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A Review of Biomass-Derived Biochar and Its Potential in Asphalt Pavement Engineering

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Biomass-derived biochar has gained significant attention due to its unique properties and potential applications in various fields, including asphalt pavement engineering. However, there has been no comprehensive review to date that systematically examines the state-of-the-art research on biochar utilization in asphalt pavements, identifies the key knowledge gaps, and provides recommendations for future research directions. This review aims to fill this gap by providing a novel and critical analysis of the sources and production methods of biochar, the techniques for modifying and characterizing its properties, and its recent applications as an asphalt binder modifier, asphalt mixture additive, and stormwater filter material. The review employs a systematic literature search and analysis methodology, using scientific databases such as Web of Science and Scopus, and keywords related to biochar, asphalt, pavement, and environmental and economic aspects. The selected studies are reviewed and synthesized to identify research gaps, challenges, and future directions, with a focus on the technical, environmental, and economic feasibility of biochar utilization in asphalt pavements. The review also examines the life cycle assessment, carbon sequestration potential, and cost-benefit analysis of biochar utilization. The novelty of this review lies in its holistic approach to assessing state-of-the-art knowledge and its identification of key research needs and opportunities for advancing this emerging field. The review aims to provide valuable insights and recommendations for researchers, practitioners, and policymakers interested in leveraging the benefits of biochar for sustainable and high-performance asphalt pavements.

Keywords: *pyrolysis, surface modification, rheological properties, mechanical performance, environmental sustainability*

1. Introduction

The rapid growth of the global population and urbanization has led to an unprecedented increase in the generation of biomass waste from various sources, including agriculture, forestry, and municipal and industrial activities. This biomass waste, if not managed properly, can pose significant environmental challenges, such as greenhouse gas emissions, soil and water pollution, and public health risks. Landfilling and open burning are common disposal methods for biomass waste, but they are unsustainable and contribute to environmental degradation [1, 2]. Therefore, there is an urgent need for innovative and sustainable solutions to manage biomass waste effectively. One promising approach to address the biomass waste management challenge is the conversion of biomass into biochar through thermochemical processes such as pyrolysis, gasification, and hydrothermal carbonization [3, 4]. Biochar is a carbon-rich, porous material that has attracted significant attention in recent years due to its unique properties and potential applications in various fields, including agriculture, environmental remediation, and energy production [5]. The physicochemical properties of biochar, such as high surface area, porosity, and the presence of functional groups, make it an ideal material for adsorbing contaminants, improving soil fertility, and sequestering carbon [6].

Asphalt pavement is a critical component of transportation infrastructure worldwide, and the demand for asphalt materials is expected to increase with the growth of the global economy and population [7]. However, the production and use of conventional asphalt materials have significant environmental impacts, including greenhouse gas emissions, energy consumption, and resource depletion. Moreover, the performance and durability of asphalt pavements are often compromised by various distresses, such as rutting, cracking, and moisture damage, which lead to premature failure and increased maintenance costs

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[8]. Therefore, there is a growing interest in developing sustainable and high-performance materials for asphalt pavement engineering.

Biochar has emerged as a potential sustainable material for asphalt pavement applications due to its unique properties and environmental benefits [9]. The incorporation of biochar into asphalt materials can potentially improve their rheological, mechanical, and durability properties while reducing their environmental footprint [10]. Biochar can be used as an asphalt binder modifier to enhance its resistance to aging, low-temperature cracking, and rutting [11]. It can also be used as an additive in asphalt mixtures to improve their strength, stiffness, and moisture resistance [12]. Furthermore, biochar can be used as a filter material for stormwater treatment in permeable asphalt pavements, helping to remove pollutants and improve water quality. Despite the promising potential of biochar in asphalt pavement engineering, there are still many challenges and knowledge gaps that need to be addressed before its widespread adoption. The production and modification of biochar from different biomass feedstocks can result in varying properties and performance, which requires systematic characterization and optimization. The compatibility and interaction of biochar with asphalt materials need to be thoroughly investigated to ensure their long-term stability and durability. The environmental and economic implications of using biochar in asphalt pavements also need to be assessed through life cycle assessment and cost-benefit analysis.

Therefore, the objective of this review is to provide a comprehensive and critical analysis of the current state of knowledge on biomass-derived biochar and its potential applications in asphalt pavement engineering. This review employed a systematic literature search and analysis methodology to identify, select, and synthesize relevant studies on biochar utilization in asphalt pavement engineering. The literature search was conducted using several scientific databases, including Web of Science and Scopus. The keywords used for the search included various combinations of "biochar", "asphalt", "pavement", "binder", "mixture", "modifier", "additive", "stormwater", "filter", "life cycle assessment", "carbon sequestration", and "cost-benefit analysis". The initial search results were screened based on their relevance to the topic, publication date (focusing on studies published in the last decade), and publication type (peer-reviewed journal articles, conference proceedings, and technical reports). The selected studies were then reviewed and analyzed in detail to extract key information on biochar production, modification, characterization, application, and environmental and economic aspects. The review covers the sources and production of biochar from various biomass feedstocks, the modification and characterization techniques for enhancing its properties, and the recent advances in using biochar as an asphalt binder modifier, asphalt mixture additive, and stormwater filter material. The review also discusses the environmental and economic aspects of biochar production and use in asphalt pavements, as well as the challenges, knowledge gaps, and future research directions. The scope of the review includes laboratory studies, field trials, and modeling studies on biochar modified asphalt materials, as well as relevant studies on biochar production, modification, and characterization. The review focuses on the technical aspects of biochar use in asphalt pavement engineering but will also consider the broader sustainability implications and potential barriers to implementation. The intended audience of the review includes researchers, practitioners, and policymakers in the fields of pavement engineering, materials science, environmental engineering, and sustainable development. The novelty of this review lies in its holistic approach to assessing the technical, environmental, and economic feasibility of biochar utilization in asphalt pavements, as well as its identification of key research needs and opportunities for advancing this emerging field.

