use of sustainable building materials in material selection, design, and construction. Asphalt pavement engineers and researchers have recently been exploring new ways to augment the performance of flexible asphalt pavements while lowering CO_2 emissions. The utilization of processed biomass waste, such as biochar, is an emerging area of study for pavement engineering because it is readily available, has a low harmful footprint, and requires less energy than conventional materials [12]. The utilization of biomaterials in both asphalt binder and mixture pavement applications has evident and significant benefits. In this section, some of the advantages mentioned in the literature are listed.

- Biochar is a sustainable and environmentally friendly substance as opposed to conventionally synthesized modifiers. Biochar has a higher potential for sustainability, according to research findings, as evidenced by its positive and improved performance in relevant literary works.
- Because they are locally created, biomaterials are affordable and made from renewable resources. They also consume less energy than materials made from petroleum and are more environmentally friendly, with low and heavy metal leaching and radioactivity.
- The need for disposal facilities can be reduced by using bio-asphalt binders made from bio-waste or biomass sources, thereby lowering carbon dioxide emissions. In addition, because CO_2 is naturally converted to biomaterials, it does not emit greenhouse gases.
- The utilization of biochar in asphalt binders has the potential to be a promising bio-asphalt for asphalt pavements. However, further research into low- and intermediate-temperature performances is recommended. Thus, biochar composites using more sustainable and environmentally friendly materials can be incorporated to improve performance at low temperatures.
- Biochar is also a potential material for use in sustainable, innovative, and game-changing carbon-neutral technologies to reduce the adverse effects of CO_2 emissions during asphalt pavement mixing and production. Furthermore, biochar is less hazardous as a modifier than other chemical modifiers.
- The integration of multiple technologies, such as biochar, bio-asphalt binders, cold mix asphalt, and the use of other waste material technologies, will result in a paradigm shift in research directions for more economical, environmentally friendly, and sustainable asphalt pavement construction.

7.3. Drawbacks and Limitations of Employing Biochar in Flexible Asphalt Pavement

Although there are many advantages to employing biochar in the pavement industry, several obstacles must be overcome before biochar can be used extensively in the pavement industry. The availability of materials, as well as the behavior of the biochar that will be used as a replacement for synthetic and polymer-based modifier materials, presents numerous challenges for researchers. In the literature, major impediments to the use of biomaterials have been identified.

- The chemical components, aging, compatibility, and elemental composition of biochar from various sources with various types of asphalt binders and mixtures should be investigated. Furthermore, the use of experimental scale procedures for assessment, which do not accurately reflect field procedures and performance, necessitates the adoption of new and more effective approaches.
- Waste material management is due to inadequate infrastructure and facilities for large-scale waste material adoption, as well as inefficient waste material processing and conversion equipment.
- There were no specifications on the effects of the technological production method on the final mixing result, nor was there detailed information on the costs, resources, timelines, and general implementation information required for field production. Many discoveries and assessments have been made in the research laboratory.
- Another issue is the location of alternative binders for road pavements that can withstand varying loads and environmental conditions. However, well-designed and built asphalt pavements depreciate during their service life because of the environment and increased traffic loading.
- According to the literature, biochar is better suited for use in tropical and subtropical regions because of its poor performance at low temperatures. Consequently, its application is restricted to low-temperature regions.
- There are concerns regarding policymaking and regulation due to a lack of strict guidelines and a designated entity to regulate the utilization of biomass waste and

adherence to relevant national policies and standards. In addition, there are no design specifications or procedures for the use of biochar in various scenarios, such as extreme cold, heat, or changing weather patterns.

- Another major hurdle is the production of an asphalt pavement modified with biochar that has adequate workability and mechanical performance, with a varied range of traffic flow and environmental factors, and requires less energy to produce, with fewer carbon emissions. In addition, there is a lack of studies on the molecular-level interface properties of biochar and pavement materials.

8. Conclusions

The pavement industry is striving to achieve greater sustainability. The application of biochar in the asphalt pavement industry is a new and intriguing field of study. This study focuses on the origins of biochar, conversion processes, and their use as modifiers for asphalt binders and mixtures, filler materials for porous asphalt mixtures, and previous concrete. An additional bibliometric analysis of research indicators and gaps was performed using VOSviewer. The benefits and drawbacks of using biochar in the pavement industry were also discussed. The following are the key findings based on the theoretical findings and analysis of the current literature review.