2. Sources and production of biochar

Biochar is a carbonaceous material produced from the thermochemical conversion of biomass under oxygen-limited conditions [13]. The production of biochar has gained significant attention

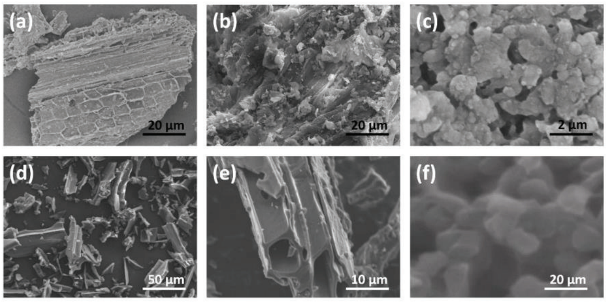

Fig. 1. SEM of biochar prepared by (a) rice straw [88], (b) water hyacinth [89], (c) crab shell [90], (d) pinewood [91], (e) eucalyptus [92], (f) sugarcane bagasse [93]

in recent years due to its potential to address various environmental challenges, such as waste management, soil degradation, and climate change mitigation. This section provides an overview of the biomass feedstocks commonly used for biochar production, the thermochemical processes involved, and the physicochemical properties of the resulting biochar.

2.1. Biomass feedstocks for biochar production

Biochar can be produced from a wide range of biomass feedstocks, including agricultural waste, forestry waste, and municipal and industrial organic waste. The selection of feedstock depends on various factors such as availability, cost, and the desired properties of the resulting biochar. Different feedstocks have varying compositions of cellulose, hemicellulose, and lignin, which influence the yield and characteristics of the biochar. Figure 1 shows some examples of biochar prepared by different sources.

Agricultural waste is one of the most abundant and readily available feedstocks for biochar production [14]. It includes crop residues, such as straw [15], stover [16], and husks [17], as well as animal manure [18] and food processing waste [19]. For example, rice straw, wheat straw, and corn stover are commonly used agricultural residues for biochar production. These materials are often left in the field after harvesting or burned in open fires, causing environmental and health problems. Converting them into biochar can help to reduce these negative impacts while generating a valuable product. Animal manure, such as poultry litter [20], dairy manure [21], and swine manure [22], is another important agricultural waste for biochar production. Manure-derived biochar has been shown to have high nutrient content and can be used as a soil amendment to improve soil fertility and crop yield [20]. However, the high moisture content and heterogeneity of manure can pose challenges for biochar production and may require pre-treatment steps such as drying and grinding. Food processing waste, such as fruit peels [23], nut shells [24], and coffee grounds [25], is also a potential feedstock for biochar production. These materials are often generated in large quantities by food processing industries and can be difficult to dispose of. Converting them into biochar can help to reduce waste and create a value-added product. For instance, biochar produced from walnut shells [26] and almond shells [27] has been found to have high surface area and porosity, making it suitable for adsorption applications.

Forestry waste, including forest residues, wood processing waste, and invasive species, is another important feedstock for biochar production [28]. Forest residues, such as tree branches [29], bark [30], and leaves [31], are often left on the forest floor after logging operations. These materials can pose a fire hazard and contribute to greenhouse gas emissions if left to decompose. Converting them into biochar can help to reduce these risks while sequestering carbon in a stable form. Wood processing waste, such as sawdust [32], wood chips [33], and shavings [34], is generated by the wood products industry. This waste is often used as a fuel for energy production but can also be converted into biochar. Biochar produced from wood waste has been found to have high carbon content and low ash content, making it suitable for various applications such as soil amendment and carbon sequestration. Invasive species, such as kudzu [35] and water hyacinth [36], are non-native plants that can cause ecological and economic damage by outcompeting native species and clogging waterways. Harvesting and converting these species into biochar can help control their spread while generating a useful product. For example, biochar produced from water hyacinth has been shown to have high adsorption capacity for heavy metals and dyes [37], making it a promising material for wastewater treatment.

Municipal and industrial organic waste, including sewage sludge, food waste, and paper mill sludge, is another potential feedstock for biochar production [38]. Sewage sludge is a solid residue generated from wastewater treatment processes. It contains high levels of organic matter and nutrients but also potentially harmful substances such as heavy metals and pathogens. Converting sewage sludge into biochar can help to reduce its volume and stabilize the contaminants, making it safer for land application or disposal. Food waste, such as kitchen scraps and restaurant waste, is a major component of municipal solid waste [39]. It is often sent to landfills where it decomposes and releases methane, a potent greenhouse gas. Converting food waste into biochar can help to divert it from landfills and reduce methane emissions. Biochar produced from food waste has been found to have high nutrient content and can be used as a soil amendment to improve plant growth. Paper mill sludge is a byproduct of the pulp and paper industry. It contains high levels of organic matter and calcium carbonate, which can be beneficial for soil amendment [40]. However, it may also contain contaminants such as heavy metals and chlorinated compounds. Converting paper mill sludge into biochar can help to concentrate the beneficial components while reducing the volume and toxicity of the waste.

2.2. Thermochemical production processes

Biochar is produced through thermochemical conversion processes, which involve heating biomass in the absence or limited presence of oxygen. The three main processes for biochar production are pyrolysis, gasification, and hydrothermal carbonization (HTC) [41]. Each process has its own operating conditions, product yields, and energy requirements, which influence the properties and potential applications of the resulting biochar.

Pyrolysis is the most common and widely studied process for biochar production. It involves heating biomass to temperatures typically between 300 and 700°C in the absence of oxygen [42]. During pyrolysis, the biomass undergoes thermal decomposition, releasing volatile compounds and leaving behind a solid residue known as biochar. The yield and properties of the biochar depend on various factors such as the type of biomass, the heating rate, the final temperature, and the residence time. Slow pyrolysis, also known as conventional pyrolysis, is characterized by slow heating rates (typically less than 10°C/min), relatively long residence times (hours to days), and low final temperatures (300–400°C). This process maximizes the yield of biochar while producing smaller quantities of bio-oil and syngas [43]. Slow pyrolysis is often used for the production of biochar for soil amendment and carbon sequestration applications. Fast pyrolysis, on the other hand, involves rapid heating rates (typically greater than 100°C/s), short residence times (seconds to minutes), and moderate final temperatures (400–600°C). This process maximizes the yield of bio-oil while producing smaller quantities of biochar and syngas [44]. Fast pyrolysis is often used for the production of bio-oil for energy applications, but the resulting biochar can also be used for various purposes, such as adsorption and catalysis. Tan et al. [44] reviewed the effects of feedstock composition and operating conditions of slow and fast pyrolysis on the quality of biochar produced from lignocellulosic and lignin-based biomass. The fixed carbon content of biochar from slow pyrolysis mostly ranged from 30.0% to 98.1%, with some variation due to differences in operating temperature and feedstock carbon content. The average fixed carbon content of biochar from fast pyrolysis was around 44.07%. The study found that biomass with high cellulose and hemicellulose content produced a high yield of tar, while a high proportion of lignin promoted carbonization and biochar formation. Lignin-based biomass exhibited higher fixed carbon content (45.36% to 94.0%) compared to lignocellulosic biomass. Slow pyrolysis of lignin-based biomass was preferred to produce biochar with high fixed carbon content, while fast pyrolysis had low biochar mass recovery and yield. Flash pyrolysis is an even faster process, with heating rates greater than 1000°C/s and residence times of less than a second [45]. This process is used for the production of high-quality bio-oil, but the biochar yield is typically low.

Gasification is a thermochemical process that converts biomass into a mixture of combustible gases, known as syngas, and a solid residue, known as char or biochar [46]. The process involves heating biomass to high temperatures (typically above 700°C) in the presence of a controlled amount of oxygen or steam. The oxygen or steam reacts with the carbon in the biomass to produce carbon monoxide, hydrogen, and other gases, while the remaining solid residue is the biochar. Gasification can be carried out in various types of reactors, such as fixed bed [47], fluidized bed [48], and entrained flow reactors [49], each with its own advantages and disadvantages. The type of reactor, the gasifying agent (oxygen or steam), and the operating conditions (temperature, pressure, and residence time) influence the composition and yield of the syngas and biochar. In a comprehensive study, Fryda and Visser [50] explored the potential of biochar derived from gasification and slow pyrolysis processes. The biochar produced through slow pyrolysis exhibited smaller specific surface areas and higher polycyclic aromatic hydrocarbons (PAH) levels, albeit within international safety norms, compared to those obtained via gasification. However, the yield from slow pyrolysis was higher. Gasification at higher temperatures not only resulted in biochars with larger total surface areas, higher pH, and ash contents but also very low tar content, indicating a cleaner product. For instance, gasification biochars had PAH values ranging from 1 mg/kg to 2 mg/kg, significantly lower than those from pyrolysis processes, which ranged from 8 mg/kg to 23 mg/kg.

HTC is a thermochemical process that converts biomass into a solid product known as hydrochar, in the presence of water and under moderate temperatures (typically 180–350°C) and pressures (2–10 MPa). HTC is particularly suitable for wet biomass feedstocks, such as sewage sludge, animal manure, and algae, as it eliminates the need for drying prior to the process [51]. During HTC, the biomass undergoes a series of reactions, including hydrolysis, dehydration, decarboxylation, and polymerization, leading to the formation of a carbonaceous solid with higher carbon content and lower oxygen and hydrogen contents than the original biomass [52]. The hydrochar typically has a spherical or granular morphology, with a high degree of aromatization and a relatively low surface area compared to biochar from pyrolysis. The yield and properties of the hydrochar depend on various factors such as the type of biomass, the reaction temperature and time, the water-to-biomass ratio, and the presence of catalysts or additives. HTC can also produce a liquid phase containing valuable compounds such as sugars, organic acids, and phenols, which can be further processed into biofuels or chemicals [53].

2.3. Physicochemical properties of biochar

The physicochemical properties of biochar are key determinants of its potential applications and environmental impacts. These properties depend on the type of biomass, the production process, and the operating conditions used. Some of the most important properties of biochar include surface area and porosity, elemental composition, and surface functional groups.

Surface area and porosity are two of the most important physical properties of biochar, as they determine its ability to adsorb and retain water, nutrients, and contaminants [54]. Biochar typically has a high surface area, ranging from a few hundred to over a thousand square meters per gram, depending on the feedstock and production conditions [55]. This high surface area is mainly due to the presence of micropores (pores with diameters less than 2 nm) and mesopores (pores with diameters between 2 and 50 nm), which are formed during the thermal decomposition of the biomass. Biochar with high surface area and porosity has been shown to be effective for various applications, such as soil amendment, water treatment, and gas adsorption. For example, biochar with a high surface area can improve soil water-holding capacity and nutrient retention, leading to enhanced crop growth and yield [56]. Biochar with high microporosity can also adsorb and remove various contaminants from water and air, such as heavy metals, organic pollutants, and greenhouse gases [57]. However, the surface area and porosity of biochar can also change over time due to various physical and chemical processes, such as weathering, oxidation, and fouling [58]. Therefore, it is important to understand the long-term stability and dynamics of biochar properties in different environmental conditions.

The elemental composition of biochar is another important property that influences its potential applications and environmental impacts. Biochar is mainly composed of carbon, oxygen, hydrogen, and ash, with smaller amounts of nitrogen, sulfur, and other elements [59]. The relative proportions of these elements depend on the type of biomass and the production conditions used. Carbon is the main component of biochar, typically accounting for 50–90% of its mass. The carbon content of biochar is an indicator of its stability and resistance to degradation, as well as its potential for carbon sequestration [60]. Biochar with high carbon content is generally more stable and can persist in the environment for longer periods of time than biochar with lower carbon content. Oxygen and hydrogen are also present in biochar, typically in the form of functional groups such as hydroxyl, carboxyl, and carbonyl groups [61]. These functional groups can influence the surface chemistry and reactivity of the biochar, as well as its interactions with water, nutrients, and contaminants. Ash is the inorganic residue that remains after the thermal decomposition of the biomass. The ash content of biochar can vary widely, from less than 1% to over 50%, depending on the type of biomass and the production conditions used [62]. Biochar with high ash content may have lower carbon sequestration potential and may also contain potentially toxic elements such as heavy metals. Nitrogen, sulfur, and other elements are also present in biochar in smaller amounts, and their concentrations depend on the composition of the biomass feedstock. These elements can influence the nutrient content and fertility of the biochar, as well as its potential environmental impacts [63].

3. Biochar modification

Biochar is a versatile material that can be modified to enhance its properties and performance for specific applications. Various physical and chemical methods can be used to modify biochar, altering its surface chemistry, porosity, and functionality. Characterizing biochar is also essential to understanding its properties and assessing the effectiveness of the modification methods.