- Research findings on biochar and its use in asphalt modification show that aromatic rings, alkanes, and hydroxyl groups dominate the chemical composition of biochar. No chemical reaction was observed during the asphalt modification process, suggesting that the application of biochar in the asphalt binder was primarily due to its physical rather than chemical properties.
- The shift in the absorption peaks and homogeneous dispersion observed in the biochar-modified asphalt indicates changes in the internal chemical environment of the asphalt and a good interaction between the biochar and the asphalt binder. These modifications have the potential to improve the stiffness, viscosity, and aging resistance of asphalt. Furthermore, the use of biochar in asphalt mixtures can reduce the need for petroleum-based asphalt binders, resulting in lower greenhouse gas emissions and more environment-friendly asphalt mixtures.
- When used in asphalt mixtures, the micrometer-scale pores and rough surface of biochar, along with the abundance of functional groups and good dispersion on the binder surface, all contribute to improved performance and environmental benefits. By increasing the carbon content, biochar has been found to improve the mechanical properties of asphalt mixtures, making them stronger and more resistant.
- Because biochar particles are small and porous, they can bind to the binder and form more durable and stable mixtures. In addition, biochar has a low water absorption rate, which helps reduce the risk of moisture and water damage. Furthermore, the fibrous and amorphous structure of biochar has been found to aid in the formation of a stiffening region in the asphalt mixture, which contributes to the improved mechanical properties of the pavement.
- The incorporation of biochar into asphalt mixtures has the potential to significantly reduce the carbon footprint of the asphalt mixture by more than 50% by reducing the amount of petroleum-based asphalt binder required. Biochar can be used in asphalt mixtures to reduce radioactive contamination and heavy metal leaching into the environment owing to its high carbon content and low heavy metal levels. Furthermore, biochar can be used to limit the release of radioactive materials from asphalt mixtures, making it a more environmentally friendly option.
- According to the literature, it is considered an environmentally friendly component of asphalt pavement. This is because there are more sustainable methods for producing biochar in the literature; this sustainable process produces less volume and less toxic gaseous products than other biochar production processes. Furthermore, compared to other conventional materials used in asphalt pavement production, the biochar production process is more environmentally friendly. However, more efforts should be made

to reduce pollutant emissions during biochar production, such as by using renewable energy sources and implementing the best production and transportation practices.

Based on the comprehensive review of the various uses of biochar in the pavement industry, the benefits of using these waste materials include their viability for reducing carbon emissions, lowering production costs, and improving pavement performance and durability through sustainable practices.

9. Future Study and Literature Gaps

- To improve the performance of biochar-pavement materials, future studies should investigate the use of advanced technologies such as micro-computed tomography, nanoindentation, molecular dynamic simulation, optical and transmission electron microscopes, and microscopy, which can be used to improve studies on biochar-asphalt interactions. These technologies can provide extensive data on the micro- and nanoscale structures and properties of biochar and asphalt, assisting in understanding how biochar influences the mechanical and thermal properties of pavements, their toughness and durability, and the adhesion and interaction between biochar and asphalt.
- To improve sustainability, more studies on the use of micro-, ultrafine, and nanoparticle biochar in pavement applications can help improve sustainability by providing detailed information on the effects of biochar on pavement material properties. These studies can investigate how the size and surface area of biochar particles affect the properties of biochar and asphalt as well as the optimal dosages and mixing processes for integrating biochar into asphalt mixtures. This can provide relevant data on the use of biochar to improve the sustainability and performance of pavement materials in the pavement industry.
- More studies using advanced modeling and simulation techniques can help to better understand biochar-asphalt interactions by providing numerical modeling, predictions, and insight into the behavior of biochar-modified asphalt pavements. ANN predictive models can be used to estimate the performance of biochar-modified asphalt using the properties of biochar asphalt binders and mixtures. It can also aid in the design and performance optimization of biochar-modified asphalt, simulate the mechanical behavior of biochar-modified asphalt, and provide information on the effects of biochar on the performance mechanisms.
- More studies and analyzes are needed to address the storage stability and low-temperature performance issues of current biochar-modified binders as well as to improve our understanding of biochar-asphalt interactions. The lack of studies on the influence of biochar at intermediate temperatures results in a limited understanding of its effects on pavement materials, making it difficult to predict the performance of biochar-modified pavements. These studies will aid in determining the optimal storage conditions, improving the low-temperature performance, and better understanding the effects of biochar on asphalt pavement properties.
- Before field applications, a comprehensive techno-economic analysis and life cycle evaluation can help to assess the technical and economic feasibility of biochar in the pavement industry, as well as the environmental impacts, leading to a better understanding of biochar-asphalt pavement interactions. The techno-economic analysis looks at the costs and benefits of producing and incorporating biochar into asphalt mixtures, whereas the life cycle assessment looks at the entire life cycle of biochar, from generation to disposal. These studies can aid in determining the long-term suitability and environmental impacts of biochar in the pavement industry as well as the best methods for incorporating biochar into asphalt pavements.
- A more in-depth study of the impact of biochar on flexible asphalt pavement materials in terms of carbon capture can aid in better understanding biochar-asphalt interactions by providing insights into the mechanisms. This research includes the physicochemical characteristics of asphalt, the role of biochar in carbon capture and

storage reduction, and its ability to enhance pavement serviceability. The studies will involve experimental, modeling, and pilot studies to validate the results and assess the performance of biochar-modified pavements under real field conditions. The outcome of these studies can help provide a greater comprehension of the impact of biochar and aid in its implementation as a carbon capture and storage solution in the transportation sector.

- More advanced studies on the properties of biochar for various applications in the asphalt pavement industry can aid the development of novel carbon-neutral pavement materials. This advances our understanding of biochar-asphalt interactions by shedding light on the use of biochar as a key component in the development of sustainable pavement materials and the potential for carbon sequestration, as well as a better understanding of carbon storage mechanisms. In addition, by studying the interactions of biochar with other asphalt pavement components, new materials that leverage the unique properties of biochar to improve conventional asphalt materials can be developed.

In summary, more studies on molecular dynamics simulations, chemical, thermal, microscopy, and rheological analyzes can be conducted to gain a better insight into the interactions between biochar and asphalt pavements. These techniques will aid in determining the elemental composition, thermal stability, microstructure, viscosity, and mechanical properties of the mixture, as well as the underlying molecular mechanisms of biochar-asphalt interactions.

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