Physical modification methods for biochar involve the use of physical processes, such as heat treatment [64], steam activation [65], and mechanical grinding [66], to alter its surface area, porosity, and morphology. These methods do not involve the addition of chemical reagents and are generally considered to be more environmentally friendly and cost-effective than chemical modification methods. Anerao et al. [67] conducted a comprehensive review of various physical treatment methods for biochar modification. The authors found that these physical treatments enhanced the physicochemical properties and adsorption capacity of biochar by increasing surface area, porosity, and functional groups. For instance, steam activation of biochar derived from the invasive plant *Sicyos angulatus* L. increased the adsorption capacity for sulfamethazine by 55% compared to pristine biochar. CO_2 activation improved the hydrophilicity and aromaticity of biochar, while ozone treatment enhanced the acidic oxygen functional groups and cation exchange capacity. Thermal activation at high temperatures (600–1500°C) removed hydrogen and oxygen atoms, increasing porosity. Microwave activation provided uniform and quick heating, resulting in higher efficiency and lower energy consumption compared to conventional methods. Ultrasound irradiation improved reaction rates by up to 80% and increased adsorption capacity. Plasma treatment using H_2S modified biochar derived from wheat straw, enhancing mercury removal efficiency from 26.4% to 95.5%.

Chemical modification methods for biochar involve the use of chemical reagents, such as acids, bases, oxidants, and organic compounds, to alter its surface chemistry and functionality [68]. These methods can introduce new functional groups, such as oxygen, nitrogen, and sulfur-containing groups, which may enhance the adsorption, catalytic, and biological properties of the biochar.

Organic modification is a chemical modification method that involves the use of organic compounds, such as surfactants, polymers, or biomolecules, to functionalize the surface of the biochar. Organic modification can introduce specific functional groups, such as amine, thiol, or carboxyl groups, which may enhance the adsorption, catalytic, and biological properties of the biochar [69]. Biochar functionalized with organic compounds can be used for various applications, such as heavy metal removal, oil spill cleanup, and drug delivery. However, organic modification can also lead to the blockage of some pores and the reduction of the surface area and porosity of the biochar.

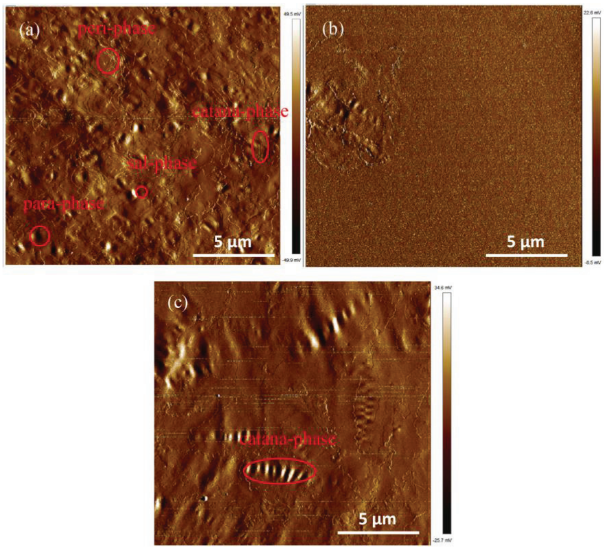

Fig. 2. (a) AFM of 0% BMBA, (b) AFM of 6% BMBA, (c) AFM of 8% BMBA [70]

4. Applications of biochar in asphalt pavement engineering

The unique properties of biochar, such as its high surface area, porous structure, and surface functional groups, have led to its increasing use in various applications, including asphalt pavement engineering. Biochar has been explored as a potential modifier for asphalt binders, an additive in asphalt mixtures, and a filter material for stormwater treatment in permeable pavements. Table 1 shows an overview of the key advantages and limitations of biochar utilization as an asphalt binder modifier, asphalt mixture additive, and stormwater filter material.

4.1. Biochar as an asphalt binder modifier

Zhou et al. [70] investigated the crystallization kinetics and morphology of biochar modified bio-asphalt binders (BMBA). Molecular simulations and experiments were conducted to evaluate the crystallization behavior. The results showed that the number of crystal nuclei, nucleation rate, and crystallinity increased with higher temperature, stress, and biochar content, indicating these factors induced crystallization in BMBA. The phase separation parameter analysis revealed that biochar acted as the nucleation agent, promoting crystallization and phase separation when its content exceeded 4%. The free volume analysis demonstrated that higher biochar content decreased the free volume, inhibiting molecular movement and promoting aggregation. Under isothermal conditions, the crystals tended to be spherical, while under non-isothermal conditions, they were lamellar. The Avrami index for 0-6% biochar was 3.06–4.17, indicating sphere crystals, but for 8% biochar, it was 3.06, indicating lamellar crystals. The Ozawa index for 0–6% biochar was 1.01–3.15, suggesting sphere to lamellar crystals. For 8% biochar, it was 1.01, indicating acicular crystals. SEM and AFM analyses showed that biochar promoted crystallization and phase separation in BMBA. The average surface roughness decreased from 8.37 nm to 4.01 nm with 6% biochar but increased to 24.7 nm with 8% biochar (Figure 2). The saturates and aromatics (peri-phase) exhibited the highest adhesive force of 9.978 nN, while asphaltenes and wax (catana-phase) had the lowest adhesive force of 8.096 nN.

Rheological properties, such as viscosity, stiffness, and elasticity, are important indicators of the performance and workability of asphalt binders.

Table 1. Summary of the advantages and disadvantages of biochar utilization in asphalt pavement engineering applications

Application	Advantages	Disadvantages
Asphalt binder modifier	– Enhances rheological properties (e.g., increased stiffness, elasticity, deformation resistance) – Improves aging resistance and temperature sensitivity – Reduces VOC emissions compared to conventional petroleum-based binders	– May have negative effects on low-temperature performance at high biochar contents – Potential variability in biochar properties depending on feedstock and production conditions
Asphalt mixture additive	– Increases rutting resistance and resilient modulus – Enhances moisture resistance, particularly at lower biochar contents – Improves cracking resistance at optimal biochar content – Reduces VOC and GHG emissions compared to conventional mixtures	– May reduce moisture susceptibility at high biochar contents – Cracking resistance may decrease at high biochar contents – Potential variability in biochar properties depending on feedstock and production conditions
Stormwater filter material	– High surface area and porosity for adsorbing pollutants – Renewable and cost-effective compared to other filter materials – Contributes to carbon sequestration and emission reduction	– Long-term performance and durability under field conditions need further investigation – Potential clogging and reduction in permeability over time

Several studies have investigated the effect of biochar on the rheological properties of asphalt binders. Zhang et al. [71] investigated the rheological performance of asphalt binders modified with biochar, a carbon-rich material derived from pyrolysis of biomass. Biochar with particle sizes ranging from 75 μm to 150 μm and less than 75 μm, and contents of 2%, 4%, and 8% were added to asphalt binder. Flake graphite with a size less than 75 μm and 4% content was used as a comparison modifier. The porous structure and rough surface of biochar led to larger adhesion interaction in the asphalt binder compared to smooth flake graphite. Consequently, biochar modified asphalts exhibited better high-temperature rutting resistance and anti-aging properties than graphite modified asphalt. For instance, the rutting indexes of 4% biochar (less than 75 μm) and 4% graphite increased by 31.70% and 2.32%, respectively, compared to the control asphalt. The aging indexes of 4% biochar (less than 75 μm) and 4% graphite were 1.24 and 1.29, respectively, indicating better anti-aging properties for biochar modified asphalt. Moreover, biochar modified asphalts with smaller particle sizes (less than 75 μm) and 4% content achieved the best combination of high-temperature rutting resistance, anti-aging properties, and low-temperature crack resistance. Similarly, Martínez-Toledo et al. [72] investigated the feasibility of using biochar from oat hulls (BO) as a potential bio-modifier to improve the physical properties of conventional asphalt binder. The BO was characterized, and asphalt binder modifications with 2.5%, 5.0%, and 7.5% BO were evaluated. The viscoelastic range of the asphalt binder was extended, with the Fraass breaking point decreasing and the softening point increasing as the BO content increased. The aging resistance was maintained, and the modifications exhibited good storage stability, particularly for the 2.5% and 5.0% BO additions. Overall, these studies demonstrate that biochar can be an effective modifier for improving the rheological properties of asphalt binders, particularly in terms of increased stiffness, elasticity, and resistance to deformation. The enhanced rheological properties of biochar modified binders can potentially contribute to improved pavement performance and durability.

Asphalt binders are prone to aging, which is a complex process involving oxidation, volatilization, and polymerization of the asphalt molecules. Aging can cause the asphalt binder to become harder, more brittle, and less durable, leading to various pavement distresses, such as cracking and raveling. Therefore, improving the aging resistance of asphalt binders is crucial for extending the service life of asphalt pavements. Several studies have investigated the effect of biochar on the aging resistance of asphalt binders. Dong et al. [73] investigated the influence of biochar on the anti-aging performance of asphalt binders. Various tests were conducted on asphalt binders with different biochar contents (0%, 5%, 7.5%, 10%, 12.5%, and 15%) before and after short-term and long-term aging. The aging tests revealed that the mass loss of biochar modified asphalt binder was higher than the base binder, indicating that biochar alleviated oxidative aging rather than reducing the volatilization of light components. The aging index and viscosity ratio of biochar modified binders decreased as the biochar content increased, suggesting improved aging resistance compared to the base binder. After aging, the dynamic shear rheometer (DSR) tests showed that the temperature sensitivity of biochar modified binders decreased. For instance, the viscosity-temperature susceptibility increased from 3.66 for the unaged base binder to 4.11 after long-term aging, while for the 15% biochar binder, it increased from 3.79 to 4.18. The rutting factor ($G^*/\sin\delta$) increased with higher biochar content, indicating enhanced high-temperature performance. The critical temperature, defined as the temperature when $G^*/\sin\delta$ equals 1.0 kPa for unaged binder or 2.2 kPa for short-term aged binder, increased from 64°C for the base binder to 70°C for the 15% biochar binder after short-term aging. The bending beam rheometer (BBR) tests at low temperatures (-12°C and -18°C) revealed that aging increased the creep stiffness and decreased the creep rate of both base and biochar modified binders, compromising their low-temperature performance. However, the impact of biochar on low-temperature performance was not significant until the content reached 15%, at which point the low-temperature grade changed from −22°C to −16°C. Similarly, Celauro et al. [74] found the presence of biochar in bitumen was found to reduce the aging process, as shown by a decrease in the Aging Index (AI) after short-term aging tests. Specifically, the aging index was reduced from 43.5% to 36.5% with the addition of 10% biochar, indicating that biochar contributes to preserving the bitumen's properties over time. These studies suggest that biochar can be a promising modifier for enhancing the aging resistance of asphalt binders. The improved aging resistance of biochar modified binders can be attributed to the antioxidant properties, physical barrier effects, and reinforcing effects of the biochar particles within the asphalt matrix. The enhanced aging resistance of biochar modified binders can potentially lead to improved long-term performance and durability of asphalt pavements.

4.2. Biochar as an additive in asphalt mixtures

Asphalt mixtures are composite materials consisting of asphalt binder, aggregates, and air voids. The properties and performance of asphalt mixtures are influenced by the characteristics and proportions of these components. Additives, such as polymers, fibers, and nanomaterials, have been used to modify the properties of asphalt mixtures and improve their performance. Recently, biochar has been explored as a potential additive in asphalt mixtures [75]. Biochar has several advantages over other commonly used additives in asphalt mixtures, such as polymers, fibers, and nanomaterials. Biochar is a sustainable and environmentally friendly material derived from waste biomass, whereas many other additives are synthetic and petroleum-based, which can have negative environmental impacts. Second, biochar has a unique porous structure and high surface area, which can improve the adhesion and interface between the asphalt binder and aggregates, leading to enhanced mechanical properties and durability of the asphalt mixture. In contrast, some other additives may have compatibility issues with the asphalt binder or may not provide sufficient bonding with the aggregates. Moreover, biochar can be produced from a wide range of locally available waste biomass sources, making it a cost-effective and accessible additive compared to some other specialty additives that may require complex production processes or have limited availability.

Mechanical properties, such as stiffness, strength, and cracking resistance, are important indicators of the performance and durability of asphalt mixtures. Several studies have investigated the effect of biochar on the mechanical properties of asphalt mixtures. Ma et al. [76] investigated the use of biochar as an asphalt modifier to improve the high-temperature performance of asphalt. The study found that incorporating biochar into the asphalt binder significantly enhanced its mechanical properties (Figure 3). The penetration of the biochar modified asphalt decreased by up to 36.5%, while the softening point increased, indicating improved deformation resistance. The complex modulus of the biochar modified asphalt increased by up to 35%, and the rutting factor also improved, contributing to better temperature sensitivity and anti-rutting properties. These improvements were attributed to the fibrous porous structure of biochar, which formed a skeleton and stiffening zone within the binder. Although biochar had a negative effect on the low-temperature properties of the binder, this could be mitigated by controlling the biochar content. SEM revealed that biochar particles dispersed well in the asphalt binder, creating a micro-network structure. FTIR indicated no new chemical functional groups after adding biochar, but the internal chemical environment of the modified binder differed from that of the unmodified asphalt.

Similarly, Zhao et al. [12] explored the performance of hot-mix asphalt modified by a pyrolytic biochar with controlled production parameters. The results showed that biochar was more effective than carbon black and carbon fiber in reducing the temperature susceptibility of the binder. It increased the rutting resistance of the mixtures, as evidenced by higher resilient modulus values and lower rut depths in the asphalt pavement analyzer test. Biochar improved the moisture resistance of the mixtures, with the modification effect being more pronounced at lower additive contents. Regarding cracking performance, the addition of biochar generally increased the dissipated creep strain energy and the critical J-integral value, indicating better cracking resistance. Other studies have also reported positive effects of biochar on the mechanical properties of asphalt mixtures. For instance, laboratory tests were conducted on asphalt mixtures modified with 5% and 10% biochar by weight of the binder [77]. The results showed that the addition of biochar significantly increased the rutting resistance of the asphalt mixture. The moisture susceptibility of the asphalt mixture was slightly reduced with biochar modification. Interestingly, the cracking resistance of the asphalt mixture increased with 5% biochar addition but decreased to levels similar to the control mix when the biochar content increased to 10%, suggesting an optimum content of 5% for enhancing cracking resistance. Zhou et al. [78] found that the addition of biochar to asphalt significantly reduced volatile organic compound (VOC) emissions and greenhouse gas (GHG) emissions compared to conventional petroleum-based asphalt. Specifically, the VOC content of biochar modified asphalt was below the critical threshold of 75 μg/L, indicating its environmental friendliness. The energy consumption of biochar modified asphalt was only 25% of that of conventional asphalt, with the material preparation stage being the main contributor. Gan and Zhang [79] found the addition of biochar significantly improved the high-temperature performance of the asphalt mixture. As the biochar content increased, the penetration decreased, and the softening point increased, indicating enhanced resistance to rutting and deformation at high temperatures. However, the ductility at 15°C decreased, suggesting a potential negative impact on low-temperature performance. These studies suggest that biochar can be an effective

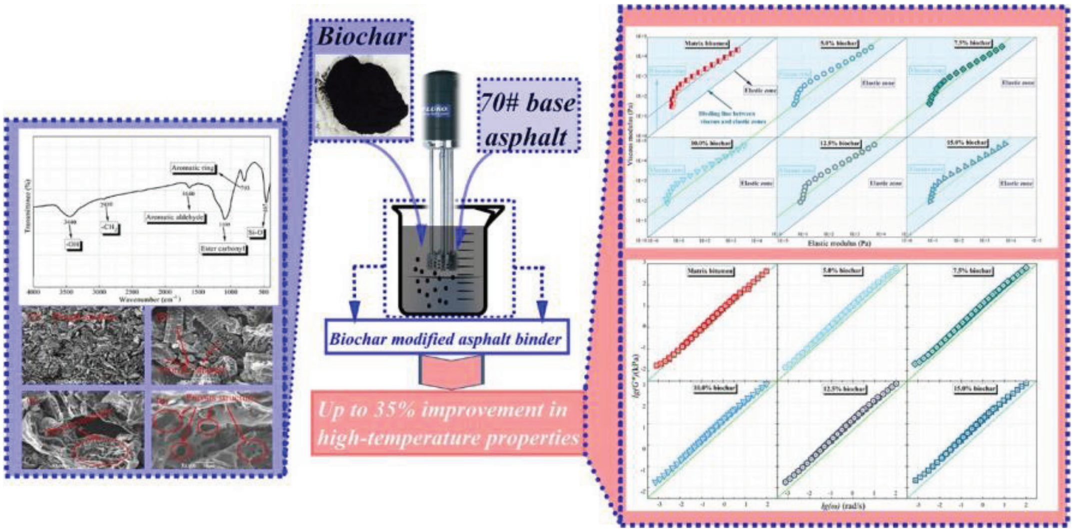

Fig. 3. Biochar greatly increases mechanical properties of asphalt mixtures [76]

additive for improving the mechanical properties of asphalt mixtures, particularly in terms of increased stiffness, rutting resistance, and cracking resistance. The enhanced mechanical properties of biochar modified mixtures can be attributed to the reinforcing effect, void-filling effect, and bonding enhancement of the biochar particles within the asphalt matrix. The improved mechanical properties of biochar modified mixtures can potentially lead to better performance and longer service life of asphalt pavements.

5. Environmental and economic analysis

The environmental and economic aspects of biochar production and utilization in asphalt pavement engineering are crucial for assessing the sustainability and feasibility of this technology. Life cycle assessment (LCA) is a widely used tool for evaluating the environmental impacts of biochar production and use, including greenhouse gas emissions, energy consumption, and resource depletion. The potential for carbon sequestration and emission reduction through biochar utilization in asphalt pavements is also an important consideration, given the increasing concerns about climate change and the need for sustainable construction practices.

5.1. LCA of biochar production and use

LCA is a systematic approach for evaluating the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal. Several studies have conducted LCA of biochar production and use in various applications, including soil amendment, carbon sequestration, and energy production. However, there are limited studies on the LCA of biochar utilization in asphalt pavement engineering [80].

Zhou et al. [78] conducted an LCA of biochar modified asphalt derived from biomass, focusing on GHG emissions and environmental pollution factors. Biochar and bio-oil were obtained from waste wood and pig manure through pyrolysis. The LCA analysis revealed that three critical factors – material preparation, construction, and demolition recovery – contributed significantly to the environmental impact. The results showed that as biochar and bio-oil contents increased, GHG emissions decreased accordingly. Material preparation made the most significant contribution to energy consumption during the LCA. Notably, the findings highlighted the importance of bioasphalt species and content on VOC decay patterns in the LCA and global warming potential. Biochar could inhibit VOC emissions, with waste wood-based biochar exhibiting higher inhibiting efficiency compared to pig manure-based biochar. The energy consumption and environmental impacts of biochar modified asphalt were lower than those of petroleum-based asphalt. The study concluded that the application of waste wood-based biochar modified asphalt in road pavement was the most environmentally friendly alternative among all options evaluated. The pyrolysis of biomass in the material preparation stage was identified as the key factor influencing the life cycle environmental impact assessments of biochar modified asphalt. The study highlights the potential environmental benefits of biochar production and utilization, particularly in terms of reducing greenhouse gas emissions, conserving energy and resources, and promoting sustainable waste management practices. Zhu et al. [81] critically analyzed the LCA of biochar production from various agricultural residues using different pyrolysis technologies. They found that despite variations in functional units and system boundaries across studies, biochar demonstrated remarkable carbon sequestration potential when used as an alternative energy source, soil amendment, or activated carbon substitute. Pyrolysis conditions, such as temperature and residence time, significantly influenced biochar yield and properties, while the choice of pyrolysis equipment depended on factors like feedstock availability and transportation distance. The LCA results showed that carbon dioxide equivalent (CO_2-eq) sequestration could be achieved by extending the system boundary to include biochar application, with reported values ranging from −200 to −1,839 kg CO_2-eq per tonne of feedstock. The study concluded that biochar is a promising avenue for achieving carbon-smart management of agricultural residues, contributing to the nexus of agroecosystem, climate change mitigation, and economic sustainability. More research is needed to specifically assess the life cycle impacts of biochar utilization in asphalt pavement engineering, considering the specific production processes, application methods, and performance characteristics of biochar modified asphalt materials.

5.2. Potential for carbon sequestration and emission reduction

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide in a stable form, such as in soils, vegetation, or geological formations. Biochar has been recognized as a promising material for carbon sequestration due to its high carbon content, stability, and resistance to decomposition [82]. When biochar is produced from biomass and applied to soils or incorporated into construction materials, it can effectively remove carbon dioxide from the atmosphere and store it for long periods of time, potentially contributing to climate change mitigation [83]. Mousavi et al. [84] evaluated the potential of acacia-derived biochar as an adsorbent for VOCs emitted from asphalt-surfaced areas. Experiments revealed that asphalt binder modified with acacia biochar exhibited a lower percentage of mass loss (16.9%) compared to binder modified with silver-grass biochar (21.2%), indicating acacia biochar's superior efficacy in reducing VOC emissions. This enhanced performance was attributed to acacia biochar's higher metal content, particularly Fe, Ca, and Al. Through density functional theory (DFT) calculations, the study demonstrated the distinct adsorption capabilities of these three metals. Fe exhibited exceptional adsorption strength across all nitrogen-containing zones of the biochar surface, surpassing the performance of Ca and Al. The adsorption energy followed the trend: Fe $>$ Ca $>$ Al $>$ no metal. Additionally, Fe demonstrated catalytic properties, facilitating the degradation of certain VOCs like dibenzo-thiophene and hexane-thiol on -N-Fe active sites. Acacia biochar's higher fixed carbon content (58.32%) compared to silver-grass biochar (52.57%) highlighted its superior carbon sequestration potential. Furthermore, a carbon footprint analysis revealed that acacia biochar had a lower net CO_2 equivalent (−1790.7 kg CO_2/ton) than silver-grass biochar (−1581.6 kg CO_2/ton) (Figure 5), indicating its greater potential for carbon management and emission reduction. The study

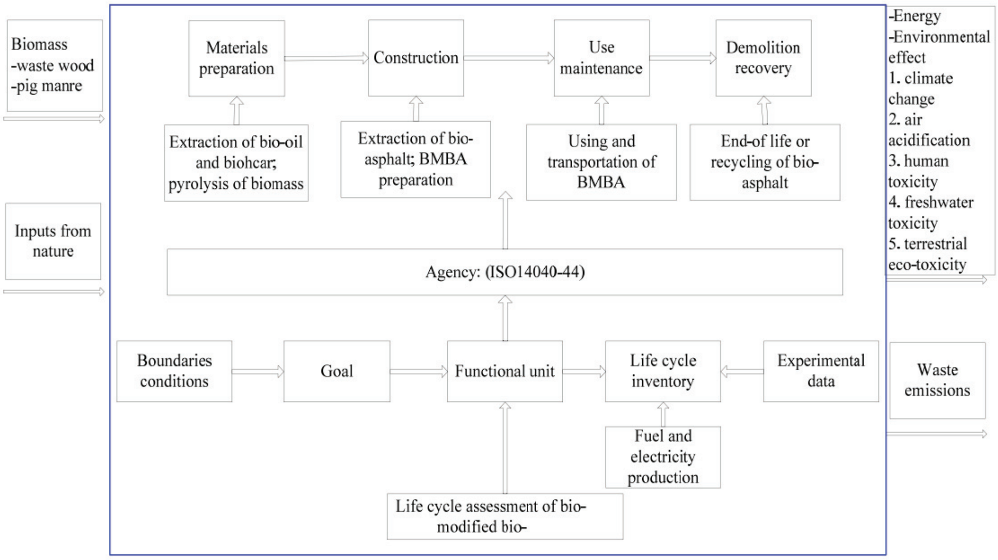

Fig. 4. LCA phases and processes of biochar utilization in asphalt [78]

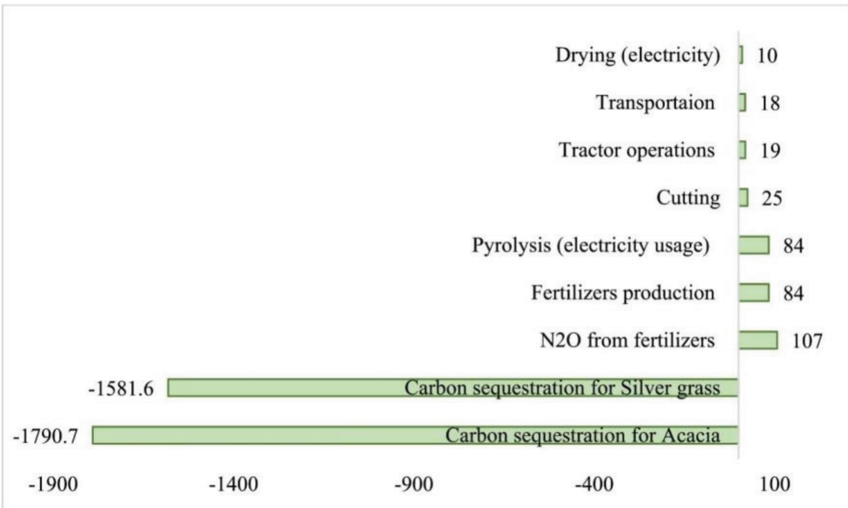

Fig. 5. Carbon-footprint analysis of processes throughout the life cycles of acacia biochar and silver-grass biochar [84]

emphasized the promising role of inherently metal-rich biomass feedstocks like acacia in mitigating VOC emissions from asphalt-surfaced areas while simultaneously contributing to carbon sequestration and overall environmental sustainability.

Pahlavan et al. [85] introduced biochar as a cost-effective additive to enhance the performance and durability of asphalt pavements while facilitating carbon management. Researchers hypothesized that the functional groups on biochar surfaces would enhance interactions between biochar and bitumen constituents, improving mechanical properties and durability. They investigated biochars derived from six different types of woody biomass and one type of algae, using polyethylene terephthalate (PET) granules as a carrier to introduce biochar into bitumen. Quantum-based molecular modeling and noncovalent interaction analysis revealed that algal biochar interacted more effectively with bitumen components due to its reactive nitrogen- and oxygen-carrying functional groups. The rheological characterization confirmed that bitumen containing algal biochar exhibited the lowest separation index, the highest percent of elastic recovery, and the highest resistance to permanent deformation. The study demonstrated that asphalt pavement durability could be enhanced by selecting the proper biochar to increase intermolecular interactions. Notably, the promising results for algal biochar promoted its use in carbon management for roadway infrastructure by sequestering CO_2 from the air through the photosynthesis of algae biomass. Integrating biochar into asphalt pavements not only improved performance but also reduced emissions and facilitated carbon sequestration, contributing to a carbon-neutral built environment.

These studies demonstrate the potential for biochar utilization in construction materials, including asphalt pavements, to contribute to carbon sequestration and emission reduction goals. However, further research is needed to quantify the specific carbon sequestration and emission reduction potentials of biochar modified asphalt materials, considering the various feedstocks, production processes, application methods, and performance characteristics of biochar in asphalt pavement engineering.

6. Future perspectives and conclusions

6.1. Future perspectives

The utilization of biochar in asphalt pavement engineering has shown promising potential for improving the mechanical, environmental, and economic performance of asphalt materials. However, there are still several challenges and limitations that need to be addressed to fully realize the benefits of this technology. This section discusses the current challenges and limitations, research gaps and opportunities, recommendations for future studies, and concluding remarks on the use of biochar in asphalt pavement engineering.

One of the main challenges facing the utilization of biochar in asphalt pavement engineering is the variability and inconsistency of biochar properties. Biochar can be produced from various biomass feedstocks, under different pyrolysis conditions, and with different post-treatment methods, resulting in a wide range of physical, chemical, and mechanical properties. This variability can affect the compatibility and performance of biochar modified asphalt materials, as well as the reproducibility and reliability of research results. For example, biochar with high ash content or low carbon stability may have negative effects on the rheological properties and aging resistance of asphalt binders [86], while biochar with high moisture content or low surface area may have limited effects on the mechanical properties and durability of asphalt mixtures [87]. Another challenge is the lack of standardized methods and specifications for the production, characterization, and application of biochar in asphalt pavement engineering. Currently, there are no widely accepted guidelines or quality control measures for ensuring the consistency and suitability of biochar for use in asphalt materials. This can lead to inconsistent results and difficulties in comparing and interpreting research findings from different studies. Moreover, the absence of performance-based specifications for biochar modified asphalt materials can hinder their adoption and implementation in practice, as transportation agencies and contractors may be reluctant to use new materials without established standards and proven track records.

The limited understanding of the long-term performance and durability of biochar modified asphalt materials is another limitation. Most of the existing studies have focused on the short-term or laboratory-scale evaluation of the mechanical and rheological properties of biochar modified asphalt binders and mixtures. However, there is a lack of field studies and long-term performance data on the behavior of biochar modified asphalt pavements under real traffic and environmental conditions. The aging, oxidation, moisture damage, and thermal cracking resistance of biochar modified asphalt materials over extended periods of time are not well understood, which can limit their practical application and market acceptance.

Despite the challenges and limitations, there are several research gaps and opportunities for advancing the utilization of biochar in asphalt pavement engineering. One research gap is the development of standardized methods and specifications for the production, characterization, and application of biochar in asphalt materials. This includes the establishment of quality control measures for ensuring the consistency and suitability of biochar properties, such as particle size distribution, surface area, carbon content, and moisture content. The development of performance-based specifications for biochar modified asphalt binders and mixtures, based on their rheological, mechanical, and durability properties, is also needed to facilitate their adoption and implementation in practice.

Another research opportunity is the investigation of the long-term performance and durability of biochar modified asphalt pavements under field conditions. This includes the monitoring and evaluation of the aging, oxidation, moisture damage, and thermal cracking resistance of biochar modified asphalt pavements over extended periods of time and under various traffic and environmental conditions. The use of accelerated pavement testing facilities and non-destructive evaluation techniques, such as infrared thermography and ground-penetrating radar, can provide valuable insights into the behavior and performance of biochar modified asphalt pavements over their service life.

The assessment of the environmental and economic impacts of biochar utilization in asphalt pavement engineering is another research opportunity. This includes the conducting of comprehensive life cycle assessment and cost-benefit analysis studies on the cradle-to-grave impacts of biochar production and utilization in asphalt pavements, considering the feedstock sources, production processes, transportation and construction activities, pavement performance and maintenance, and end-of-life recycling and disposal. The use of sustainability assessment tools, such as the Greenroads rating system and the Envision framework, can help to evaluate the environmental, social, and economic sustainability of biochar modified asphalt pavements, and to identify opportunities for improvement and optimization.

6.2. Conclusions

In conclusion, the utilization of biochar in asphalt pavement engineering has shown promising potential for improving the mechanical, environmental, and economic performance of asphalt materials. Biochar, as a sustainable and renewable material derived from waste biomass, can enhance the rheological properties, aging resistance, and low-temperature performance of asphalt binders, as well as the mechanical properties, moisture resistance, and rutting resistance of asphalt mixtures. Biochar can also reduce the environmental impacts of asphalt pavements, by sequestering carbon, reducing greenhouse gas emissions, and promoting the recycling and reuse of waste materials. However, there are still several challenges and limitations that need to be addressed to fully realize the benefits of biochar utilization in asphalt pavement engineering, such as the variability and inconsistency of biochar properties, the lack of standardized methods and specifications, the limited understanding of long-term performance and durability, and the uncertain economic and environmental feasibility. Future research should focus on addressing these challenges and exploring the research gaps and opportunities by developing standardized methods and specifications, investigating the long-term performance and durability under field conditions, optimizing the biochar production and modification methods, and assessing the environmental and economic impacts using life cycle assessment and cost-benefit analysis methods.

Conflict of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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None

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